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Original article

Distribution of Nutrients in the Bottom Waters of the East Siberian Sea and the Laptev Sea

A. A. Polukhin [1], Yu. S. Gurova [2, ✉]

[1] *Shirshov Institute of Oceanology of the Russian Academy of Sciences, Moscow, Russian Federation*
[2] *Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation*
✉ *Gurova@mhi-ras.ru*

Abstract
Purpose. This study aims to identify patterns of spatial variability in the concentrations of key nutrients (nitrite and nitrate, phosphate, and silicate) and carbonate system parameters (pH and total alkalinity) in the bottom waters of the Laptev and East Siberian seas.
Methods and Results. Bottom waters of the Laptev and East Siberian seas were investigated using data collected during the 69th cruise of R/V *Akademik Mstislav Keldysh* in summer and autumn 2017. Bottom water samples were collected along four transects: Khatanga and Lena (Laptev Sea), and Indigirka and Kolyma (East Siberian Sea). Sampling was performed using the Neimisto corer, which allowed layer-by-layer collection from three horizons (0–15, 15–30, and 30–45 cm) above the seabed. Hydrochemical variables were measured using standard methods. Total alkalinity generally increased from coastal stations toward offshore areas, reflecting the influence of river runoff (1.1–1.9 mM/L), and toward the outer shelf (2.2–2.5 mM/L). Slightly alkaline conditions (pH 7.8–8.1) were observed throughout the study area. The lowest oxygen saturation (56–73 %) occurred in zones directly influenced by large rivers and in areas with limited water exchange. Maximum phosphate (up to 1.43 μM) and silicate (up to 41.22 μM) concentrations at coastal stations confirm the effect of river runoff. Conversely, anomalously high concentrations and nonconservative vertical distributions in some deeper offshore areas may indicate additional sources, including diagenetic processes and inputs associated with submarine permafrost thaw.
Conclusions. The results highlight the key role of the near-bottom layer as an active zone of nutrient transformation, where coupled physical, chemical, and biological processes significantly affect benthic ecosystem functioning. These findings are relevant for assessing climate-change impacts on the Arctic shelf, particularly in the context of submarine permafrost degradation and shifts in river runoff regimes.

Keywords: Arctic, East Siberian Sea, Laptev Sea, Arctic shelf, hydrochemistry, carbonate system, bottom waters, nutrients, bottom layer

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Introduction

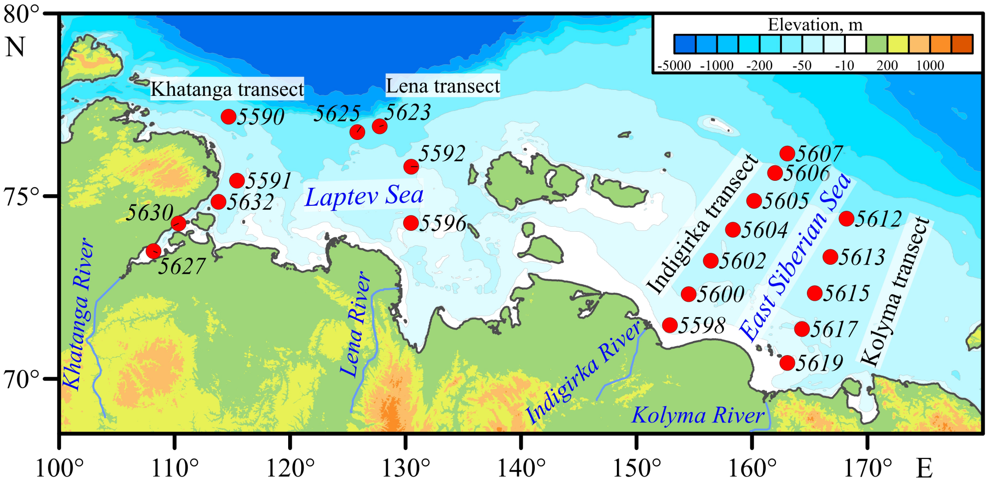
Arctic ecosystems have undergone significant transformation in recent years, primarily due to climate change [1]. A large number of studies have been devoted to investigating biogeochemical processes in the water column [1–6], while the hydrochemical features of bottom and pore waters have been studied much less frequently and only episodically [7–9]. Meanwhile, analyzing the variability of parameters such as the concentrations of major nutrients (nitrites, nitrates, phosphates, silicates) and total alkalinity allows assessment of the influence on the benthic ecosystem of both external factors and processes occurring within it.

The bottom water layer is key to the transformation of nutrients supplied from the water column and bottom sediments [10]. This layer exhibits pronounced vertical concentration gradients caused by the interaction of physical, chemical, and biological processes [2]. The bottom layer is of particular importance on the Laptev Sea shelf, where the discharge of the Lena and Khatanga rivers is concentrated: it creates stable stratification of the water column and also drives active inputs of terrigenous organic matter (OM) and nutrients [11, 12]. Under such conditions, zones with reduced oxygen content can form in the bottom water layer [13, 14]. The influence of river discharge on the formation of bottom waters in the East Siberian Sea is significantly weaker than in the Laptev Sea, which determines differences in their hydrochemical characteristics. The Laptev Sea accounts for ~ 30% of the total continental runoff into the Russian Arctic seas, while the East Siberian Sea receives only ~ 10% [15, 16]. This contrast shapes unique features in the distribution of nutrients: a homogeneous bottom water mass forms in the East Siberian Sea, whereas the influence of the riverine nutrient load is clearly pronounced in the Laptev Sea. Deep-water areas of the Arctic shelf, unlike shallow-water areas, are characterized by a more uniform distribution of parameters in the bottom layer due to the limited influence of river discharge and the predominance of vertical mixing processes [17]. However, even here, the bottom water layer acts as a kind of buffer, regulating the exchange between bottom sediments and the water column [14].

The purpose of the study is to identify patterns of spatial variability in the concentrations of key nutrients (nitrites and nitrates, phosphates, and silicates) and carbonate system parameters (pH and total alkalinity) in the bottom waters of the Laptev and East Siberian seas.

Materials and methods

The study used data obtained during a comprehensive expedition aboard the R/V *Akademik Mstislav Keldysh* in September 2017. In the Laptev Sea, two transects were completed: the Khatanga transect (from Khatanga Bay to the continental slope – stations *5627*, *5630*, *5632*) and the Lena transect (in the area influenced by the Lena River discharge – stations *5596*, *5592* – and at the location of seeps on the continental slope – station *5623*). In the East Siberian Sea, two latitudinal transects from the estuarine areas of the Indigirka and Kolyma rivers to the continental slope were also completed: the Indigirka transect (stations *5598*, *5600*, *5602*, *5604*, *5605*, *5606*, *5607*) and the Kolyma transect (stations *5612*, *5613*, *5615*, *5617*, *5619*) (Fig. 1, Table).



F i g. 1. Scheme of sampling stations (red circles). See the table for station coordinates

Coordinates of the stations at four transects

Sea	Transect	Period	Station number	Latitude, ˚N	Longitude, ˚E
Laptev	Khatanga	September 17–18	5627	73.494	108.181
			5630	74.254	110.340
			5632	74.847	113.809
			5590	77.174	114.675
			5591	75.424	115.409
	Lena	September 2–16	5592	75.808	130.489
			5596	74.263	130.475
			5623	76.908	127.761
East Siberian	Indigirka	September 5–7	5598	71.467	152.890
			5600	72.320	154.513
			5602	73.234	156.430
			5604	74.080	158.348
			5605	74.873	160.183
			5606	75.636	161.996
			5607	76.165	163.054
	Kolyma	September 8–9	5612	74.383	168.192
			5613	73.337	166.788
			5615	72.347	165.440
			5617	71.362	164.341
			5619	70.434	163.069

Bottom water samples were collected using a Neimisto corer. After retrieval on deck and allowing the water in the bottle to settle, water was first drawn from the layer 0–15 cm above the sediment-water interface using a thin silicone hose, then from the 15–30 cm layer, and finally from the 30–45 cm layer. Thus, near-bottom water was obtained layer-wise from three horizons directly above the bottom. This method ensures sampling accuracy unattainable when using a standard water sampler.

The concentrations of phosphates (PO_4^{3-}), silicates (SiO_3^{2-}), nitrites (NO_2^-), and nitrates (NO_3^-), as well as parameters of the carbonate system (pH on the NBS scale and total alkalinity, Alk) were determined using standard methods developed for marine hydrochemical research [18, 19]; the optical density of samples after staining was measured using a Hach Lange DR 2800 spectrophotometer (Germany). The concentration of dissolved oxygen was determined by the Winkler method; samples were collected in special small-volume (30 mL) bottles, with 0.5 mL of manganous chloride and an alkaline iodide solution (KI + KOH) added for fixation. Titration was performed according to the standard method using a semi-automatic Aquilon burette and a 0.02 N sodium thiosulfate ($Na_2S_2O_3$) solution. Oxygen saturation was calculated using the Weiss formula. Conversion of pH to *in situ* values was performed using the CO_2Sys program [20].

Samples for determining nutrient concentrations were pre-filtered through Millex-HV membrane filters (Merck Millipore, Germany) with a pore size of 0.45 µm.

Results and discussion

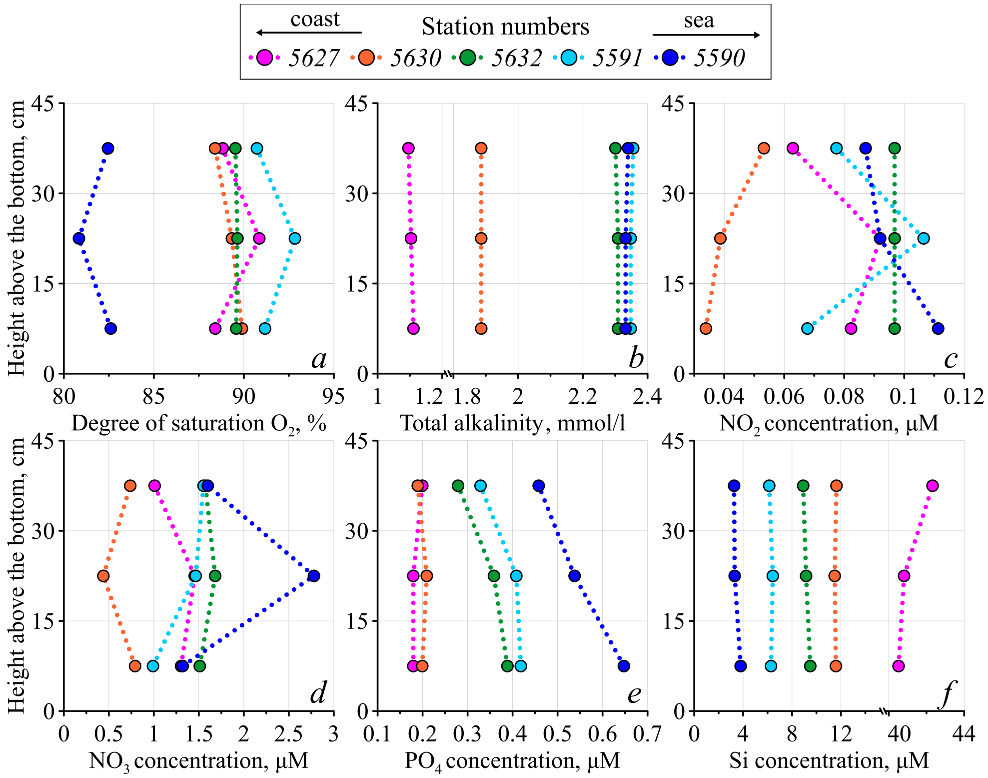
The Khatanga transect in the Laptev Sea

Studies were conducted along a transect in the Khatanga Bay area of the Laptev Sea. The transect length was 617 km, extending from the offshore part of the Khatanga River mouth and Khatanga Bay towards the continental slope.

In the bottom water layer (0–45 cm above the sediment surface), total alkalinity values increased with distance of the stations from the river mouth zone – from 1.1 mM/L (Fig. 2, *c*) at st. *5627* to 2.3 mM/L at st. *5632* (Fig. 2, *b*). Weakly alkaline conditions (pH values ranged from 7.87 to 8.02) were observed at all stations, which is characteristic of the zone of active interaction between the water column and bottom sediments.

The NO_2 content at all stations and horizons varied insignificantly and did not exceed 0.11 µM. The minimum average NO_3 concentration (Fig. 2, *d*) in the bottom layer for the Khatanga transect was noted at st. *5630* (0.6 µM on average), which is likely a consequence of mixing between fresh and marine waters.

The PO_4 content in the 30–45 cm layer generally increased in the estuarine zone from 0.19 µM at st. *5627* to 0.55 µM at st. *5590* (Fig. 2, *e*), which is apparently related to the transformation of riverine and marine waters within the marginal filter. At the offshore station (st. *5590*), hydrological characteristics anomalous for the transect were also noted (water temperature −1.6 °C, salinity 33.8 PSU), which may indicate additional input of PO_4 with waters from the Kara Sea or meltwaters from the north. In the offshore part of the transect (st. *5590*), concentrations decreased. A similar distribution pattern was noted for total alkalinity and nitrite and nitrate concentrations.



F i g. 2. Distribution of hydrochemical parameters: oxygen saturation (*a*); total alkalinity (*b*); and nutrient concentrations: NO_2 (*c*); NO_3 (*d*); PO_4 (*e*); Si (*f*) in the bottom waters of the Khatanga transect

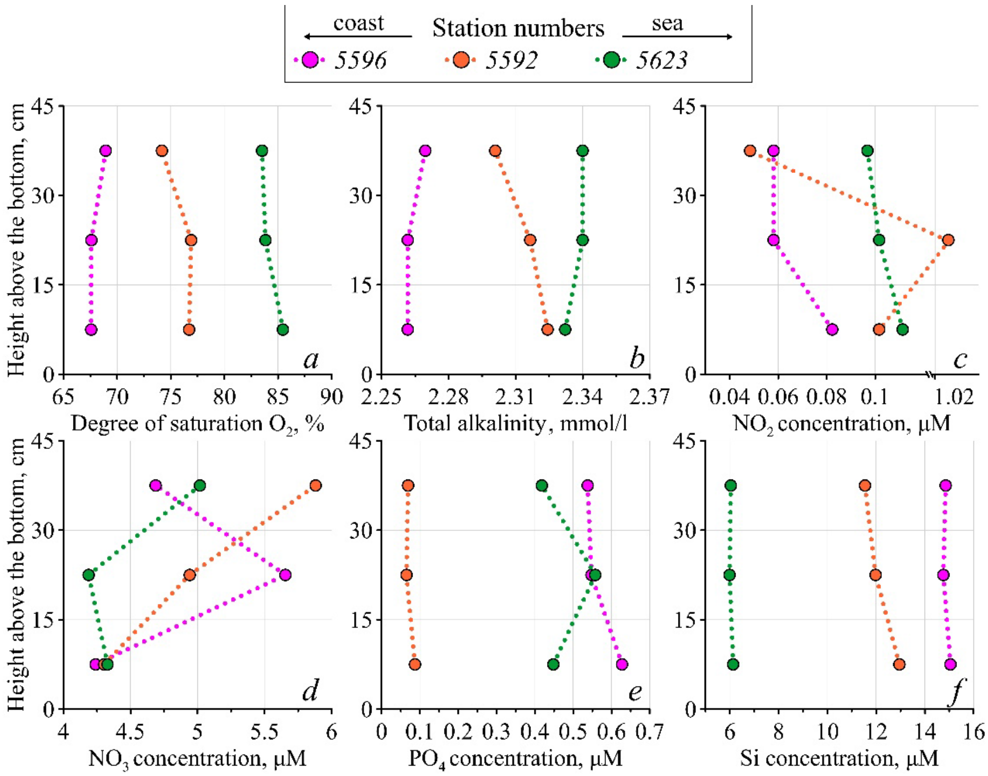
An exception is the distribution of silicate concentration (Fig. 2, *f*), the maximum value of which was recorded at st. *5627* (41.22 µM); then, with distance offshore, its concentration sharply decreased, varying in the range of 3.5–11.6 µM at the remaining stations, indicating a significant influence of river discharge.

The bottom water layer was saturated with oxygen; the degree of saturation varied insignificantly – in the range of 89.2–91.6% (Fig. 2, *a*), which is generally consistent with the obtained nutrient concentrations. The minimum values, noted at st. *5590* located in the northern part of the transect, are due to the increase in station depth (62 m) and, possibly, the decomposition of organic matter (OM) in the bottom sediments. This assumption is supported by elevated NO_3 concentration values (1.3–2.8 µM) at this station.

The Lena transect in the Laptev Sea

Studies were conducted in the central part of the Laptev Sea shelf from the continental slope towards the Lena River delta. The transect length was 246 km.

The distribution of total alkalinity along the transect was uniform (Fig. 3, *b*); its values averaged 2.3 mM/L, which may indicate an acid-base equilibrium at the water–bottom interface characteristic of shelf zones. The hydrogen ion concentration (pH) of the waters along the transect varied from 7.95 to 8.09, corresponding to weakly alkaline conditions. Oxygen saturation of the waters was uneven (Fig. 3, *a*). At st. *5596*, located closer to the river delta, it averaged 68%, indicating an active process of OM decomposition. As the stations moved away from the shore, the waters became more saturated with oxygen – up to 86% at st. *5623*. This increase in saturation can be explained by the weakening influence of river discharge, which supplies OM to the shelf, and the strengthening influence of marine waters. This conclusion is supported by a decrease in water temperature (from +1.2 to −1.8 °C) and an increase in salinity (from 32.2 to 34.1‰).



F i g. 3. Distribution of hydrochemical parameters: oxygen saturation (*a*); total alkalinity (*b*); and nutrient concentrations: NO_2 (*c*); NO_3 (*d*); PO_4 (*e*); Si (*f*) in the bottom waters of the Lena transect

The maximum NO_2 concentration was noted at st. *5592* (1 μM) (Fig. 3, *c*), which may indicate incomplete denitrification occurring under oxygen-deficient conditions (76%). The distribution of NO_3 was relatively uniform (averaging 4.8 μM), except for a slight decrease in the area of seeps (averaging 4.5 μM/l) (Fig. 3, *d*). The maximum concentrations of phosphates and silicates, noted at st. *5596* (0.57 μM and 14.9 μM, respectively), indicate a significant influence of the Lena River discharge in this area (Fig. 3, *e*, *f*). As the distance from the delta increases, the silicate concentration gradually decreases (to 6.1 μM). However, silicate concentrations at the station near the Lena River delta (st. *5596*) were lower than at st. *5627* (Khatanga transect), which is explained by the greater distance of st. *5596* from the mouth area. Phosphate concentrations first decrease significantly (from 0.6 to 0.1 μM) and then increase in the area of the seeps (0.5 μM at st. *5623*), indicating the seeps as a possible source of PO_4 input [21]. At st. *5623*, an inversion in the vertical distribution of phosphates was also noted: their concentration increased from 0.4 μM (30–45 cm layer) to 0.6 μM (15–30 cm layer) and then decreased to 0.41 μM (0–15 cm layer) (Fig. 3, *e*). It is also worth noting that similar changes in silicate concentration in the area of the seeps were not observed.

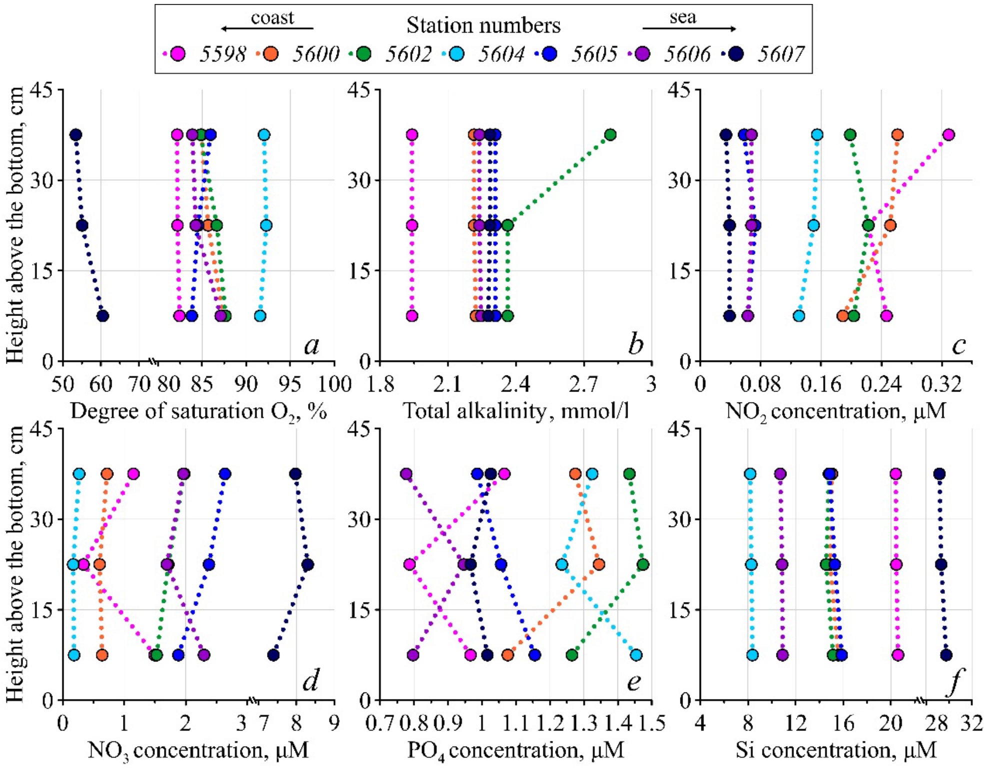
The Indigirka transect in the East Siberian Sea

Studies were conducted in the East Siberian Sea from the estuarine area of the Indigirka River towards the continental slope. The transect length was 614 km.

A reduced (relative to the entire transect) value of total alkalinity (1.94 mM/L) was noted at the southern station of the transect (st. *5598*) (Fig. 4, *b*), which is characteristic of this area and is associated with the influence of continental runoff and lower water salinity (down to 24.6 PSU). At the remaining stations of the transect, alkalinity stabilized and varied within 2.2–2.5 mM/L under weakly alkaline conditions (pH = 7.8).

Oxygen saturation of bottom waters increased from 82% (st. *5598*) to 92% (st. *5604*) (Fig. 4, *a*), which may indicate its consumption during the oxidation of OM in the zone of river discharge influence (st. *5598*, *5600*, *5602*). The development of hypoxia (56%) in the northern part of the transect (st. *5607*) is likely related to the increased depth of the sampling station (58 m) and the decomposition of OM in sediments against a background of weak water exchange with the Arctic Basin. This is confirmed by the anomalously high nitrate (NO_3) concentration at st. *5607* (7.9 μM on average), exceeding by several times its maximum values at the nearby stations st. *5605* (2.3 μM) and *5606* (1.98 μM) along the transect and by an order of magnitude – at st. *5600* (0.65 μM/L) and *5604* (0.21 μM) (Fig. 4, *d*). In general, the excess of nitrate concentrations in the northern part of the transect (st. *5604*, *5605*, *5606*, *5607*) over the values in the southern part, subject to river discharge influence, confirms the hypothesis that at the time of the study, the main source of nutrients in the Arctic seas was recycling, not continental runoff, as shown in [22].

Maximum phosphate concentration values (1.43 μM) were noted at st. *5602* and *5604* just before a depression in the bottom relief forming a trough about 10 m deep; minimum values (0.84 μM) were at st. *5606* in the zone of interaction between marine and continental waters (Fig. 4, *e*). Three types of vertical phosphate distribution in the bottom layer were identified: conservative (increase towards the bottom, st. *5605*), inversion (maximum in the intermediate layer, st. *5600*, *5602*, and *5606*), and reverse inversion (minimum in the intermediate layer 15–30 cm above the sediment, st. *5598* and *5604*). The amplitude of phosphate concentration variability in the near-bottom 45-cm layer is ~ 0.1 μM for inversion and 0.2 μM for reverse inversion.



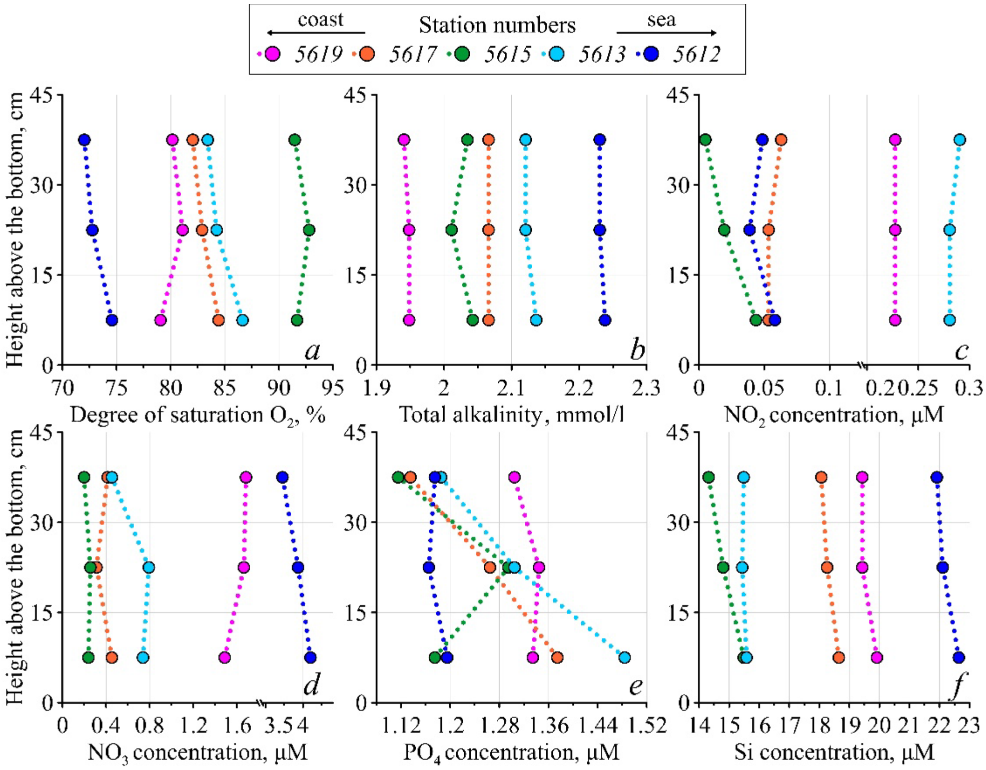
F i g. 4. Distribution of hydrochemical parameters: oxygen saturation (*a*); total alkalinity (*b*); and nutrient concentrations: NO_2 (*c*); NO_3 (*d*); PO_4 (*e*); Si (*f*) in the bottom waters of the Indigirka transect

The distribution of silicates was also uneven: concentrations decreased from 20.5 μM (st. *5598*) to 8.28 μM (st. *5604*), which, like total alkalinity, indicates the influence of continental runoff (Fig. 4, *f*). Anomalously high silicate concentration values (29.4 μM on average) at st. *5607*, uncharacteristic for this depth (58 m), may be related to their input from thawing permafrost [23]. The nitrite (NO_2) concentration smoothly decreased with increasing distance of stations from the shore – from a maximum at st. *5598* (0.27 μM on average) to a minimum at st. *5607* (0.04 μM on average) in the area of the depression, which, given the maximum nitrate concentrations and the minimum oxygen saturation of the waters (56%), may indicate the occurrence of the second stage of the nitrification process (Fig. 4, *c*).

The Kolyma transect in the East Siberian Sea

Studies on the transect were conducted in the East Siberian Sea from the estuarine area of the Kolyma River to the deep part of the shelf. The transect length was 538 km.

Total alkalinity along the transect smoothly increased from 1.9 mM/L at st. *5619* to 2.2 mM/L at the station farthest from the shore, st. *5612* (Fig. 5, *b*), which is explained by the decreasing influence of river discharge.



F i g. 5. Distribution of hydrochemical parameters: oxygen saturation (*a*); total alkalinity (*b*); and nutrient concentrations: NO_2 (*c*); NO_3 (*d*); PO_4 (*e*); Si (*f*) in the bottom waters of the Kolyma transect

Oxygen saturation of bottom waters was uneven; its maximum value (92%) was noted at st. *5615* (in the middle of the transect), likely due to active mixing (Fig. 5, *a*). The minimum saturation value (73%) at st. *5612* corresponds to the maximum nitrate concentrations, indicating the nitrification process. Elevated values of nitrates (1.61 μM) and nitrites (0.3 μM) at st. *5619* are explained by the influence of continental runoff (Fig. 5, *c*, *d*). The absolute maximum nitrite content was noted at st. *5613* (0.29 μM). The pH distribution along the transect correlated with the distribution of dissolved oxygen content and its saturation degree, which is related to common determining factors (water temperature and the balance of production and destruction processes).

A fairly uniform distribution of phosphate concentrations along the transect (range of average values 1.2–1.3 μM) may indicate active water mixing in this part of the area (Fig. 5, *e*). At st. *5613* and *5617*, a sharp vertical phosphate gradient is observed: in the 30–45 cm layer, variability amounts to 0.3 μM, which may be related to bottom orography (dynamic shelf slope and a depression in relief, respectively). At st. *5615*, an inversion of phosphate concentration is observed: values increase from the 30–45 cm layer to the 15–30 cm layer by 0.19 μM, then decrease by 0.17 μM in the 0–15 cm layer.

The silicate content was high for depths up to 20 m (averaging 17 μM), confirming the strong impact of continental waters on the studied area (Fig. 5, *f*). Substantial spatial variability in silicate content in the bottom layer was noted: a maximum (19.6 μM) at st. *5619* near the shore in the zone of river water input, a minimum (14.9 μM) at st. *5615* in the central part of the transect, and at the most offshore station, st. *5612*, the content increases again to an anomalously high value of 22.2 μM, which may indicate the influence of thawing subsea permafrost [23].

Conclusion

As a result of the study on the shelf of the Laptev and East Siberian seas, features of spatial and vertical variability in the concentrations of major nutrients (nitrites and nitrates, phosphates, silicate), dissolved oxygen, and parameters of the carbonate system (pH, total alkalinity) in the bottom water layer have been revealed. Layer-by-layer sampling using a Neimisto corer made it possible to obtain vertical profiles of the studied components in the 0–45 cm layer above undisturbed sediment. Spatial patterns reflecting the influence of river discharge on the bottom layer have been identified. Analysis of data from the four transects (Khatanga, Lena, Indigirka, and Kolyma) showed that total alkalinity tends to increase from coastal stations near river mouths (1.1–2.3 mM/L) to remote shelf areas (2.2–2.3 mM/L), which serves as an indicator of decreasing river discharge influence with distance from the shore. At the same time, the minimum alkalinity values in the Khatanga River mouth area are explained by limited water exchange between the waters of Khatanga Bay and the Laptev Sea. Weakly alkaline conditions (pH 7.8–8.1) characteristic of Arctic shelf seas were maintained in all studied areas.

It has been established that the minimum values of water oxygen saturation (56–68%) were noted in zones of direct influence of large rivers (Khatanga, Lena, Indigirka, and Kolyma). This is associated with intensive oxygen consumption during the decomposition of organic matter. At stations remote from the mouth areas of Arctic rivers, oxygen saturation reached 85–92%, reflecting active mixing of water masses.

Significant heterogeneity in the spatial distribution of nutrients was revealed not only between the two considered sea areas but also within these areas. Maximum concentrations of phosphates (up to 1.43 μM) and silicates (up to 41.22 μM) at coastal stations confirm the leading role of river discharge in supplying these nutrients, while anomalously high concentration values at individual remote stations may indicate additional sources, such as diagenetic processes in sediments and the influence of thawing subsea permafrost. These same processes most likely influence the non-conservative vertical distribution of phosphates in the relatively thin bottom layer, where significant vertical gradients (0.1–0.3 μM per 1 cm layer or up to 25% of absolute values) were recorded. The distribution of nitrates and nitrites in the bottom water layer, in particular the minimum nitrate values in the central parts of transects and local nitrite maxima, indicates the active occurrence of nitrification and denitrification processes, the intensity of which may be determined by features of bottom topography and water dynamics.

The results obtained emphasize the key role of the bottom layer as a zone of active transformation of nutrients, where the interaction of physical, chemical, and biological processes can significantly influence the state and development of benthic ecosystems on the Arctic shelf. Further research is necessary to understand the functioning of Arctic ecosystems under climate change conditions, especially in the context of forecasting the consequences of subsea permafrost degradation on the shelves of the Laptev and East Siberian Seas and changes in the river discharge regime.

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About the authors:

Aleksandr A. Polukhin, Senior Researcher, Head of Bio-Hydrochemistry Laboratory, Shirshov Institute of Oceanology of the Russian Academy of Sciences (36 Nakhimovsky Ave., Moscow, 117997, Russian Federation), CSc. (Geogr.), **ORCID ID: 0000-0003-1708-1428**, **Scopus Author ID: 47561889400**, **ResearcherID: S-2879-2016**, **SPIN-code: 5383-5138**, aleanapol@gmail.com

Yulia S. Gurova, Researcher, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), CSc. (Geogr.), **ORCID ID: 0000-0002-9826-4789**, **Scopus Author ID: 57964475800**, **ResearcherID: AAB-5628-2019**, **SPIN-code: 9777-8929**, gurova@mhi-ras.ru

Contribution of the co-authors:

Aleksandr A. Polukhin – data preparation, formulation of the problems, discussion of results and formulation of conclusions, critical analysis

Yulia S. Gurova – literature review, writing of the original draft, discussion of results, preparation of illustrative materials, formulation of conclusions, work with editors on paper preparation for publication

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