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Diatom Distribution Pattern in Surface Sediments of the Kara Sea and Adjacent Areas

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Abstract: Surface sediment samples from the Kara Sea and adjacent areas were analyzed to investigate diatom distribution patterns in high latitude regions based on species and their relationship with temperature. Samples from the deep Arctic Basin and Kara Sea primarily comprised pennatic diatoms and centric diatoms, respectively. Rare Sea ice diatoms, including *Fragilariopsis oceanica* and *Fragilariopsis cylindrus,* were found in the northern regions of the Kara Sea, close to the Center Arctic Ocean. This region usually has sea ice and ice packs, which account for a relatively low surface temperature. Diatoms near Arctic regions, which are located south of the Kara Sea, included *Bacterosira bathyomphala*, *Thalassiosira antarctica borealis*, *T. antarctica*, *Dentonula confervaceae*, and *Porosira glacialis* resting spores. Melting of the Arctic sea with a rise in seasonal temperature has been observed in this region. Coastal Benthic diatoms, such as *Paralia sulcata* and *Delphineis,* were found near the surface runoff of the Yenisey, Ob, Pyasina, and Kara. Based on the findings, the distribution and growth of diatoms in surface sediments are strongly influenced by perennial sea ice in the Arctic Ocean regions.

Keywords: Diatoms; Distribution pattern; *Fragilariopsis;* Surface sediments; Kara Sea

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1. Introduction

Over the past few decades, the Arctic Ocean has experienced significant environmental changes. The decline in sea ice has influenced the production of marine phytoplankton and shifted their distribution patterns. Recent environmental changes, including sea ice reduction, increased water column, and stratification changes due to rising water temperature and decreased salinity, may have impacted the sedimentation processes and patterns in the Kara Sea and adjacent areas. In the Arctic seas, sedimentation has been conducted to understand the processes connected to climatic change and identify the trends in changes in the environment [1].

Diatoms, the most prevalent microfossils in Arctic Ocean and marginal sea sediments, are particularly valuable due to their well-preserved siliceous frustules. These remains act as proxies for reconstructing paleoenvironment conditions in high-latitude regions. Calcareous nannoplankton and foraminiferans are less abundant and more easily destroyed than diatoms. Analyzing the diversity and composition of diatom species in seafloor sediments is essential for making a detailed and reliable reconstruction of sedimentation conditions that can prove useful in predicting changes expected in the future.

Detection of diatom tanatocenoses at the bottom sediment surface reflects biocenoses and is key to the fossil diatom flora. In recent decades, diatoms in surface sediments of the Kara Sea have attracted considerable attention. These studies highlight the influence of various parameters related to surface sediments, such as ice cover, surface runoff, and current, on diatoms and their species.

The present study focuses on analyzing changes in the diatom distribution pattern in surface sediments of the Kara Sea and adjacent areas to understand how climate change has affected diatoms over recent decades in this ecosystem.

2. Materials and methods

2.1. Study area

The Kara Sea, a marginal sea within the Arctic Ocean, is situated off western Siberia (Russia). It is bounded by the Novaya Zemlya archipelago to the west, Franz Josef Land to the Northwest, the Severnaya Zemlya islands to the East, and the Eurasian mainland to the South (**Figure 1**). The sea is linked to the Arctic Ocean in the north, demarcated by conventional boundaries along the shelf edge. It also connects to the Arctic Basin to the north, the Barents Sea to the west, and the Laptev Sea to the east. The study region spans between 65ºE–86ºE and 71ºN–86ºN, covering an area of 340,000 square miles (880,000 square km). The sea has an average depth of 127 meters, with its deepest point reaching 620 meters.

Several deep inlets of the Kara Sea extend into the Siberian mainland. Major rivers such as the Yenisey, Ob, Pyasina, and Kara rivers discharge into the sea. These rivers are located in high-latitude regions, receive limited solar radiation, resulting in minimal radiant heating of the Arctic seas. The substantial freshwater input from these rivers plays a critical role in shaping the hydrological conditions of the Arctic seas [2–3].

As part of the Siberian shelf, the Kara Sea has a relatively shallow profile, with around 40% of its area having depths of less than 50 meters and only 2% exceeding 500 meters. The northern part of the shelf is cut by two deep-sea troughs: the Svyatoy Anny Trough, located east of Franz Josef Land with a depth of 620 meters, and the Voronin Trough, situated approximately 290 kilometers to the east, reaching depths of up to 450 meters.

Figure 1. Location of various study sites in the study area showing diatom distribution. Red stars indicate samples rich in diatom abundance, while red circles represent those with low diatom abundance

2.2. Methodology

Surface sediment samples were collected from the Arctic Ocean using a box-corer in 2018. Seven samples (Stations 1 to 7) from the Kara Sea and adjacent areas were analyzed. Stations 1–3 are located in central of Arctic Ocean, while Stations 4–7 are situated in the middle of the Kara Sea.

For light microscopy analysis, sample slides were prepared following a standard chemical treatment procedure involving hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2) [4]. Dried samples (2 g) were treated with 30% H_2O_2 to remove the organic matter, followed by the addition of 10% HCl to dissolve calcite matter. The samples were then rinsed with distilled water, and the process was repeated 5 times until all acids and part of the clay were removed. The remaining sediments were filtered through a 10-µm mesh, and the residue was collected. After the reaction was complete, the samples were carefully transferred using latex tubes. After the material was fully dried, cover slips were placed on top of the slides for microscopic analysis.

Diatom species were identified and counted using a Nikon Ni-E optical microscope at x400 magnification. 10 slides were prepared and analyzed to ensure accurate representation of diatom composition.

3. Results

Among the seven surface sediment samples analyzed, only a small number of diatoms (Station 1–3) were detected in the high-latitude stations (**Figure 2**). These three stations are located within the region of minimum sea ice extent in the Arctic Ocean, an area characterized by perennial ice and snow cover, as indicated by data from the National Snow and Ice Data Center. In contrast, the remaining four samples (Stations 4–7), collected from a region south of the minimum sea ice extent near Novaya Zemlya, contained a significantly higher abundance of diatoms. The diatom counts ranged from 100 to 300 valves per sample on average, with a minimum of 128 and a maximum of 426 valves. In fact, diatom concentrations exhibited a marked increase in the central Kara Sea, particularly around the gulfs, the Yamal Peninsula, and the Belyeye Islands.

Analysis of the surface sediment samples revealed that Arctic diatom species can be categorized into three main groups: sea ice diatoms, Arctic diatoms, and coastal benthic diatoms.

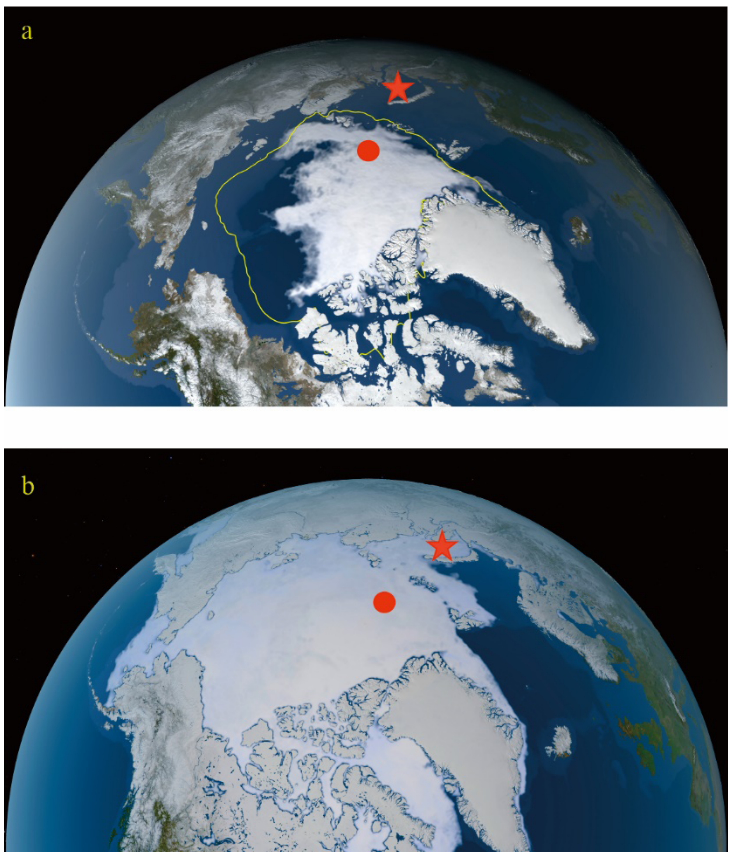

Figure 2. Arctic sea ice changes in 2023. a. Arctic sea ice minimum extent on September 19, 2023: 4.23 million km^2. It was the 6th smallest summer minimum on record. The yellow line shows the average from 1981 to 2010. b. Arctic sea ice maximum extent on March 5, 2023: 15.05 million km^2. Image from NOAA Climate.gov, based on data from the National Snow and Ice Data Center. The red star represents samples in the Kara Sea rich in diatoms (abundance), while the red circle represents samples in the Arctic Ocean with a low diatom count

3.1. Sea ice diatoms

Fragilariopsis oceanica and *F. cylindrus*, two closely related diatom species, were widely distributed in sea ice, being commonly found in the Arctic Ocean and the adjacent area. Previous studies indicated an abundance of those species in sediments from the Northern part of the Arctic Ocean, particularly along the minimum sea ice extent in the Kara Sea. This distribution pattern suggests that both species exist in environments characterized by low sea surface temperatures and high latitudes.

3.2. Arctic diatoms

The main diatom species identified in the Arctic water of the Kara Sea include *Bacterosira bathyomphala*, *Thalassiosira hyperborean, T. antarctica borealis*, *T. antarctica* resting spore, *Diploneis interrupta*, *D. stroemii, D. smithii, Nitzschia hybrid, Amphora laevis, Navicula kjellmanii,* as well as *Dentonula confervaceae* and *Porosira glacialis* resting spores. Their presence suggests a strong association with ice-free regions in the Arctic.

Resting spores were frequently observed in the Kara Sea due to their high preservation potential. The resting spores can be found in all samples, and they play a significant role in areas with minimal sea ice extent. The percentage of North-boreal species tends to increase with higher latitudes, including the resting spores (**Figure 3**).

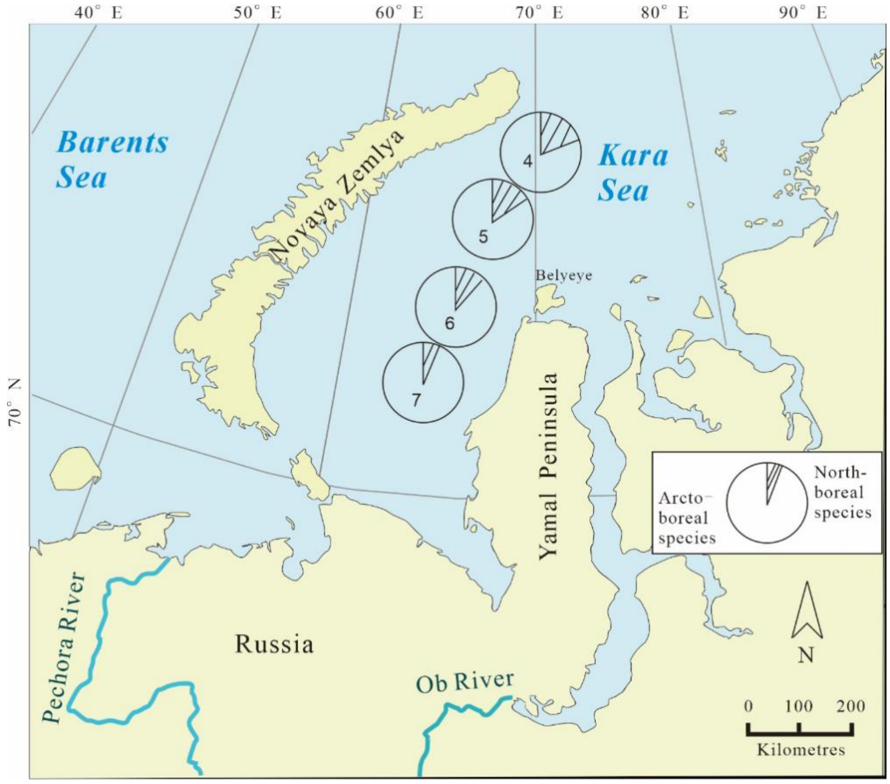

Figure 3. Biogeographical composition of diatom species in surface samples from the Kara Sea

B. bathyomphala and *T. antarctica borealis* were consistently observed in the central Kara Sea. *B. bathyomphala* was particularly abundant in coastal regions of Greenland, Laptev Sea, Okhotsk Sea, and the Bering Sea, spanning various depths from shallow coastal zones to deep basins. Meanwhile, *T. antarctica* exhibited a broad distribution, ranging from the Southern to the Northern Hemisphere. The highest concentration of Arctic diatom species was recorded in the deeper regions of the Kara Sea, while the lowest abundance was found near Western Siberia. This result indicates that diatom distribution is strongly influenced by coastal water dynamics, with changes in coastal currents playing a key role in shaping the spatial patterns of Arctic diatoms (**Figure 4**). In station 4, planktic diatoms dominated, accounting for 90.3% of the total diatom population, likely due to the effects of seasonal ice melt. In contrast, at Station 6, the proportion of littoral species increased by 32%, potentially driven by the growth of planktic and benthic species associated with ice flora.

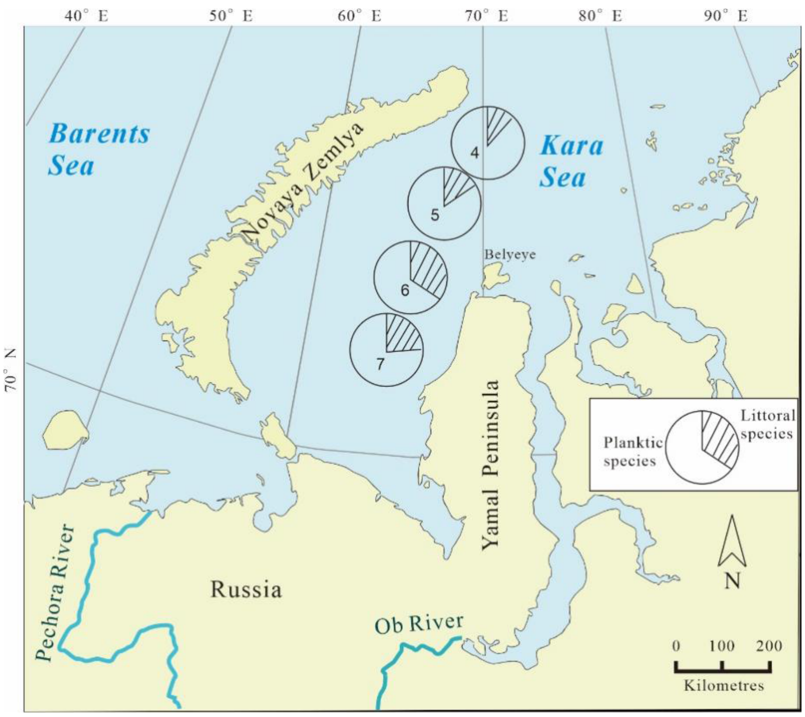

Figure 4. Composition of diatom species in surface samples collected from the Kara Sea according to the habitat

3.3. Coastal benthic diatoms

Coastal benthic diatoms were predominantly found in the coastal waters surrounding deltas, islands, peninsulas, and shorelines. Key species identified in the bottom of coastal regions include *Aulocoseira islandica*, *A. granulate, Paralia sulcata*, and *Delphineis*. Previous studies have highlighted that *Delphineis* is a unique diatom species usually found near islands or attached to sand grains and other particles, which could get mixed in turbulent waters.

The results reveal that the abundance of coastal benthic diatoms increased in the regions with surface runoff near the sediments. In contrast, diatom concentrations decreased in sediments located farther from shelves, estuaries, deltas, or islands. This finding indicates that river discharge and coastal currents play a crucial role in shaping the distribution of coastal benthic diatoms, as they provide abundant nutrients from the continent that support diatom growth.

4. Discussion

Diatom growth has been significantly impacted by the perennial sea ice covering the Arctic Ocean [4]. Over the past 43 years, the Arctic has been warming at a rate nearly four times faster than the global average, based on multiple observational datasets covering the region. At a regional scale, areas in the Eurasian Arctic have warmed even up to seven times faster than the global rate. Between 1979 and 2021, a substantial portion of the Arctic Ocean was warming faster than 0.75°C per decade, with a maximum warming in the Eurasian sector of the Arctic Ocean, particularly near Svalbard and Novaya Zemlya [5–6].

Surface sediment samples from high-latitude regions of the Arctic Ocean contained a relatively low concentration of diatoms. Silty sediments from high latitude regions (stations 1–3) have a poor diatom composition, while silty sands from stations 4–7 contain a rich composition of diatoms, including both Arctic and coastal benthic diatoms. In surface sediments, the authors identified 12 diatom taxa from the class *Centrophyceae* and 8 taxa from the class *Pennatophyceae*. The dominant centric species included *T. gravida* (8.5%–18.7%), *T. Antarctica* (7.4%–16.4%), *T. hyaline* (2.1%–7.5%), *T. nordenskioldii* (9.3%–15.2%), *T. kryophila* (5.7%–15.8%), *Porosira glacialis* (6.9%–18.7%), and *Coscinodiscus oculus-iridis* (8.7%–11.8%). Other species, such as *Melosira arctica*, *F. oceanica*, F. *cylindrus*, *Nitzschia frigida*, and *Navicula directa*, were present in low amounts.

Samples with high species content were collected from regions near the Yamal peninsula and Novaya Zemlya islands. Samples taken from stations 1, 2, and 3 mainly comprised pennatic diatoms, while samples taken from stations 4, 5, 6, and 7, located in seasonal ice-free areas, were dominated by centric diatoms. *Fragilariopsis oceanica* and *Fragilariopsis cylindrus* were the diatom species dominating in the surface sediments of the Kara Sea and sediments under ice packs [3].

Sea ice and Arctic diatoms are marine diatoms, including *T. hyperborean*, *Achnanthes taeniata*, *A. brevipes*, *D. interrupta*, *D. stroemii*, *D. smithii*, *Nitzschia hybrid*, *Amphora laevis*, and *Navicula kjellmanii*. Freshwater species included *A. islandica*, *A. granulate*, and *Amphora ovalis.* All species were present in relatively low concentrations (**Figure 5**). The presence of brackish water diatom species might be influenced by freshwater from melting sea ice.

The distribution of brackish water species may be significantly affected by the effect of melting sea ice. The presence of freshwater diatoms in the Kara Sea stations indicates that the diatoms survive in sea ice formed in a proximal freshwater-dominated environment, followed by a drift to the open marine areas [7].

Samples from stations 6–7 were predominantly composed of neritic species. Panthalassic species, such as *Actonocyclus curvatulus*, *Coscinodiscusoculus-iridis*, rise slowly from station 7 to station 5 at a water depth of 20–50 meters. Litoral species increased to 30% at these stations. In shallow regions of the Kara Sea, among ice diatoms, benthic coastal species were dominant, while in deep waters, planktic sea ice diatom species were dominant. Samples from stations 7 and 6 near the Byrange Plateau, coastal areas, also contained bipolar planktic species. Diatom distribution is influenced by the strong water exchange between the land rivers and the Kara Sea. Lower seawater salinity may affect the environment and sedimentation patterns in coastal areas of the Kara Sea. Among the four stations in the Kara Sea, Station 7 exhibited the lowest diatom abundance (110 frustules per gram), likely due to the dissolution of diatom valves and strong bottom currents near the Pyasina Gulf [8]

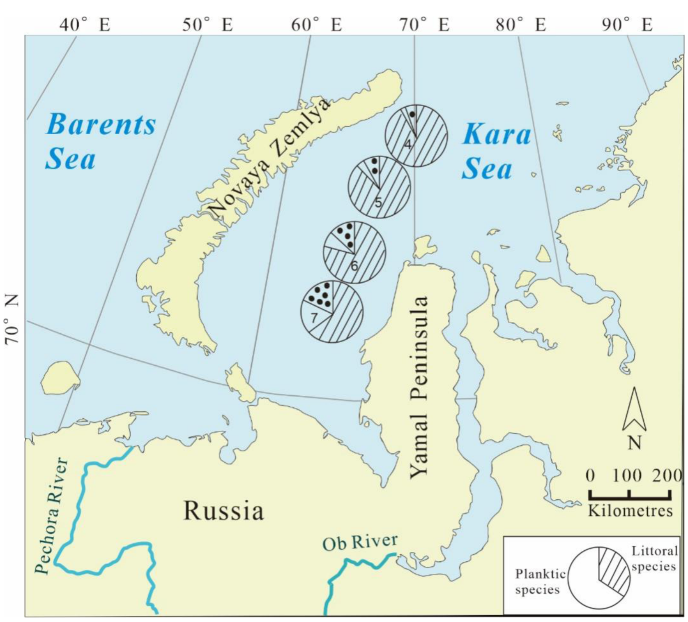

Figure 5. Diatom species composition of surface samples from the Kara Sea according to facies types

In samples from stations 4–5 located near bordering waters, littoral diatom species were abundant. In contrast, surface sediment samples from high-latitude Stations 2–3 showed a low diatom content, while diatoms are absent from Station 1. The reason for the low abundance of sea ice diatoms may be due to the influence of sea ice. The content of sea ice diatoms (*F. oceanica* and *F. cylindrus*) results from a preference for sea ice and ice packs at relatively low surface temperature [9–10].

Previous research showed that the sea ice is a critical factor influencing diatom distribution in the Arctic Ocean, including Greenland, Kara Sea, Bering basin, Laptev Sea, and Chukchi Sea [11]. Diatom growth is significantly limited in areas north of the Arctic sea ice minimum extent, where sea ice persists throughout the year [2]. Sea ice diatoms dominate the area along the Arctic sea ice and the minimum extent, as in the Kara Sea. Arctic water diatoms were primarily distributed in the central and northern areas between the Arctic Sea ice minimum and maximum extent, while coastal benthic diatoms were found close to the Yamal peninsula, where surface runoff or coastal current provides nutrients from the continent.

5. Conclusion

Diatom distribution patterns vary based on samples collected from surface sediments from the Kara Sea and the adjacent areas. The deep Arctic basin mainly contained pennatic diatoms, while seasonal ice-free areas are dominated by centric diatoms. *F. oceanica* and *F. cylindrus* were dominant in the surface sediments of the Kara Sea.

Sea ice influences diatom distribution in the Kara Sea and adjacent regions. Surface sediment samples from high-latitude stations, which are typically covered by Arctic sea ice, showed an absence of diatoms. In contrast, Arctic water diatoms were primarily found in the central and northern parts of the Kara Sea, while coastal benthic species were concentrated near the Yamal Peninsula.

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Disclosure statement

The authors declare no conflict of interest.

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