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Original article

Oxygen in the Bottom Layer of the Amur Bay Waters (Sea of Japan) During the Cold Season 2013–2014

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Abstract
Purpose. This study aims to analyze oxygen concentration data from the bottom waters of Amur Bay during the cold season and to identify the causes of its decrease in late February to March, when the bay remains ice-covered.
Methods and Results. Variations in bottom water characteristics during the cold season were investigated in the area of summer hypoxia at a depth of 22 m (1 m above the seafloor) using the Water Quality Monitor autonomous bottom station (Wet Labs). Temperature, salinity (measured by conductivity), dissolved oxygen (*DO*), and chlorophyll a (measured by fluorescence) were recorded every 4 hours. Monitoring data from the cold period of 2013–2014 were compared with the data previously collected at the same station and location in summer 2011. The basic patterns of changes in oxygen content and the periods of dominance of production and organic matter mineralization in the bottom waters of Amur Bay during the cold season were identified.
Conclusions. During the winter season, upwelling of the Japan Sea waters delivers nutrients to the bottom waters of Amur Bay. Enhanced vertical mixing, driven by low water column stability, supplies the euphotic layer with nutrients, enabling photosynthesis throughout the bay's water column. Over four months in winter, the Amur Bay waters become supersaturated with oxygen relative to atmospheric levels. The onset of the summer monsoon (late February to early March) initiates the formation of summer hypoxia in the bottom waters of Amur Bay.

Keywords: Japan Sea, Amur Bay, dissolved oxygen, hypoxia, upwelling, downwelling, nutrients, photosynthesis

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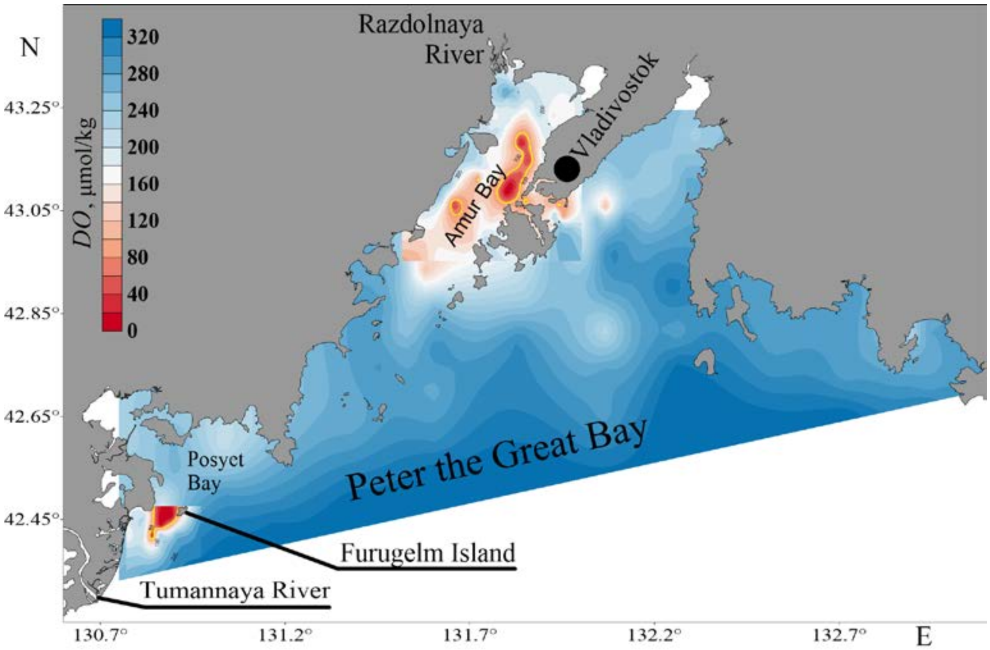
Introduction

Deoxygenation of the World Ocean and its continental shelves is a pressing global issue under intensive scientific investigation. There is broad consensus on the causes of hypoxia/anoxia on ocean shelves, with eutrophication of coastal waters being the primary driver [1]. In Peter the Great Bay (PGB), two depressions (Fig. 1) experience hypoxia (oxygen content below 76 µmol/kg) during the summer season. One depression, located near Furugelm Island in the southwestern part of the bay, exhibits irregular hypoxia, while the other, in the central part of Amur Bay, experiences consistent seasonal hypoxia [2]. The primary cause of hypoxia in these areas is nutrient influx during floods from the eutrophic Tumannaya and Razdolnaya Rivers [2].

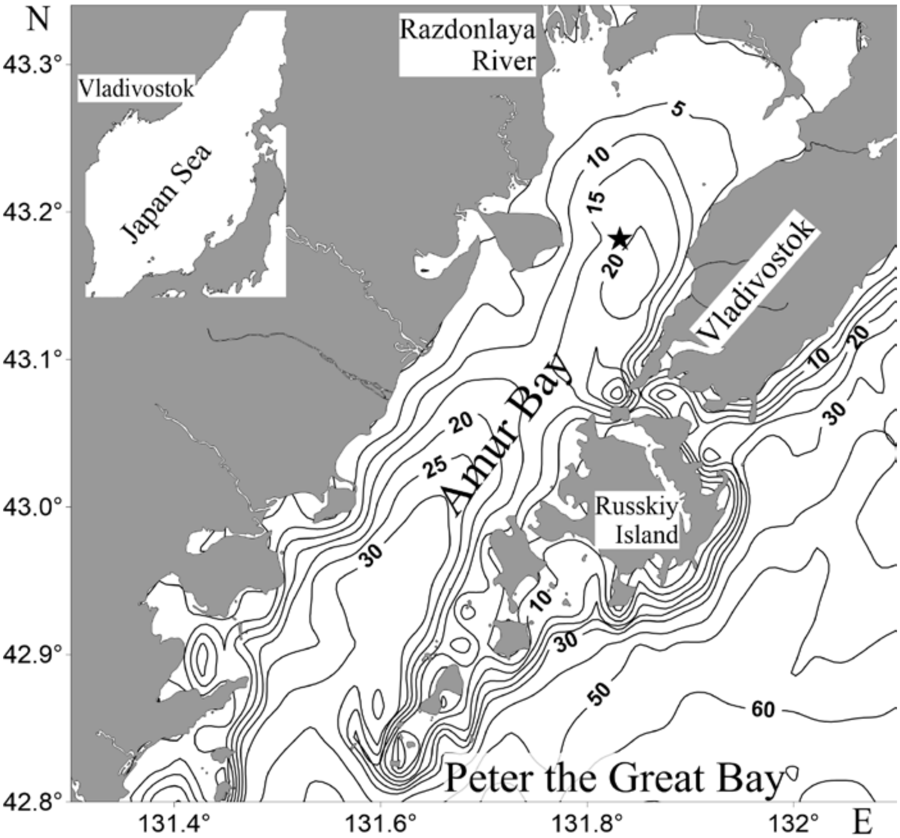


F i g. 1. Hypoxia areas in Peter the Great Bay

Amur Bay, a part of PGB, extends from northeast to southwest. The bay is 70 km long, with a width varying from 10 to 22 km [3]. Its maximum depths, located in the southernmost part, does not exceed 53 m, while the average depth is about 30 m [4]. The northern part of the bay features an extensive shallow zone with depths up to 10 m. The central part contains a deep-water depression with depths of 20–25 m. In the southeast, this depression is bounded by the Muravyov Ridge, which extends southeastward from the Peschaniy Peninsula to Russkiy Island (Fig. 2). During summer, hypoxia develops in the bottom waters of the depression, with its upper boundary at depths of 15–17 m [5]. Hypoxia is defined as an ecosystem state with oxygen levels low enough to cause quantitative and qualitative changes in the ecosystem. Literature sources suggest various threshold values for oxygen concentration as hypoxia criteria, typically ranging from 63 to 89 μmol/kg [6]. In this study, a threshold of 76 μmol/kg is adopted as the hypoxia criterion.

The monsoon climate of Primorye [7] drives downwelling circulation in Amur Bay during the spring-summer season, promoting hypoxia formation, and upwelling circulation during the autumn-winter season, facilitating its dissipation [8].

Numerous hydrochemical studies of Amur Bay have been conducted during the warm season, focusing on the processes of hypoxia formation and dissipation [6]. In contrast, hydrochemical processes during the winter season have received far less attention. Our research reveals high oxygen concentrations (400–500 μmol/kg) in both the surface and bottom waters of Amur Bay during winter [5]. Moreover, the bottom waters are supersaturated with oxygen relative to atmospheric levels, except in Tavrichanka Estuary and Uglovoy Bay [1]. Winter observations also indicate significant under-ice primary production (0.1–0.3 gC/m²) [9]. At the same time, extensive hydrological studies, including oxygen and chlorophyll measurements using a probe, led the authors of [10] to hypothesize the potential formation of hypoxia in the bottom waters of Amur Bay during winter. This study presents monitoring data collected during the cold season using an anchored station deployed in the area of summer hypoxia in Amur Bay.



F i g. 2. Geographical location of Amur Bay and depth map. Star indicates the WQM station location

This study aims to examine changes in water parameters and identify the primary causes of oxygen content variations in the bottom waters during the cold season.

Measuring methods

Variability in bottom water characteristics during the cold season was investigated in an area prone to summer hypoxia, at a depth of 22 m (1 m above the seabed), using the Water Quality Monitor (WQM) autonomous bottom station

[1] Tishchenko, P.P., 2013. *Seasonal Hypoxia of Amurskiy Bay*. Thesis Cand. Geogr. Sci. Vladivostok: POI FEB RAS, 166 p. (in Russian).

(Wet Labs). The station was positioned at 43°10.894′N, 131°49.949′E (Fig. 2). Measurements were conducted from September 11, 2013, to May 15, 2014. Temperature, salinity (measured by conductivity), dissolved oxygen (*DO*), and chlorophyll a (measured by fluorescence) were recorded every 4 hours with a 1-second interval over 5-minute periods using the DH4 submersible logger (Wet Labs). To mitigate biofouling, WET Labs employed copper housings, chlorine injection, and pesticide-containing inserts for the WQM station, ensuring stable sensor performance over extended periods [11]. The cited article provides detailed specifications of the WQM sensors. The discrepancy between oxygen measurements obtained by the WQM station and those using the Winkler method ranged from 1.2 to 14.0 μmol/kg [8]. The variation is primary attributed to the spatial mismatch between the WQM station and bathometer sampling locations. Monitoring data from the cold season of 2013–2014 were compared with data from the summer season of 2011, previously collected by the same station at nearly identical coordinates (43°10.881′N, 131°49.893′E) [8].

Summer and winter conditions in Amur Bay were compared using Apparent Oxygen Utilization (*AOU*), as this parameter reflects the balance between oxygen production and respiration processes. *AOU* values were calculated using the following equation:

$$AOU = [O_2]_o - [O_2].$$

Here, *AOU* is calculated as the difference between the oxygen concentration in seawater at equilibrium with the atmosphere ($[O_2]_o$) for a given temperature and salinity and the measured oxygen concentration ($[O_2]$). Oxygen solubility in seawater at specific temperature and salinity was determined using the equation from [12]. Seawater is supersaturated with oxygen relative to atmospheric levels when $AOU < 0$ and undersaturated when $AOU > 0$.

On March 22, 2011, a hydrochemical survey was conducted in the area of summer hypoxia in Amur Bay (43°11.816′N, 131°50.139′E). The survey was performed from a rescue vessel during the ice-melt period, when the northern part of Amur Bay was covered with broken ice, while the southern part was ice-free. Vertical profiles of CO_2 partial pressure (pCO_2), oxygen concentration, ammonium nitrogen, phosphates, and silicates were measured in the summer hypoxia area. Alkalinity was determined by direct titration in an open cell with 0.02N hydrochloric acid using a mixed indicator (methyl red + methylene blue) [2]. pH was measured potentiometrically at 20°C in a cell without liquid junction [13]. pCO_2 was calculated following the method described in [14]. Nutrient concentrations were determined using standard analytical methods [3].

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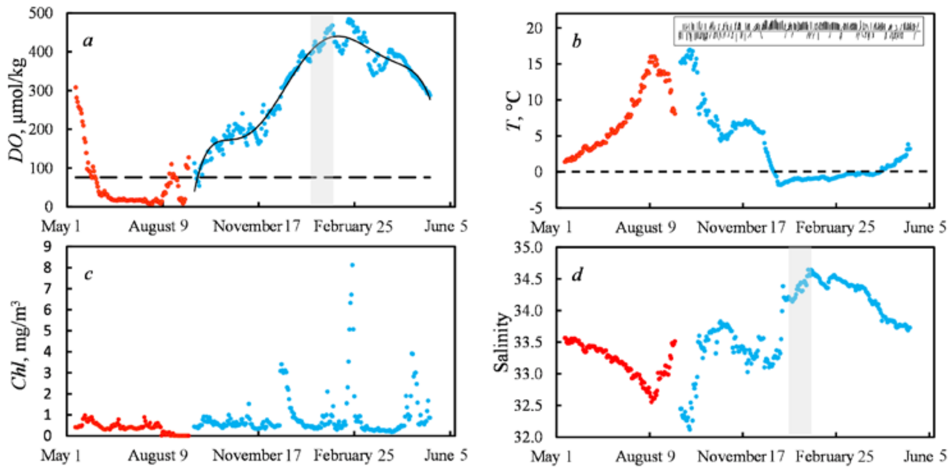
[2] Bruevich, S.V., 1944. [*Instructions for Chemical Investigation of Seawater*]. Moscow: Glavsevmorput, 83 p. (in Russian).

[3] VNIRO, 1988. [Methods of Hydrochemical Studies of Major Biogenic Elements]. Moscow: VNIRO, 120 p. (in Russian).

Results

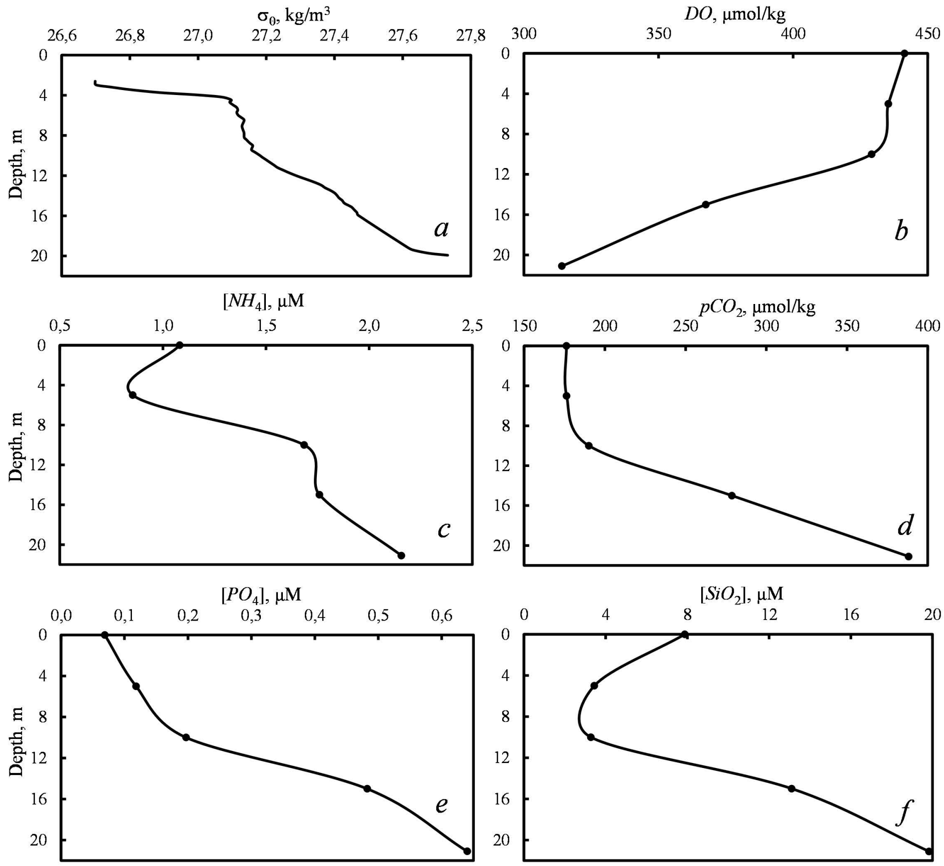
The detailed variability in the hydrological characteristics of the bottom waters of Amur Bay in the hypoxia formation area during the cold season of 2013–2014 is present in Fig. 3. To analyze a complete annual cycle, the data from the WQM station collected in 2011, previously analyzed in detail [8], were used.



F i g. 3. Temporal variability of dissolved oxygen concentration (dashed line indicates the hypoxia level – 76 μmol/kg) (*a*), temperature (*b*), chlorophyll a content (*c*) and salinity (*d*) in the Amur Bay bottom layer at the location of the WQM autonomous bottom station: in 2011 (●); in 2013–2014 (●). The inset in Fig. 3, *b* shows temporal variability of wind direction in 2013–2014. Grey area corresponds to the period December 27 – February 02 when salinity increases due to brine formation

In late August to autumn, bottom hypoxia in Amur Bay dissipates due to upwelling of the Sea of Japan waters [8], as evidenced by increased *DO*, absence of chlorophyll, decreased water temperature, and increased salinity. Elevated nitrate concentrations, absent in the bottom waters of Amur Bay during summer, indicate the intrusion of the Sea of Japan waters [1] from depths of 250–300 m. At these depths, silicate, nitrate, phosphate, and *DO* concentrations are 29.3, 17.2, 1.36, and 285 μM, respectively [15]. In 2013, the displacement of oxygen-depleted waters by cold, saline Sea of Japan waters occurred between September 12 and October 24 due to autumn upwelling (Fig. 3). This process was accompanied by a decrease in water temperature from 17.0 to 4.3 °C, an increase in salinity from 32.12 to 33.69, and an increase in *DO* from 54 to 213 μmol/kg. During this period, wind direction was variable, alternating between southerly and northerly (inset in Fig. 3, *b*).

The period from October 25 to December 9 marks the transition from the summer to winter monsoon in Amur Bay. This period is characterized by variable wind directions, resulting in altered bay water circulation and temporal variations in measured parameters: *DO* ranging from 159 to 263 μmol/kg, temperature from 4.6 to 7.2 °C, and salinity from 33.03 to 33.79. These significant variations are driven not only by changes in wind direction but also by wind-induced mixing of the Sea of Japan waters with residual summer shelf waters, alongside atmospheric cooling, which enhances the dissolution of atmospheric gases. The increase in oxygen concentration during this period is partly attributed to higher gas solubility at lower temperatures and enhanced primary production.



F i g. 4. Vertical profiles of conditional density (*a*), oxygen concentration (*b*), ammonium nitrogen concentration (*c*), partial pressure of carbon dioxide (*d*), and phosphate (*e*) and silicate (*f*) concentrations in the area of hypoxia formation (43°11.816′N, 131°50.139′E) in Amur Bay, March 22, 2011

On December 10, 2013, snowfall occurred along the coast of Amur Bay, initiating intensive ice formation in the bay. Water temperature dropped to the freezing point of seawater, − 1.818 °C, by December 27. Subsequently, salinity increased to 33.323, and oxygen concentration reached 353 µmol/kg. During this period, a peak chlorophyll concentration of 3.4 mg/m³ was recorded on December 17 (Fig. 3, *c*). From December 10 to 27, winter cooling led to the formation of continuous ice cover in the northern part of Amur Bay (north of 43°8.5′N to the mouth of the Razdolnaya River) and triggered winter convection. South of 43°8.5′N, ice formation occurred but remained discontinuous. Dominant northerly winds intensified this effect. On December 8, 2013, the average daily air temperature was 1.15 °C dropping to − 5.51 °C on December 9 (http://www.rp5.ru/). Satellite imagery from https://worldview.earthdata.nasa.gov/ indicates that by December 11, the northern part of Amur Bay was covered with continuous ice, with the WQM station located beneath it. The bottom water temperature reaching the seawater freezing point on December 27 suggests vertically uniform water parameters throughout the bay, as freezing occurs at the surface. From December 27 to February 2, salinity increased to 34.578 and *DO* rose to 468 μmol/kg (Fig. 3 *a*, *d*, grey area). During the same period, a slight increase in water temperature to −0.878 °C was observed. The maximum salinity of the Sea of Japan waters is 34.070 ± 0.002 [15], while Amur Bay waters exhibit significantly lower salinity during the warm season (Fig. 3, *d*) [3]. The salinity increase to 34.578 is attributed to brine formation during ice formation. The slight temperature increase is likely due to residual summer heat retained by the seabed [16, 10]. This bottom heating enhances vertical mixing, maintaining water column homogeneity with minor temporal variations in *T* and *S* (Fig. 3, *b*, *d*).

February was characterized by minor fluctuations in hydrological parameters. From February 2 to 12, *DO* decreased slightly to 396 μmol/kg, water temperature increased to −0.69 °C, and salinity decreased to 34.413. Conversely, from February 12 to 23, *DO* increased to 477 μmol/kg, water temperature decreased to −0.856 °C, and salinity rose to 34.56. These fluctuations are most likely driven by water advection in the bay, with the *DO* increase attributed to phytoplankton blooms. The peak chlorophyll concentration of 8 mg/m^3, observed on February 23, coincided with the maximum *DO* concentration (Fig. 3).

Vertical stratification of Amur Bay waters began forming in March (Fig. 4), driven by ice melt and seasonal temperature increases. During this period, upwelling circulation transitioned to downwelling due to variations in wind direction (Fig. 3, *b*) [8].

Discussion

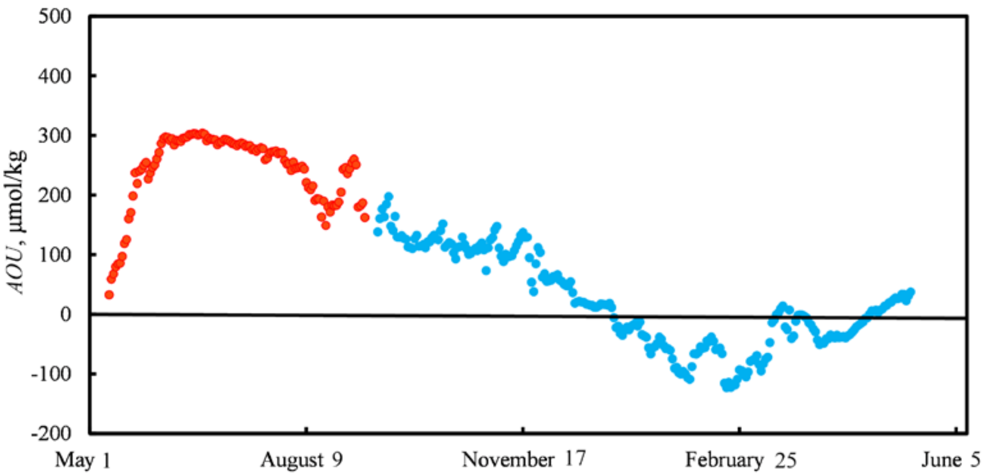
The monsoon climate of Primorye plays a critical role in the formation and dissipation of hypoxia in the bottom waters of Amur Bay. Southeasterly winds in summer drive downwelling circulation in the bay [8], limiting interaction between subsurface Sea of Japan waters and PGB shelf waters. This season also experiences the highest atmospheric precipitation [7]. In summer, the inflow of eutrophic waters from the Razdolnaya River into Amur Bay increases significantly. This, combined with other factors, establishes river runoff as the primary nutrient source for the bay, triggering phytoplankton blooms in surface waters. Oxygen produced during photosynthesis partially escapes to the atmosphere and partially remains in the upper water column due to stable stratification. Excess phytoplankton biomass, unconsumed by zooplankton and zoobenthos, settles to the bay floor. In the bay's depressions below 15–17 m, where photosynthetically active radiation (PAR) does not penetrate, hypoxia develops due to microbial decomposition of the settled phytoplankton biomass [2].

In the cold season, northwesterly winds drive upwelling circulation in the bay. During this period, atmospheric precipitation decreases significantly [7]. The Razdolnaya River discharge in winter is over 100 times lower than during summer floods. Meanwhile, subsurface Sea of Japan waters, upwelling from depths of 250–300 m, contain high concentrations of nutrients and dissolved oxygen: silicates (29.3 μM), nitrates (17.2 μM), phosphates (1.36 μM), and dissolved oxygen (285 μmol/kg) [15]. In winter, the primary nutrient source for Amur Bay is subsurface Sea of Japan waters. These waters are transparent, allowing PAR to reach the seafloor in the ice-free southern part of the bay. Photosynthesis occurs actively under ice when it is not snow-covered. Additionally, these waters enter the bottom waters of the bay and are mixed through winter convection. Nutrients from the Sea of Japan waters support winter photosynthesis in Amur Bay, resulting in elevated oxygen concentrations (Fig. 2). Using Redfield stoichiometry [17], the photosynthesis process can be represented as follows:

$$106 \cdot CO_2 + 122 \cdot H_2O + 16 \cdot HNO_3 + H_3PO_4 \leftrightarrow$$
$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138 \cdot O_2$$

We propose that the Sea of Japan waters fully replace Amur Bay shelf waters during upwelling. If photosynthesis occurs in these waters, the *DO* concentration would be (285 + 138 × [PO_4]) = 473 μmol/kg, comparable to the maximum winter *DO* concentration of 482 μmol/kg (Fig. 3, *a*). An additional nutrient source for the bay is the nutrient flux from the seabed [18].

The comparison of *AOU* between the warm and cold seasons is presented in Fig. 5. In summer, under downwelling conditions, decomposition processes dominate in the bottom waters of Amur Bay, with *AOU* values reaching up to 300 μmol/kg (Fig. 5). The influx of the Sea of Japan waters in autumn significantly reduces this dominance by supplying oxygen to the bottom waters. However, the transition from net decomposition to net production (*AOU* < 0) occurs only on December 29. This delay is attributed to the origin of the Sea of Japan waters from depths of 250–300 m, where photosynthesis is absent, and these waters exhibit an oxygen deficit relative to atmospheric levels. Comparison Figs. 3, *a* and 5 indicates that the shift in production-decomposition balance results solely from intensified organic matter production in December, driven by nutrient supply from the Sea of Japan waters and coinciding with winter convection when the entire water column reaches freezing temperatures. Fig. 5 shows that bottom waters of Amur Bay are supersaturated with oxygen relative to atmospheric levels for nearly four months (December 29, 2013 – April 22, 2014).



F i g. 5. Temporal variability of AOU in the Amur Bay bottom layer at the location of WQM station: in 2011 (●); in 2013–2014 (●)

The bottom waters at the WQM station exhibit consistently high *DO* concentrations throughout the winter season, exceeding the hypoxic threshold of 76 μmol/kg by 4–6 times. This phenomenon primarily stems from distinct nutrient delivery mechanisms compared to summer conditions. Unlike the stratified summer period, winter nutrient supply to the bottom waters occurs under conditions of high water transparency and the absence of density stratification in the Sea of Japan waters. Winter photosynthesis influences the entire ice-free water column through vertical mixing, delivering waters with $AOU < 0$ to the bottom waters, indicating oxygen supersaturation relative to atmospheric equilibrium. Notably, phytoplankton blooms can develop even under ice cover, as described in [19]. Although ice reduces PAR intensity, photosynthesis persists in shallow basins such as Novgorod Bay (10–15 m depth) and Posyet Bay due to winter convection processes. Winter convection in the shallow waters of Amur Bay facilitates complete vertical mixing, continuously supplying nutrients to the sub-ice layer where photosynthesis occurs. Phytoplankton cells undergo continuous cycling, being transported downward by convection and returning to the photic zone, with the shallow basin depth preventing their permanent export from layers influenced by PAR. We propose that this mechanism applies specifically to ice-covered areas of Amur Bay without snow cover, where sufficient light penetration supports sustained winter productivity despite surface ice conditions.

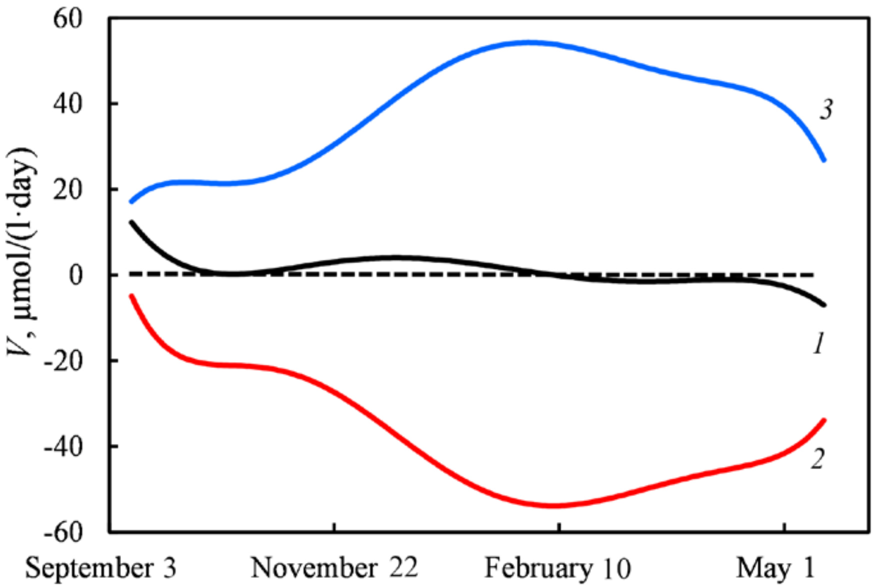
The observed decrease in oxygen levels after February 23 suggests the presence of mechanisms contributing to oxygen depletion in the bay waters. We propose two primary processes. During the winter season, when $AOU < 0$, gas exchange in ice-free areas of the bay reduces oxygen concentrations. The ice-free area expands from late February to early March, and by early April the bay becomes completely ice-free (https://worldview.earthdata.nasa.gov). This mechanism of oxygen removal from the bay waters is effective only when *DO* concentrations exceed atmospheric levels, i.e., until approximately April 26 (Fig. 5). However, even after the bay ecosystem shifts from dominance by production processes ($AOU < 0$) to dominance by decomposition processes (AOU > 0), *DO* concentrations in the bottom waters continue to decline (Figs. 3, 5). The second process contributing to *DO* reduction is biochemical oxygen consumption during organic matter mineralization at the water -sediment interface. We utilized previously determined rates of biochemical oxygen consumption V_{BOC} (μmol/(L·day)) for the bottom waters of Amur Bay [8]:

$$V_{BOC} = -0.1225 \cdot [O_2].$$

Observational data for oxygen concentration over time (Fig. 2) were processed using least squares method. An empirical equation for $[O_2]$ (μmol/L) was obtained:

$$[O_2] = -2.21703 \cdot 10^{-10} \cdot t^6 + 1.754836 \cdot 10^{-7} \cdot t^5 - 5.246808 \cdot 10^{-5} \cdot t^4 + \\ 7.23196 \cdot 10^{-3} \cdot t^3 - 0.453612 \cdot t^2 + 13.1475 \cdot t + 27.52. \quad (1)$$

Here t represents time in days from the start of observations. The derivative of this equation yields the total rate of oxygen change (V_{tot}) at any given time. The biochemical oxygen consumption rate (V_{BOC}) was calculated using the relation (1), and the ventilation rate (V_{vent}) was derived as the difference between V_{tot} and V_{BOC}. The results are presented in Fig. 6. Biochemical oxygen consumption is a second-order reaction [8], meaning the consumption rate peaks at maximum *DO* concentrations (Fig. 6; equation (1)).



F i g. 6. Dependence of rate of oxygen concentration change on time: *1* – total rate V_{tot} calculated by equation (1); *2* – rate of biochemical oxygen consumption of organic matter V_{BOC}; *3* – rate of water ventilation V_{vent}

In March 2011, profiles of hydrochemical parameters were obtained in Amur Bay (Fig. 4). By March 22, density stratification had developed due to ice melt and seasonal temperature increases. During this period, upwelling transitioned to downwelling, which limited the influence of the Sea of Japan waters on Amur Bay. Consequently, the profiles in Fig. 4 reflect geochemical processes at the bay's bottom. *DO* concentrations decreased toward the bottom, while nutrient concentrations increased, indicating organic matter mineralization at the water – sediment interface. The organic carbon content in sediments at hypoxia sites ranges from 2–3% [20], with mineralization in these sediments occurring via anaerobic pathways. Downwelling resuspends surface sediments in Amur Bay, increasing bottom water turbidity and enhancing the flux of mineralization products from sediments into the water column [8]. Therefore, despite relatively high *DO* concentrations, ammonium was the dominant form of mineral nitrogen (Fig. 4, *c*). Nitrate concentrations were also measured but were 2–3 times lower than those of ammonium. Another possible pathway is the formation of a thin low-oxygen layer [4] at the water – sediment interface in reduced sediments [21]. In this layer, organic

[4] Gurova, Yu.S., 2023. *Features of the Formation of Redox Conditions at the Water-Bottom Sediments Boundary in the Coastal Areas of the Russian Sector of the Azov-Black Sea Basin*. Thesis Cand. Geogr. Sci. Sevastopol, 182 p. (in Russian).

matter mineralization would primarily produce ammonium rather than nitrate [6]. This phenomenon warrants further investigation.

The transition period in late February to early March is crucial: the wind direction shifts from winter to summer monsoon, altering the bay's circulation from upwelling to downwelling. During this period, the interaction between the Sea of Japan waters and the shelf weakens, reducing nutrient supply from the Sea of Japan waters. Photosynthesis in the bay declines, and these factors collectively initiate the formation of summer hypoxia.

Conclusions

The oxygen content in the bottom waters of Amur Bay is shaped by the complex interplay of hydrodynamic processes and biogeochemical transformations.

Two primary natural sources govern nutrient dynamics and ecological conditions in Amur Bay: 1) eutrophic waters discharged by the Razdolnaya River; 2) the deep Sea of Japan waters originating from depths of 250–300 m.

During the winter months, upwelling of the Sea of Japan waters transports nutrients to the bottom waters of Amur Bay. The low static stability of the water column facilitates vertical mixing, effectively supplying the euphotic zone with nutrients. This mixing enables photosynthetic activity to extend throughout the entire water column. As a result, winter waters maintain oxygen supersaturation relative to atmospheric equilibrium for approximately four months, with *DO* concentrations ranging from 353 to 482 μmol/kg.

The Amur Bay ecosystem undergoes transitions twice per year corresponding to shifts in circulation patterns. From February to March, the establishment of downwelling circulation triggers several interconnected processes: increased nutrient input from the Razdolnaya River, the development of pronounced vertical stratification, and a progressive decline in near-bottom *DO* concentrations, ultimately reaching hypoxic conditions (less than 76 μmol/kg) by summer. Conversely, from September to October, the onset of upwelling circulation dissipates summer hypoxia while delivering nutrient-rich subsurface Sea of Japan waters.

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