The Spatial Distribution of Plankton Picocyanobacteria on the Shelf of the Kara, Laptev, and East Siberian Seas

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Abstract—The spatial distribution of picocyanobacteria at the arctic longitude section passing through the shelf of the Kara, Laptev, and East Siberian seas from 58° to 168° E was studied. The average abundance of picocyanobacteria was 0.48 ± 1.2 × 10⁹ cells/m³ in the Kara Sea, 0.16 ± 0.24 × 10⁹ cells/m³ in the Laptev Sea, and 0.25 ± 0.43 × 10⁹ cells/m³ in the East Siberian Sea. The fluctuations of picocyanobacterial abundance were determined by their presence in allochthonous sources: river flow and transformed North Atlantic waters. The highest abundance was observed in the areas of the runoff influence of the Ob, Khatanga, Indigirka, and Kolyma Siberian rivers: 0.5 × 10⁹, 0.2 × 10⁹, 0.4 × 10⁹, and 1.6 × 10⁹ cells/m³, respectively. The average contribution of picocyanobacteria to the total abundance and biomass of picophytoplankton in the western part of the Kara Sea was 37 and 36%, respectively. In other regions, the average contribution of picocyanobacteria to the total abundance and biomass of phototrophic picoplankton did not exceed 7 and 6%, respectively. A highly reliable (p < 0.01) positive correlation between the abundance and biomass of picocyanobacteria and the water temperature (p = 0.003) was revealed in the entire dataset obtained.

Keywords: picophytoplankton, picocyanobacteria, Arctic, Ob, Khatanga, Indigirka, Kolyma.

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Picocyanobacteria (PCB, cell size less than 3 μm) [1] compose an essential component of phytoplankton in the World Ocean [2]. However, the abundance of PCB in the Arctic ecosystems is small or PCB are even completely absent locally [3, 4]. In polar waters, PCB are mainly represented by species of the genus Synechococcus, which are either autochthonous [4] or allochthonous forms [4–6]. The main sources of allochthonous PCB in the Arctic are river flow [5] and North Atlantic [4] and Pacific waters [6]. Changes in abiotic factors in the Arctic under the effect of the climatic trend [7] (elevated surface temperature, high river flow [8] and a high amount of warm salty North Atlantic waters entering the Arctic [9], increased stratification, etc.) enhance the role of picoforms (PCB and picoeukaryotes) in the substance flow in the Arctic ecosystems [10]. A possible increase in the PCB’s share in the total abundance of picophytoplankton in the Arctic waters is suggested to be associated with global warming [11].

The data of PCB abundance and their spatial distribution in the seas of the Russian Arctic are scarce. Only information about the estuary of the Lena River and the adjacent region of the Laptev Sea is available [12]. The Laptev, Kara, and East Siberian seas are characterized by considerable river and North Atlantic water flows [8, 13]; this fact suggests the presence of allochthonous PCB. The predicted increase of PCB role in the functioning of the Arctic ecosystems and the lack of data of PCB abundance in the Russian sector of the Arctic determined the goal of this research. This was to assess the PCB abundance, biomass, and contribution to the total abundance of picophytoplankton, as well as to identify the spatial distribution of PCB on the shelf of the Kara, Laptev, and East Siberian seas.

MATERIALS AND METHODS

The material was obtained during the 69th cruise of the Akademik Mstislav Keldysh scientific research vessel from August 25 to September 9, 2017. Samples were collected from the surface horizon of the stations located on the shelf of the Laptev, Kara, and East Siberian seas (Fig. 1). A total of 61 samples were collected and analyzed.

The temperature, pressure, and electrical conductivity of the surface water layer were measured using a CTD flow system equipped with a SeaBird SBE911 sensor (Sea-Bird Scientific, United States) [14]. According to these characteristics, salinity was calcu-
lated. The concentration of dissolved forms of silicon was determined colorimetrically [15].

The abundance of photosynthetic picoforms (cyanobacteria and eukaryotes) was determined using a Leica DM1000 luminescent microscope (Leica Microsystems, Germany) by the method described previously [16] as well as an Accury C6 flow cytometer (BD Bioscience, United States). The use of two accounting methods is explained by the fact that the Accury C6 cytometer provides underestimated numbers of cyanobacteria [17]. To calculate biomass, the carbon content in PCB cells was considered to be 470 fg C per cell [18]. In picoeukaryotic cells \( C_c \), it was determined using cell volumes \( W_c \) and the following dependence: \( C_c = 0.433 W_c^{0.863} \) [18]. The volume of picoeukaryotic cells was calculated on the basis of the volume of the corresponding stereometric figures [19].

To assess the similarity of the stations by abiotic factors, including water temperature, salinity, and concentration of dissolved silicon (a conventional indicator of the river flow), cluster analysis using the PRIMER6 software was carried out [20]. To assess the relationship between the variables, Spearman’s correlation coefficient was calculated; the significance of differences between the average values was indentified using the Mann–Whitney U test. The calculations were performed using the PAST 3.20 software (University of Oslo, Norway).

**RESULTS**

**Abiotic conditions.** The temperature and salinity of the surface layer varied from —1.1 to 8.1°C and from 13 to 32‰, respectively. The concentration of dissolved silicon changed within 0.24 and 52 μmol/L. The cluster analysis of station similarity, according to these abiotic factors, revealed two groups of stations (Fig. 2). One group included stations with a pronounced influence of river flow of the following large Siberian rivers: Ob, Khatanga, Indigirka, and Kolyma (freshened stations, \( F_{st} \)). The surface water layer at these stations was characterized by elevated temperature, increased silicon concentration, and reduced salinity (Table 1). Another group of stations with less-pronounced desalination (marine stations, \( M_{st} \)) can be divided into subgroups M1, M2, and M3. The M1 subgroup united the stations of the southwestern part of the Kara Sea, where salty and relatively warm waters, which were transformed North Atlantic waters, entered from the Barents Sea. The M2 subgroup included stations in the Vilkitsky Strait and northern part of the East Siberian Sea, the waters of which were characterized by low temperature and high salinity. Stations of the central areas of the shelf of all three seas composed the subgroup M3.

**Abundance and biomass of PCB.** The abundance \( (N_{PCB}) \) and biomass \( (B_{PCB}) \) of PCB varied considerably (Table 1), while the average values of these parameters differed insignificantly between the seas. The highest abundance and biomass of PCB were found in the southwestern part of the Kara Sea (sub-

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**TABLE 1**

| Sea          | Average Temperature (°C) | Average Salinity (‰) | Average Dissolved Silicon (μmol/L) |
|--------------|---------------------------|-----------------------|------------------------------------|
| Kara Sea     | —1.1 — 8.1               | 13 — 32               | 0.24 — 52                          |
| Laptev Sea   | 5 — 50                    | 13 — 32               | 0.24 — 52                          |
| East Siberian Sea | 5 — 50          | 13 — 32               | 0.24 — 52                          |

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**Fig. 1.** Sampling locations.
group M1) and the areas affected by the river flow (Fst group), although the average values of $N_{PCB}$ and $B_{PCB}$ in the M1 subgroup and Fst group did not differ significantly. The average values of $N_{PCB}$ and $B_{PCB}$ in the M1 subgroup and Fst group were higher ($p < 0.01$) than the average values in the cold waters of the Vilkitsky Strait and the northern part of the East Siberian Sea (subgroup M2) as well as in the central regions of the shelf (M3 subgroup of stations).

The PCB abundance in the aquatic areas with the highest desalination reached $0.5 \times 10^9$ cells/m$^3$ (Ob flow), $0.2 \times 10^9$ cells/m$^3$ (Khatanga flow), $0.4 \times 10^9$ cells/m$^3$

### Table 1. Ranges of temperature ($T$, °C), salinity ($S$, ‰), silicon concentration (Si, μmol/L), abundance ($N_{PCB} \times 10^9$, cells/m$^3$), and biomass ($B_{PCB}$, mg C/m$^3$) of picocyanobacteria, average values (± standard deviation) of the abundance and biomass of cyanobacteria in certain areas of the Kara, Laptev, and East Siberian seas and in each of the seas in general

| Area                                      | $T$   | $S$       | Si  | $N_{PCB}$ | $B_{PCB}$ |
|-------------------------------------------|-------|-----------|-----|-----------|-----------|
| Areas of influence of river flow (Fst)     | 3.1–6.8 | 13.4–20.4 | 15.1–52.0 | 0.02–1.58 | 0.01–0.740 |
| Marine stations (Mst)                     |       |           |     | 0.39 ± 0.48 | 0.18 ± 0.23 |
| M1. Western part of the Kara Sea          | 4.2–8.1 | 27.4–32.0 | 0.4–2.0 | 0.04–5.50 | 0.02–2.60 |
| M2. Vilkitsky Strait. Northern shelf of the East Siberian Sea | −1.4–1.2 | 27.4–32 | 0.2–8.6 | 0.02 ± 0.02 | 0.01 ± 0.01 |
| M3. Central shelf areas of three seas     | 2.1–6.5 | 21.2–28.1 | 6.8–20.0 | 0.12 ± 0.14 | 0.05 ± 0.07 |
| Kara Sea                                  | −1.1–8.1 | 17.9–32.0 | 0.2–52.0 | 0.48 ± 1.2 | 0.23 ± 0.57 |
| Laptev Sea                                | 1.2–5.3 | 13.4–29.9 | 1.1–29.7 | 0.16 ± 0.24 | 0.07 ± 0.11 |
| East Siberian Sea                         | −1.4–6.8 | 13.6–30.3 | 5.0–30.0 | 0.25 ± 0.43 | 0.12 ± 0.17 |
In the entire dataset obtained, a highly reliable ($p < 0.01$) positive relationship between the abundance (and biomass) of PCB and water temperature ($p = 0.003$) was found. The interrelation with the water salinity turned out to be reliable only at a significance level of 0.03.

The contribution of PCB to the total abundance and biomass of picoforms. In almost the entire aquatic area studied, $N_{\text{PCB}}$ and $B_{\text{PCB}}$ were lower than those of photosynthetic picoeukaryotes. $N_{\text{PCB}}$ and $B_{\text{PCB}}$ were higher than the abundance and biomass of picoeukaryotes only at stations 5584, 6901, 6902, and 6903 from the M2 subgroup in the western part of the Kara Sea; the contribution of PCB to the total number and biomass of picoforms reached 67–82%. The average contribution of PCB to the number and biomass of picoforms in the subgroup of M1 stations was 37 and 36%, respectively. In other $M_{st}$ subgroups and the $F_{st}$ group of freshened stations, the average contribution of PCB did not exceed 7%.

**DISCUSSION**

A study of the spatial distribution of PCB, carried out in August and September 2017, was the first research that dealt with the surface layer of the shelf of all three seas of the Russian Arctic simultaneously: the Kara, Laptev, and East Siberian seas. The studied area was characterized by a pronounced spatial heterogeneity of the water masses, which was caused by processes such as strong river flow, the influence of the Barents Sea waters (transformed North Atlantic waters), and the effect of the waters of the central Arctic basin. The mesoscale heterogeneity of abiotic conditions on the shelf of the Arctic seas determined the significant variability of the PCB abundance parameters, on which temporary variability is overlaid. In particular, the volume of river flow into the Laptev, Kara, and East Siberian seas, as well as the direction of distribution of desalinated waters, change seasonally [8]. The seasonal variability was also observed for the value of the volume of the North Atlantic waters entering the Arctic [21]. The interannual variability of the volume of river flow and entering Atlantic waters was also revealed [8, 9]. The temporal variability of the main sources of allochthonous PCB can result in the seasonal and interannual variability in the abundance and spatial distribution of PCB on the shelf of the Siberian seas.

The spatial variability of PCB abundance was mainly determined by the presence of the sources of allochthonous PCB, due to which the highest values
of PCB abundance and biomass were observed. River flow is the main source of allochthonous PCB on the shelf of the Kara, Laptev, and East Siberian seas. With distance from river estuaries in both latitudinal and meridional directions, the PCB abundance decreases significantly due to the effect of dilution and, probably, the death of freshwater forms. A similar pattern was observed in the Canadian Arctic in autumn, where the PCB number decreased according to the following gradient: the waters of the Mackenzie River—the estuary—the coastal waters of the Beaufort Sea—open Arctic waters [5]. The limits of the PCB abundance variations in the areas affected by the river flow ($F_{\text{en}}$) proved to be slightly less than those on the Beaufort Sea shelf ($0.39\times2.3\times10^9\ \text{cells/m}^3$) [5]. However, taking into account the fact that the number of PCB in the Buor–Khaya Gulf influenced by the flow of the Lena River varies from 1 to 40 $\times 10^9$ cells/m$^3$ in September [12], we can conclude that this agrees with the limits of variation in the PCB abundance in the Russian shelf seas and on the Canadian Arctic shelf. Transformed North Atlantic waters are other sources of allochthonous PCB, the number of which can reach $21\times10^9\ \text{cells/m}^3$ [4]. As Atlantic waters move to the Arctic region, the PCB abundance decreases significantly. Water flowing from the Barents Sea to the southwestern part of the Kara Sea was characterized by a higher number of PCB (the greatest abundance was $5.5\times10^9\ \text{cells/m}^3$) compared to the central and northern shelf regions of the Kara, Laptev, and East Siberian seas.

Until recently, autochthonous marine PCB were believed to be absent in the Arctic [3]. However, metagenomic studies revealed the presence of endemic marine Synechococcus, which even predominated in the number of sequences over allochthonous forms at some stations [4]. We suggest that PCB are represented in the cold waters of the Vilkitsky Strait and the northern shelf of the East Siberian Sea by autochthonous forms, the numbers of which do not exceed $0.05\times10^9\ \text{cells/m}^3$. The PCB abundance reached the same values in the northern part of the Chukchi Sea and in the Beaufort Sea in summer; however, the authors of those studies did not exclude the possibility of PCB advection to the Arctic regions with Pacific waters [22].

The revealed insignificant contribution of PCB to the total abundance and biomass of photosynthetic picoforms on the shelf of the Siberian seas agrees with the data on other Arctic regions [4]. The predominance of eukaryotes in the picofraction is believed to be associated with their greater adaptability to severe Arctic conditions, in particular, to variations in salinity in a wide range [23] and low water temperature [24].

Water temperature is one of the main factors determining the macroscale distribution of PCB, Synechococcus in particular [25]. The spatial distribution of PCB on the shelf of the Kara, Laptev, and East Siberian seas also shows a positive relationship between the water temperature and PCB abundance. This indicates a possible increase of PCB abundance in the shelf seas of the Russian Arctic and their role in the functioning of Arctic ecosystems under the observed climatic trend.

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COMPLIANCE WITH ETHICAL STANDARDS
The authors declare no conflict of interest. This article does not contain any studies involving animals or human participants performed by the authors.

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