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ORIGINAL PAPER

Distribution of diatoms in seafloor surface sediments of the Laptev, East Siberian, and Chukchi seas: implication for environmental reconstructions

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Abstract
Our research was motivated by significant warming in the Arctic in recent decades and the influence of this warming on diatoms, which are the main producers in the seas of the Eastern Arctic. For this purpose, we studied the qualitative concentrations and quantitative ratio of diatoms from the surface sediments of the Laptev Sea (LS), the East Siberian (ESS) and Chukchi seas (ChS), and the Arctic Ocean (AO), obtained by box corers in 2016 and 2018. The ecological structure of the diatom assemblages of these sediments, reflecting the current environmental conditions, was also analyzed. Compared with the end of the last century, there were significant changes in species composition and quantitative ratio of the diatom assemblages in the sediments from the AO and the LS and ESS. In contrast, the diatom assemblages in the sediments from the ChS had not significantly changed in terms of species composition or quantitative ratio over the same three decades. The observed transformations in the diatom assemblages of the surface sediments were associated with substantial changes in water temperature, current flow, salinity, ice melting, and prolonged ice-free periods associated with global warming in the Northern Hemisphere in recent decades. The foregoing processes have clearly had strong impacts on the environment and the biota of the Arctic region.

Keywords Diatoms · Surface sediments · Arctic Ocean · Laptev Sea · East Siberian Sea · Chukchi Sea

Introduction

During the late twentieth and early twenty-first centuries, the Northern Hemisphere was characterized by abnormally high temperatures (IPCC 2014, 2021; Mann et al. 2016, 2017). Temperatures increased dramatically in the Arctic Ocean and the seas of Russian Arctic (Akentyeva et al. 2017; Roshydromet, 2021), the ice cover became severely degraded (Stroeve et al. 2007; Rodrigues 2009; Pistone et al. 2019). The permafrost melted on land (Biskaborn et al. 2019) and on the adjacent shelf (Shakhova et al. 2019).

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The diatom assemblages in the surface sediments of the Arctic seas reflect the physicochemical characteristics of the overlying water bodies (Jousé 1962; Maynard 1976; Kravitz et al. 1987; Polyakova 1988, 1989, 1997, 2003; Abelmann 1992; Cremer 1999; Jiang et al. 2001; Matul et al. 2007; Obrezkova et al. 2014; Astakhov et al. 2015; Polyakova et al. 2016; Tsoy and Obrezkova 2017; Miettinen 2018) and ice cover distribution (Meguro et al. 1966; Abelmann 1992; Crosta et al. 1997, 1998; Gersonde and Zeilinski 2000; Belt et al. 2015; Fragoso et al. 2018; Tsukazaki et al. 2018; Fukai et al. 2021). Studying the diatoms predominating in the water column and surface sediments of the seas of Eastern Siberia and adjacent regions enables the assessment of the impact of climate change on the environment (Polyakova 1996, 1997; Cremer 1998, 1999; Tsoy 2001; Bauch and Polyakova 2003; Polyakova et al. 2005, 2011, 2014, 2016, 2019, 2021; Matul et al. 2007; Poulin et al. 2011; Gusev et al. 2014; Obrezkova et al. 2014; Astakhov et al. 2015; Ren et al. 2020). However, most of the data reported in the foregoing sources were collected during the 1980s and 1990s. More recent data (2016, 2018) were gathered during joint

Russian-Chinese expeditions of the research vessel (RV) “Akademik M.A. Lavrentiev”. These findings facilitated the analysis of the effects of Arctic climate change on the biota and especially the diatoms in the seas of Eastern Siberia and the Arctic Ocean. Diatoms are the primary producers in these water bodies and indicate the impact of climate change on sedimentation regime.

The purpose of this work is to study diatoms from the surface sediments of the Laptev, East Siberian and Chukchi seas, obtained by box corers in 2016 and 2018, and compare the results with data from the end of the last century, to understand how climate change over the past decades has affected diatoms.

Physical and geographical characteristics of the region

The Laptev, East Siberian, and Chukchi seas of Eastern Siberia all have a shelf structure, extensive total ice coverage, and oceanic permafrost zone consisting of Late Quaternary permafrost at < 0 °C and newly formed sediments (Dudarev et al. 2003, 2006, 2016). These seas are all located beyond the Arctic Circle. To the south, they are delimited by the coast of Eurasia. To the north, they communicate with the Arctic Ocean and are separated from it by conditional lines running approximately along the shelf margin. The Transpolar Drift is the main current in the Arctic Ocean. It transports fresh water and sea ice southward from the Laptev and East Siberian seas across the North Pole to Greenland (Haller et al. 2014).

The Eastern Siberian seas are located almost entirely within the shelf and have average depths in the range of 40–60 m (Dobrovolskiy and Zalogin 1982). As they are located at high latitudes, they lack solar heat and cause weak radiant heating of the Arctic seas. River runoff significantly contributes to the hydrological conditions of the Arctic seas (Dong et al. 2022). Mixing of river and ocean water causes the surface Arctic waters to be somewhat desalinated and relatively warm. These mixtures occupy most of the volume of the Arctic seas. In shallow areas (≤ 25–50 m), these waters are distributed from the surface to the bottom. From the north, the cold surface waters of the Central Arctic Basin enter the Arctic seas and are typical of the northern regions of them. From the west and east, the waters of the Atlantic and Pacific oceans enter the Arctic seas, respectively. The warm and saline Atlantic Ocean waters brought by the North Atlantic Current, due to their high density, sink under the freshened Arctic waters and in the Arctic Basin are already traced in the form of a warm deep current that follows along the continental shelf of Eurasia (Morgunov 2011). Atlantic waters play a great role in the loss of sea ice cover in the Eurasian Basin of the Arctic Ocean, especially in recent decades (Polyakov et al. 2005, 2017; Grabon et al. 2021). Pacific waters entering through the Bering Strait form a surface current in the Chukchi Sea. As they move north, the waters of this current cool and, plunging in the northern regions of the Chukchi Sea under less dense Arctic waters, spread further in the Arctic Basin in the form of a relatively warm deep current (Morgunov 2011).

In the northern regions of the Arctic seas, surface water moves from west to east along the mainland coast and back (Dobrovolskiy and Zalogin 1982), there are noticeable currents around the islands, and ice is present year round. Fast ice spreads over thousands of kilometers in the eastern part of the Laptev Sea and in the western part of the East Siberian Sea. Large and, in certain cases, permanent ice polynyas form in the Arctic seas. The ice polynyas create nearly continuous strips varying in width and stretching along the coast of Eurasia. Collectively, they are known as the Great Siberian Polynya (Gukov 2009). Polynyas significantly affect the hydrological regime of the surrounding waters (Bauch et al. 2012) and are vital sources of ice formation and important sites of intense biological activity (AMAP 1998).

Materials and methods

Samples of surface sediment containing diatoms to be analyzed were collected during the Russian-Chinese expeditions (cruises No. 77 and 83) of the RV “Akademik M.A. Lavrentiev” in the Laptev Sea, the East Siberian and Chukchi seas, and the Arctic Ocean in 2016 and 2018 (Fig. 1). Sediment samples were collected with a box corer designed and manufactured by POI FEB RAS at 45 stations on cruise No. 77 and at 33 stations on cruise No. 83 (supplementary material S1). This technique permitted sampling of the undisturbed surface layer. Most of the sediment samples from the Laptev and East Siberian seas were silty silts, whereas they were sandy material admixtures on the coastal part of the seas and silty clays on the outer shelf and continental slope (Sattarova et al. 2021).

The strewn slides for counting diatom concentrations per 1 g of air-dried sediment were prepared according to a standard method (Jousé et al. 1974). For qualitative diatom analysis, the samples were enriched with heavy liquid K-Cd (specific gravity = 2.6). MOUNTEX synthetic medium (refractive index = 1.67) (Histolab Products AB, Gothenburg, Sweden) was used to prepare permanent mounts. The diatoms were identified and enumerated with an IMAGER. A1 light microscope (magnification = × 1000; Carl Zeiss AG, Oberkochen Germany) and imaged with an AxioCam-MrC digital video camera (Carl Zeiss AG). The quantitative ratio between taxa was determined after counting 100–300 diatom valves and spores per sample depending on their abundance. At some northern stations diatoms occurred

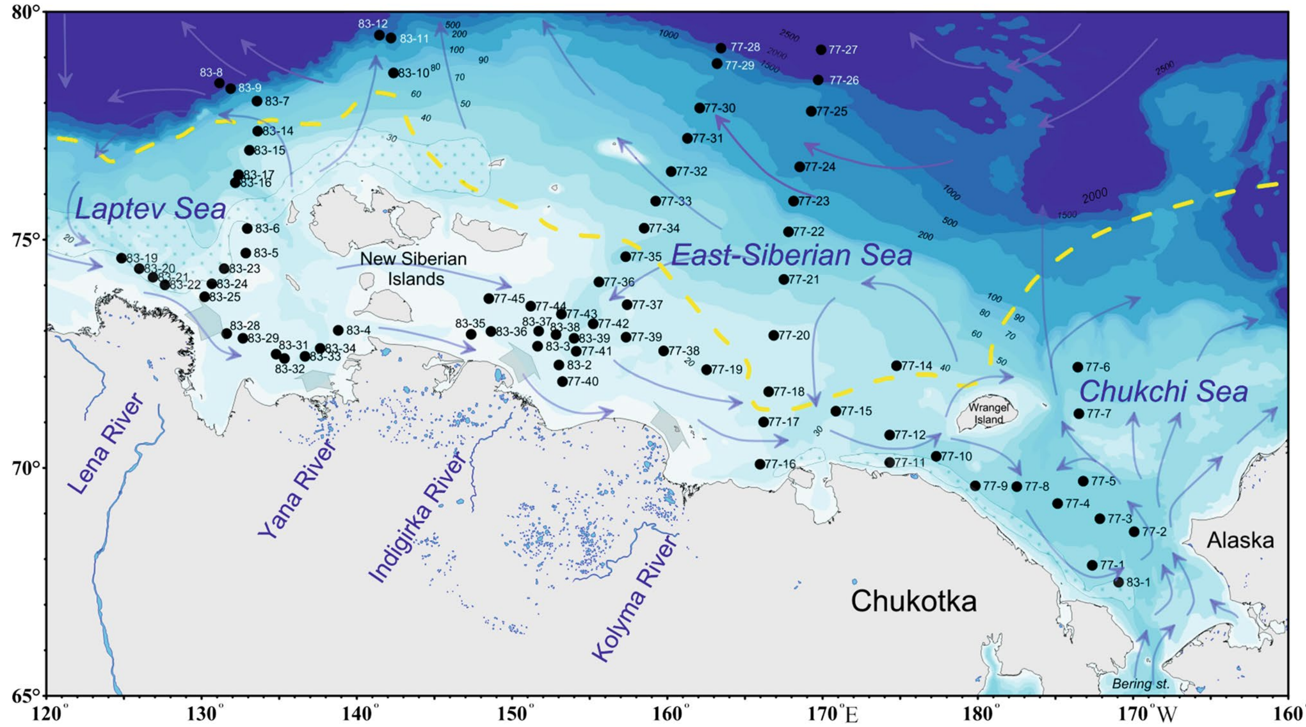

Fig. 1 Map of sampling stations. Thin arrows show surface currents (Coachman et al. 1975; AMAP 1998), thick gray arrows show river outflow (Sattarova et al. 2021). Dotted yellow line shows ice distribution each September from 1981 to 2010. (NSIDC 2018). Zone with dots—polynya (Popov and Gavrilo 2011)

sporadically or even just diatom fragments, therefore, we only noted their single presence (supplementary material S2).

Nomenclature transformations were considered according to the AlgaeBase Global Algological Database for Taxonomy, Nomenclature, and Distribution (http://www.algaebase.org) (Guiry and Guiry 2021). Taxonomic references and photographs of most species mentioned herein are listed in the Atlas (Tsoy and Obrezkova 2017).

To analyze diatom distribution in the surface sediments of the investigated region some diatom taxa were grouped based on similar ecological preferences of some species. *Chaetoceros* group consists of resting spores (RS) of *Chaetoceros* aff. *coronatus, Chaetoceros debilis*, *Chaetoceros diadema*, *Chaetoceros furcellatus*, *Chaetoceros holsaticus*, *Chaetoceros ingolfianus*, *Chaetoceros mitra*, *Chaetoceros septentrionalis*, and *Chaetoceros* spp. (Polyakova 1997; Tsoy et al. 2009, 2017; Obrezkova et al. 2014, 2022; Ran et al. 2013; Ren et al. 2014; Astakhov et al. 2020). *Chaetoceros* RS wasn't excluded when calculating percentages of other species, as their concentrations were not too high and not diluted the variation information of other diatom species. Cryophilic group includes sea ice species *Fossulaphycus arcticus*, *Fragilariopsis cylindrus*, *Fragilariopsis oceanica*, and *Fragilariopsis reginae-jahniae* (Polyakova 1997; Quillfeldt et al. 2003; Tsoy et al. 2017; Obrezkova et al. 2022).

Results

The sediments contained 181 diatom species and an intraspecific taxa in 64 diatom genera. The following genera included the most species: *Pinnularia* (18), *Navicula* (14), *Chaetoceros* (10), *Diploneis* (10), *Thalassiosira* (9), *Aulacoseira* (7), *Eunotia* (6), *Nitzschia* (6), *Coscinodiscus* (5), and *Gomphonema* (5). There were 88 marine, 19 brackish-water, 57 freshwater, and 13 extinct diatoms along with three others of indeterminate ecology (ESM 2).

Arctic Ocean

In the sediments of the Arctic Ocean (stations 77–25–77–30; 83–11, 83–12; depth 977–2570 m), the diatom concentrations were very low ($1–17 \times 10^3$ valves g^{-1}) except at station 77–25 (depth 297.7 m) where the diatom content was 1.609×10^6 valves g^{-1} (Fig. 2).

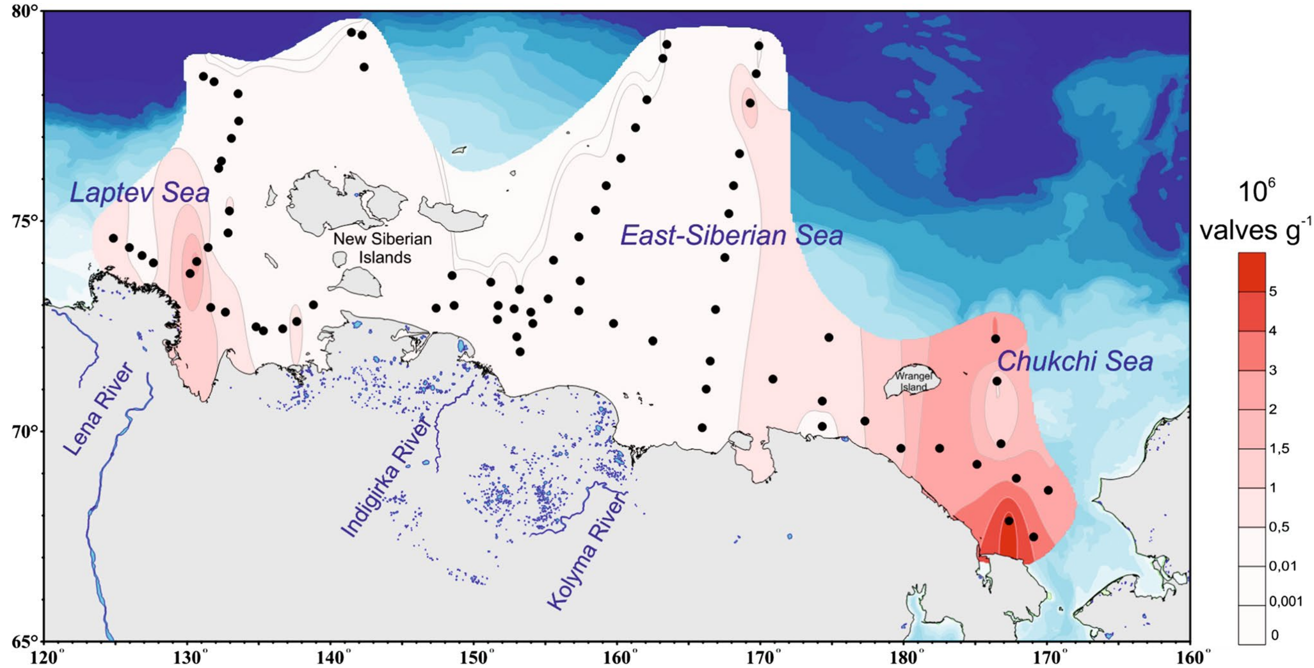

Fig. 2 Quantitative distribution of diatoms in surface sediments of the Laptev, East Siberian, and Chukchi seas (10^6 valves g^{-1})

In the sediments of several stations (77–26–77–30; depth 133–2569.8 m), the diatoms appeared as single valves or their fragments. One to seven species of different ecological affiliations were identified including the marine planktonic *Coscinodiscus asteromphalus*, *Rhizosolenia hebetata*, *C. diadema*, and *C. mitra*, the brackish-water planktonic-benthic *Thalassiosira baltica*, *Thalassiosira hyperborea*, *Melosira arctica*, and *Paralia sulcata*, the freshwater planktonic *Aulacoseira granulata*, and the extinct marine Neogene *Eupyxidicula zabelinae*.

In the sediments of station 83–11 (depth 976.6 m) and station 83–12 (depth 1268.7 m), the diatom assemblages had low species richness (9–10) but abundant marine species (80–94.2%) (Fig. 3).

The benthic-planktonic (tychopelagic) neritic species *P. sulcata* and especially the variety *P. sulcata* var. *biseriata* predominated (46–59%) (Fig. 4a). By contrast, the planktonic arctic-boreal oceanic species *Actinocyclus curvatulus* subdominated (16–32%) (Fig. 4b).

The assemblages also included the brackish-water species *M. arctica* (2–18%) (Fig. 4c), *T. hyperborea* (2–10%)

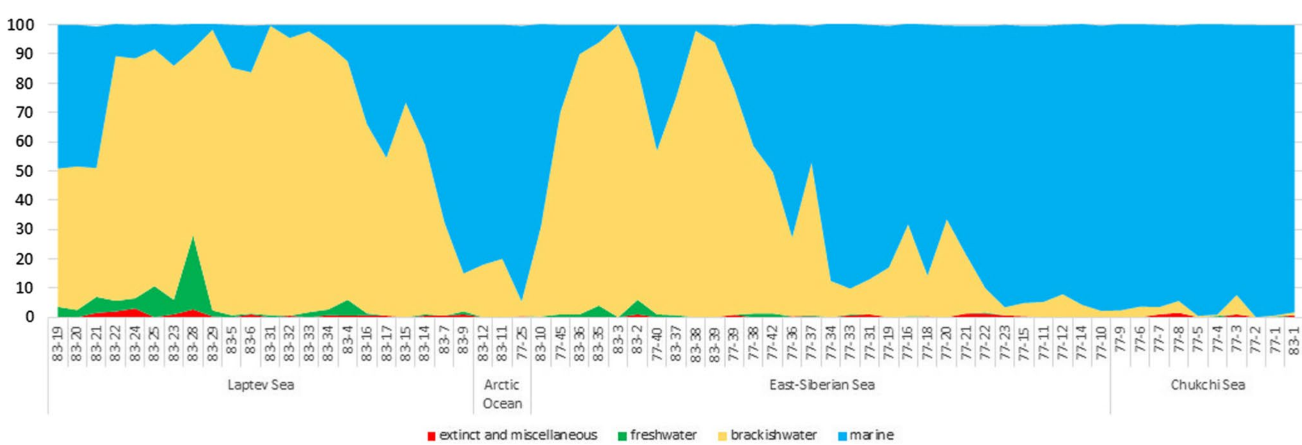

Fig. 3 Relative abundances of diatom ecological groups in relation to salinity in surface sediments of the Laptev, East Siberian, and Chukchi seas

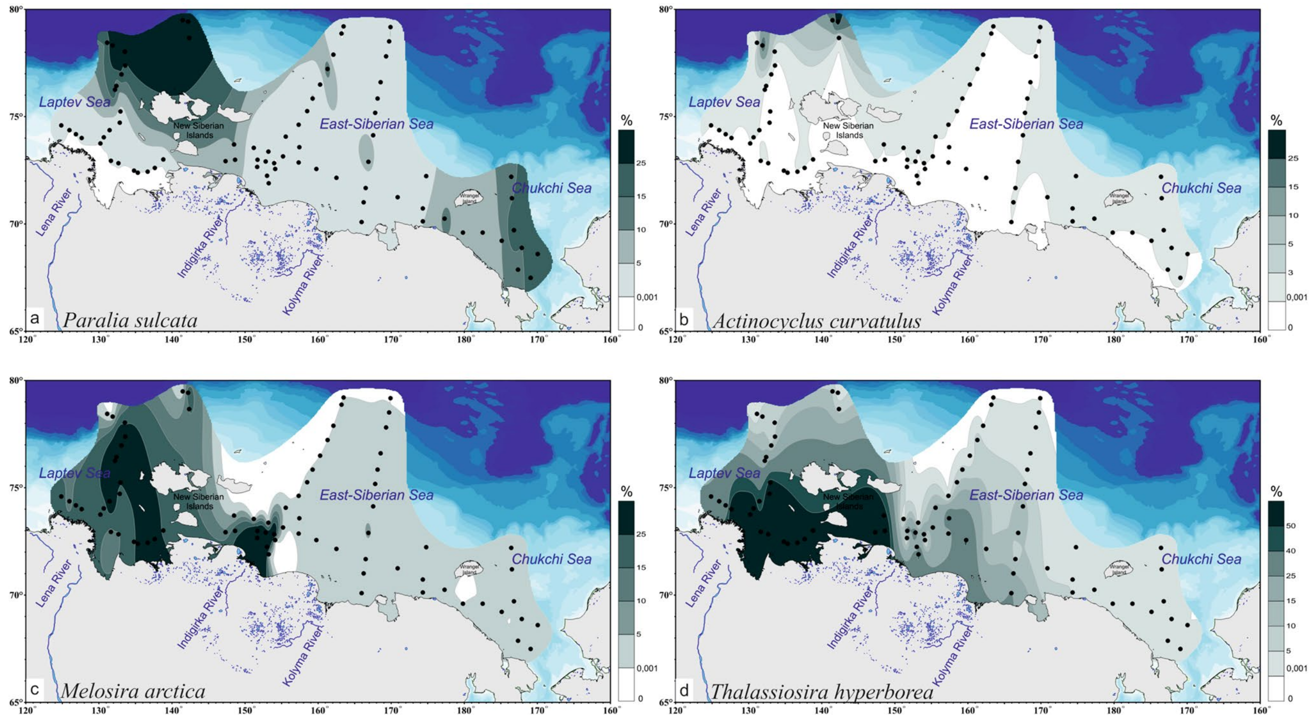

Fig. 4 Distributions of *Paralia sulcata* (**a**), *Actinocyclus curvatulus* (**b**), *Melosira arctica* (**c**), and *Thalassiosira hyperborea* (**d**) in surface sediments of the Laptev, East Siberian, and Chukchi seas

(Fig. 4d), *Navicula peregrina* (6%), and the stenohaline eurythermal species *C. asteromphalus* (ESM 2). Reworked fragments of extinct Cretaceous-Paleogene *Hemiaulus frigidus*, *Hemiaulus* spp., and *Eupyxidicula* spp. were sourced in deposits from this age and were common at the bottom of the Arctic Ocean, the Arctic seas, and their adjacent land (Strelnikova 1974, 1992; Tapia and Harwood 2002; Kim and Glezer 2007; Obrezkova et al. 2019).

In the sediments at station 77–25 (depth 297.7 m) in the northern East Siberian Sea, we detected a diatom assemblage consisting of 23 species. It was dominated by the marine bipolar species *Thalassiosira antarctica* (37.4%) mainly in spore form and cryophiles (33.2%) inhabiting the lower surfaces and ice edges and destroying the ice cover (Quillfeldt 1997; Quillfeldt et al. 2003; Polyakova 1997). *Bacterosira bathyomphala* (9.6%) and *Chaetoceros* RS (8%) (Fig. 5) constituted a noticeable proportion of the total. Brackish-water species such as *T. hyperborea*, *M. arctica*, *Melosira lineata*, and *Melosira moniliformis* var. *octagona* were recorded only in small numbers.

The diatom assemblages in the deep sea sediments of the open Arctic Ocean comprise oceanic, marine, brackish water planktonic, planktonic-benthic, benthic, and freshwater species. Most of these are common in the sediments of the coastal areas of the Laptev and East Siberian seas. This composition reflects transport by the Transpolar Drift Current which carries fresh water, ice, and the diatoms they bear from the coastal regions of the seas of Eastern Siberia. It also reflects the influence of the warm North Atlantic Current passing through this region. Dominance of the siliceous marine planktonic-benthic species *P. sulcata* typical of freshened coastal waters was probably the result of the transport of terrigenous material, perennial ice, and shelf diatoms from the continental shelf to the open sea (Wang and Wang 2008). Lateral transport by wind action may also contribute to the significant abundance of neritic *P. sulcata* in the deep-water sediments of the open sea (Witon et al. 2006). The high relative abundance of *P. sulcata* in the Transpolar Drift Current and selective silica dissolution might be explained by the deficiency of dissolved silicic acid in the water column and sediment pore water (Polyakova 1997; März et al. 2015; Polyakova et al. 2019).

Laptev Sea

The maximum diatom concentration ($\leq 2.4 \times 10^6$ valves g^{-1}) was detected northeast of the river delta. The Lena River (stations 83–24 and 83–25) presented with far higher valve densities than those previously recorded for this area (Cremer 1998, 1999; Matul et al. 2007; Obrezkova et al. 2014) (Fig. 2). At all stations in the zone of influence of the Lena River runoff, the sediment diatom concentrations were in the range of $0.731–0.989 \times 10^6$ valves g^{-1}. To the north of the river delta, the diatom concentration decreased. Its lowest

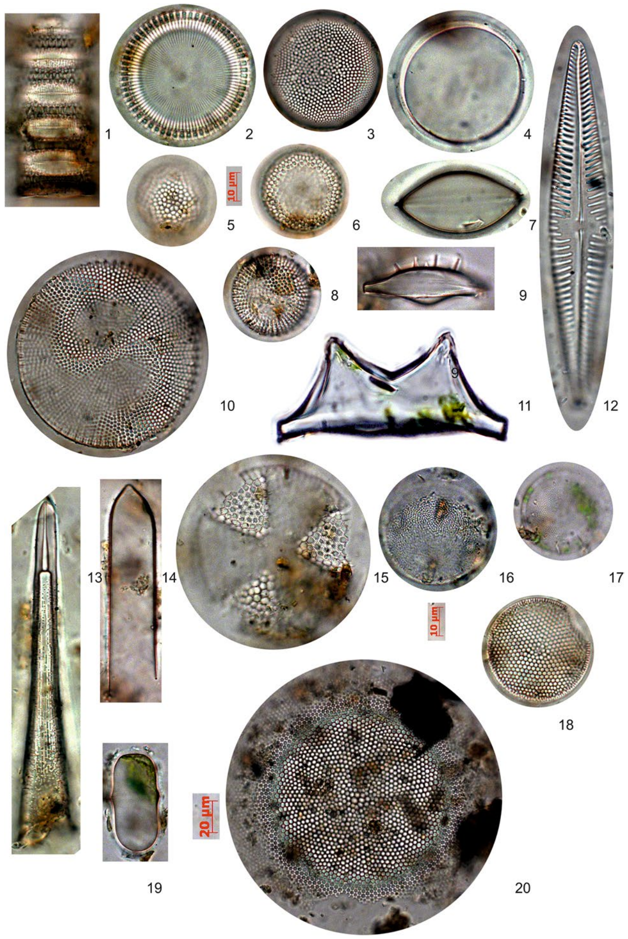

Fig. 5 Dominant and typical diatoms in surface sediments of the Laptev, East Siberian, and Chukchi seas. 1, 2–*Paralia sulcata* (Ehrenberg) Cleve; 3–*Actinocyclus curvatulus* Janisch; 4, 7–*Melosira arctica* (Ehrenberg) Dickie; 5, 6–*Thalassiosira antarctica* Comber (spore); 8–*Thalassiosira hyperborea* (Grunow) Hasle; 9–*Chaetoceros diadema* (Ehrenberg) Gran; 10–*Thalassiosira hyperborea* var. *pelagica* (A.Cleve) G.R.Hasle; 11–*Chaetoceros mitra* (Bailey) Cleve; 12–*Navicula peregrina* (Ehrenberg) Kützing; 13–*Rhizosolenia hebetata* Bailey; 14–*Pseudopyxilla dubia* (Grunow) Forti; 15–*Actinoptychus senarius* (Ehrenberg) Ehrenberg; 16–*Porosira glacialis* (Grunow) Jorgensen; 17–*Thalassiosira nordenskioeldii* Cleve; 18–*Shionodiscus latimarginatus* (Makarova) Alverson, Kang & Theriot; 19–*Melosira lineata* (Dillwyn) Agardh; 20–*Coscinodiscus asteromphalus* Ehrenberg. Scale bars are 10 µm except in Fig. 20, 20 µm

range was $0.028–0.043\times10^6$ valves g^{-1} in the sediments of the continental slope at depths of 2157.5–2447.4 m (stations 83–8 and 83–9). In the sediments of Yana Bay (stations 83–31–83–34), the diatom concentrations were in the range of $0.301–0.688\times10^6$ valves g^{-1}. The lowest diatom concentration (0.027×10^6 valves g^{-1}) was recorded at station 83–4 in the southeastern part of the Laptev Sea near the entrance to the Dm. Laptev Strait. For the sediments obtained in this area in 1999, the diatom concentrations were only in the low range of $0.003–0.181\times10^6$ valves g^{-1} (Tsoy 2001). In other areas of the Laptev Sea, the diatom concentrations in the

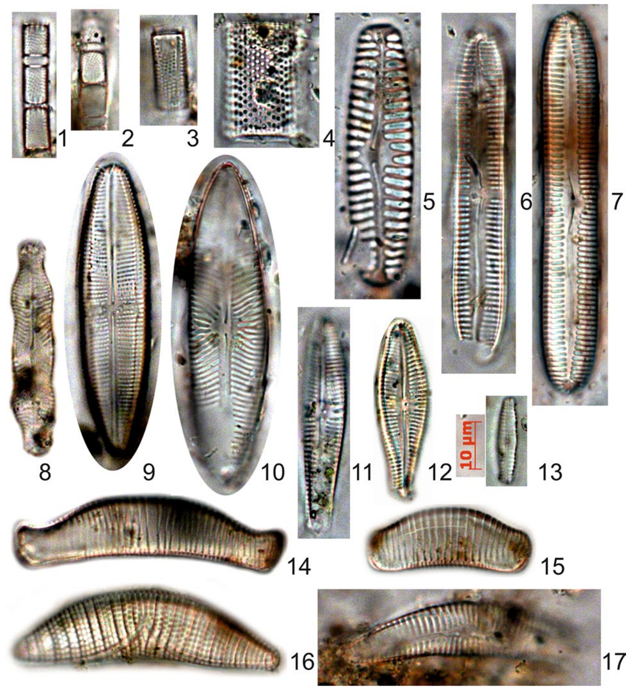

Fig. 6 Freshwater diatoms in surface sediments of the Laptev, East Siberian, and Chukchi seas. 1, 2–*Aulacoseira subarctica* (O. Müller) Harworth; 3–*Aulacoseira granulata* (Ehrenberg) Simonsen; 4–*Aulacoseira islandica* (O. Müller) Simonsen; 5–*Pinnularia neorabenhorstii* Gogorev; 6–*Pinnularia rupestris* Hantzsch; 7–*Pinnularia brevicostata* Cleve; 8–*Pinnularia mesolepta* (Ehrenberg) W.Smith; 9–*Neidiumam pliatum* (Ehrenberg) Krammer; 10–*Navicula digitoradiata* (W.Gregory) Ralfs; 11–*Gomphonema affine* Kützing; 12–*Gomphonema ventricosum* Gregory; 13–*Reimeria sinuata* (Gregory) Kociolek & Stoermer; 14–*Eunotia exigua* (Brébisson ex Kützing) Rabenhorst; 15–*Eunotia Praerupta* Ehrenebrg; 16–*Epithemia turgida* (Ehrenberg) Kützing; 17–*Cymbella arctica* (Lagerstedt) Schmidt. Scale bar is 10 µm

surface sediments corresponds to those previously reported (Cremer 1999).

The sediments of the Laptev Sea were dominated by brackish water planktonic diatom species (32–99%). However, there was also a noticeable admixture of freshwater species in the zone of influence of the Lena River runoff (Figs. 3, 6).

Sediments from the continental slope (station 83–8, depth 2447.4 m; station 83–9, depth 2157.5 m) were characterized by low diatom concentrations ($0.028–0.043\times10^6$ valves g^{-1}) and poor species composition (11–12). The marine *P. sulcata* predominated (42%) (Fig. 4a). The planktonic oceanic arctoboreal species *A. curvatulus* (20%) (Fig. 4b) and *Chaetoceros* RS (16%) subdominated. The single freshwater species *Epithemia turgida* and *Pinnularia* spp. and fragments of the extinct Cretaceous-Paleogene species *Eupyxidicula* spp. and *Hemiaulus* sp. were also detected (Fig. 7). This assemblage compositionally resembled those described for the sediments of the Arctic Ocean.

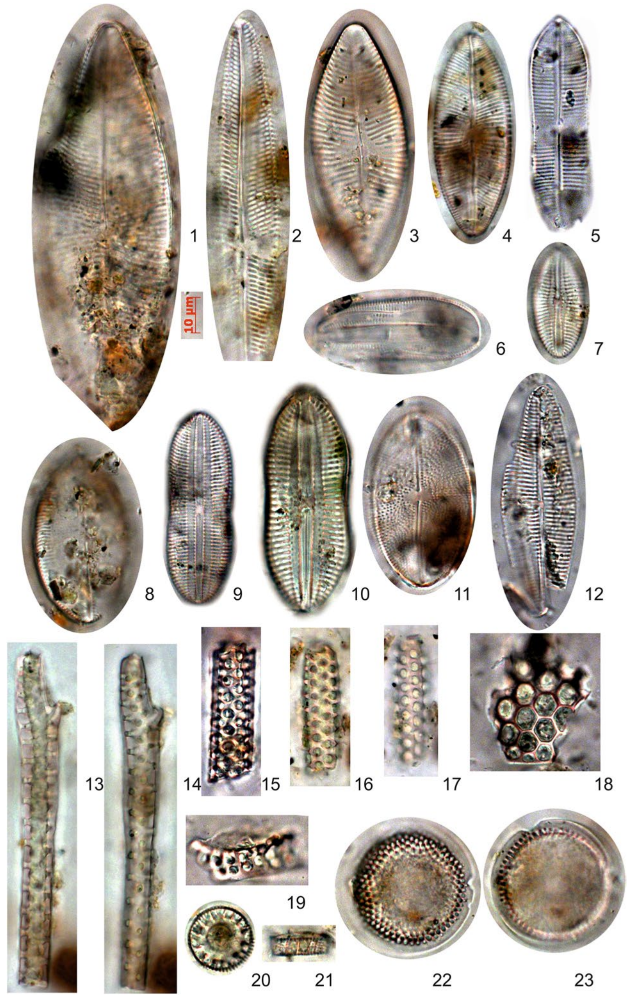

Fig. 7 Marine benthic (1–12) and extinct (13–23) diatoms in surface sediments of the Laptev, East Siberian, and Chukchi seas. 1—*Navicula imperfecta* Cleve; 2—*Trachyneis aspera* (Ehrenberg) Cleve; 3—*Navicula valida* Cleve & Grunow; 4—*Navicula semen* Ehrenberg; 5—*Pinnularia quadratarea* var. *constricta* (Østrup) Heiden; 6—*Amphora proteus* Gregory; 7—*Diploneis elliptica* (Kützing) Cleve; 8—*Craspedopleura kryophila* (Cleve) M.Poulin; 9—*Petroneis glacialis* (Cleve) Witkowski; 10—*Diploneis didyma* (Ehrenberg) Ehrenberg; 11—*Diploneis subcincta* (Schmidt) Cleve; 12—*Navicula superba* var. *elliptica* Cleve; 13, 14—*Pyxilla oligocaenica* var. *tenuis* Jousé; 15—*Pyxilla gracilis* Tempere & Forti; 16, 17—*Pyxilla cretacea* Jousé; 18 –*Eupyxidicula* sp.; 19—*Hemiaulus* sp.; 20, 21—*Alveolophora robusta* (Khursevich) Usoltseva & Khursevich; 22, 23—*Eupyxidicula zabelinae* (Jousé) S. Blanco & C.E. Wetzel. Scale bar is 10 µm

In the sediments of the outer shelf of the Laptev Sea (station 83–7, depth 61.2 m; stations 83–14–83–17, depth 38.2–48.5 m), the ice-neritic species *M. arctica* predominated (22–58.7%) (Fig. 4c) while the subdominants were *P. sulcata* (8–58.5%) and *T. hyperborea* (9–21%). The *Chaetoceros* RS content was high (2.3–21%). *C. asteromphalus*, *T. antarctica*, and *N. peregrina* were also observed, but their numbers were not significant.

The diatom assemblages in the sediments of the southeastern part of the sea near the Lena and Yana River deltas (stations 83–4-6, 83–22–83–25, and 83–28–83–34) were dominated by the brackish water planktonic species *T. hyperborea* and especially *T. hyperborea* var. *pelagica* (41–75%) (Fig. 4d), *M. arctica* (13.3–38%), *Chaetoceros* RS (≤ 12%), and single specimens of 49 freshwater species (ESM 2).

A significant abundance of freshwater species (10.7–25.3%) was recorded for the sediments of the zone of direct influence of the Lena River runoff (stations 83–25 and 83–28). Diatom assemblages dominated by freshwater species are typical of the shelf sediments near the mouths of the rivers in the Laptev Sea (Tsoy 2001) and other Arctic seas (Abelmann 1992; Polyakova 1997; Polyakova et al. 2003). *T. hyperborea* is relatively more common in areas affected by the large rivers of Siberia and Canada than it is in the open parts of the Arctic Ocean (Hasle and Lange 1989). *T. hyperborea* abounds in waters with salinity 2–30 psu (Cremer 1999). It actively vegetates during springtime sea ice melting (Syversten 1990) and predominated in both the ice communities and the subglacial water layers of the study area (Ilyash and Zhitina 2009). *M. arctica* is a brackish ice-neritic species characterized by ecological preferences and distributions resembling those of *T. hyperborea* (Hasle and Lange 1989). Nevertheless, it forms massive aggregations on the lower surfaces of Arctic drift ice in the central part of the Arctic Basin (Melnikov and Bondarchuk 1987).

The sediments in the study region were characterized by a predominance of *T. hyperborea* (Tsoy 2001). In certain samples, however, *T. baltica* was both the dominant and subdominant species, and cryophiles were observed in small numbers. In the present study, though, cryophiles were not detected in the sediments, and only individual *T. baltica* were found.

The sediments of the study region presented with single fragments of the extinct Paleogene species *Pyxilla gracilis* and *Pyxilla oligocaenica* var. *tenuis* (Fig. 7). Reworked Cenozoic species were previously recorded for the study area (Polyakova 1997; Tsoy 2001) and were associated with the erosion of Cenozoic deposits on the adjacent land and shelf.

The diatom assemblages in the sediments of the underwater valley of the western Lena (stations 83–19–83–21, depth 28.9–30.8 m) were characterized by a predominance of *T. hyperborea* (24.5–33.5%) and *T. antarctica* (22–32%) (Fig. 8a), a subdominance of *M. arctica* (13–18%), and noticeable amounts of the cryophiles (0.8–9%) and *Chaetoceros* RS (3–6.4%). The single benthic species *Pseudogomphonema kamtchaticum*, *Diploneis elliptica*, *Diploneis didyma*, *Diploneis smithii*, and *Diploneis subcincta* were also detected. The freshwater species *Aulacoseira*

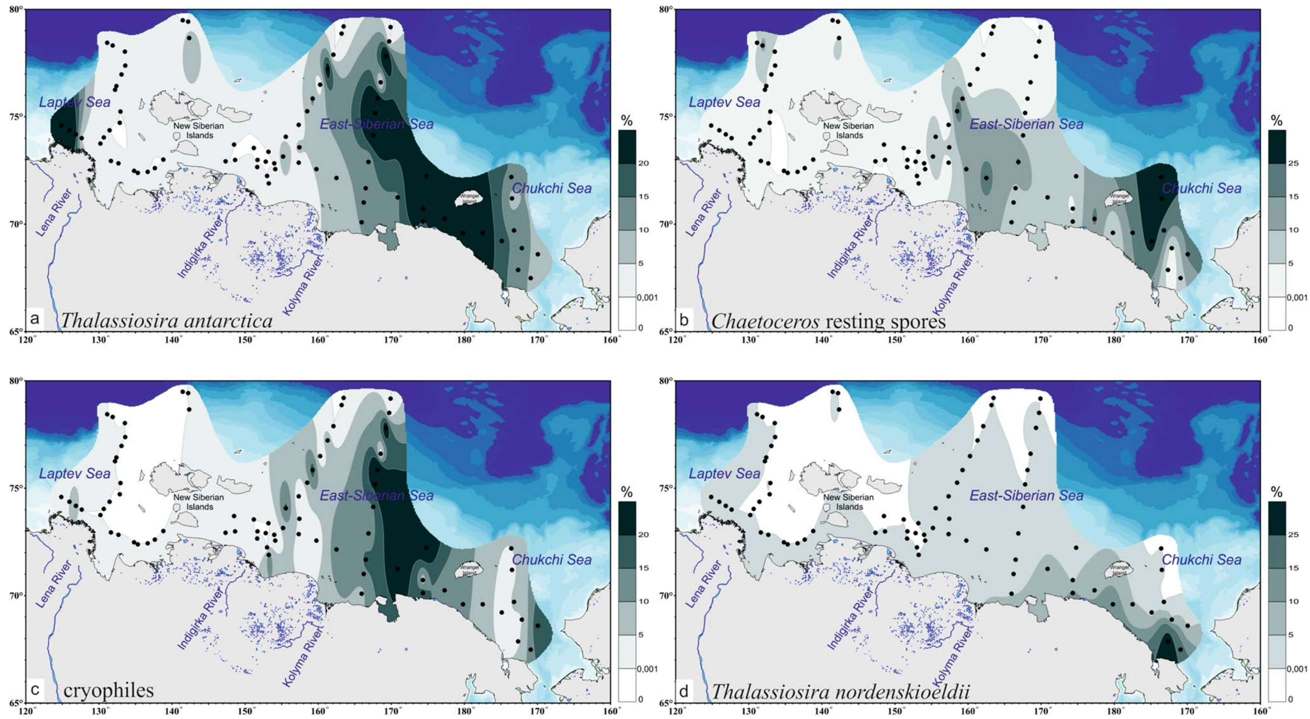

Fig. 8 Distributions of *Thalassiosira antarctica* (**a**), *Chaetoceros* resting spores (**b**), cryophiles (**c**), and *Thalassiosira nordenskioeldii* (**d**) in surface sediments of the Laptev, East Siberian, and Chukchi seas

subarctica, *Stauroneis phoenicenteron*, *Gomphonema affine*, and others constituted 2.5–5.5% of the total.

The maximum numbers of total species (25–38) and freshwater species were noted for the samples from the zone of influence of the Lena River runoff (stations 83–21, 83–22, 83–25, and 83–28). The minimum number of species (3–8) was determined mainly for the samples from the coastal areas of the Laptev Sea (stations 83–31 and 83–32).

East Siberian Sea

The diatom concentrations were low in the sediments of the ESS (average 0.094×10^6 valves g^{-1}). The lowest concentrations ($0.004–0.066 \times 10^6$ valves g^{-1}) were noted in the western part of the sea north of the mouth of the Indigirka River. In the eastern part of the sea, the diatom concentrations gradually increased and reached a maximum of $0.748–1.02 \times 10^6$ valves g^{-1} in the Long Strait. The diatom concentrations increased in the sediments from east to west (Polyakova 1997; Obrezkova et al. 2014; Tsoy and Obrezkova 2017). Similar distribution patterns were observed for phytoplankton primary production according to chlorophyll levels measured by satellite (Romankevich and Vetrov 2001). Elevated diatom content in the sediments of the eastern part of the ESS was confirmed from the high Cd content in these sediments (Sattarova et al. 2021). Cd accumulates in diatoms transported by the highly productive waters of the Bering Sea. The ecological structures of the diatom assemblages in the sediments of the ESS varied widely from west to east. Brackish-water diatoms predominated in the western part (52–100%) while marine diatoms predominated in the eastern part (66.4–95.7%).

In the sediments of the western part of the sea (station 83–10, depth 77.2 m), *Paralia sulcata* predominated (38.8%), *M. arctica* subdominated (15.3%), the marine planktonic species *T. antarctica* (8%) and *Chaetoceros* RS (12%), as well as the brackish-water species *T. hyperborea* (8%) and *N. peregrina* (6.5%) were abundant. Single extinct *Pyxilla gracilis* and *Eupyxidicula* spp. and freshwater *Stauroneis gracilis* were also detected.

In the sediments of the zone of influence of the Indigirka River runoff (station 83–2, depth 15 m; station 83–3, depth 14 m), the diatom assemblages were dominated by *M. arctica* (59–94%), *T. hyperborea* and especially *T. hyperborea* var. *pelagica* (2–16%), and the brackish, benthic *N. peregrina* (4%). The freshwater *Pinnularia brevicostata*, *Pinnularia major*, *Pinnularia stomatophora*, *Pinnularia borealis*, *Pinnularia neorabenhorstii*, and others constituted 5% of the total assemblage.

The sediments of the ESS north of the Indigirka River mouths were dominated by the brackish-water planktonic species *T. hyperborea* (18–78%) (stations 77–36–77–40, 77–42, 77–45, 83–35, and 83–36) (Astakhov et al. 2022), *M. arctica* (36–94%) (stations 83–2, 83–3, and 83–37–83–39) and subdominated by the benthic species *N. peregrina* as well as the marine planktonic *Chaetoceros* RS (Fig. 8b). The latter predominates in the plankton to the north of the Indigirka River region (Sukhanova et al. 2021) and in those of all Arctic seas in general (Gogorev and Samsonov 2016). The abundances of the cryophiles were high (7.3–13.0%) (stations 77–34, 77–36, and 77–40) (Fig. 8c) as were those of *P. sulcata* (stations 77–45 and 77–36).

Brackish-water and marine benthic *Diploneis littoralis* var. *clathrata*, *D.smithii*, *Entomoneis kjelmanii*, *Navicula directa, Nitzschia hybrida*, and others were sporadically found. The ice species *Craspedopleura kryophila* is endemic to the marine Arctic (Poulin 1993) and was detected in the sediments of the ESS. The freshwater *Cyclotella meneghiana*, *Cymbella arctica*, *A. subarctica*, and *Tryblionella hungarica* and the extinct *E. zabelinaei* were also seen. Moreover, *T. hyperborea* was nearly monodominant in this area (Polyakova 1997).

In the eastern (stations 77–10–77–20) and northern (stations 77–21-77–23, 77–31, 77–77-33) parts of the ESS, the cold-water neritic species *T. antarctica* (6.8–47.3%) (Fig. 8a), *Chaetoceros* RS, and cryophiles predominated (Fig. 8c). *Thalassiosira hyperborea*, *T. nordenskioeldii*, *B. bathyomphala*, and *P. sulcata* were abundant while *M. arctica* and oceanic *R. hebetata* were constantly detected albeit in non-significant numbers. The diatom distributions observed here generally corresponded to those previously identified (Polyakova 1997; Obrezkova et al. 2014).

In the sediments at stations 77–24, 77–32, 77–35, 77–41, 77–43, and 77–44, the diatoms were represented by single valves of the marine and brackish-water species *T. hyperborea*, *P. sulcata*, *M. arctica*, and *N. peregrina* which are typical to this region. Freshwater *A. granulata* and *E. zabelinae* extinct in the Neogene were also observed.

Chukchi Sea

The diatom concentrations in the surface sediments of the Chukchi Sea were higher than those in the Laptev Sea, ESS, and Arctic Ocean (average 2.991×10^6 valves g^{-1}). The maximum concentration ($5.642–7.998 \times 10^6$ valves g^{-1}) was recorded in the southern part of the sea coinciding with the zone of influence of the highly productive Bering Sea waters. High diatom content is typical of the recent sediments in this region of the Chukchi Sea (Polyakova 1997; Obrezkova 2012; Obrezkova et al. 2014; Astakhov et al. 2015; Tsoy et al. 2017; Obrezkova and Pospelova 2019). In the southwestern part of the Chukchi Sea, there were $1.338–2.72 \times 10^6$ valves g^{-1}. In the remainder of the Chukchi Sea, however, there were $0.95–3.13 \times 10^6$ valves g^{-1}. Overall, these data were consistent with those previously published (Polyakova 1997; Obrezkova et al. 2014, 2022; Tsoy and Obrezkova 2017; Sattarova et al. 2022).

In the sediments of the Chukchi Sea, the diatom assemblages were dominated by marine planktonic and planktonic-benthic neritic species (72.6–96.7%) and significant amounts of oceanic species (≤ 10%). In the western part of the Chukchi Sea (stations 77–8 and 77–9) at the zone of influence of the Siberian coastal current, *T. antarctica* (27.3–32%) and *Chaetoceros* RS (11.9–32.4%) predominated (Fig. 8a, b). However, cryophiles (8.6–12.7%) and *T. nordenskioeldii* (5.6–13.5%) (Fig. 8c, d) were also relatively abundant. The sediments of the southernmost part of the Chukchi Sea (stations 77–1 and 83–1) were dominated by the arctoboreal-tropical species *T. nordenskioeldii* (17.3–38.8%) (Shevchenko et al. 2020) which also occurs in large amounts in the waters and sediments of the western part of the Bering Sea (Semina 1981; Sancetta 1982; Ran et al. 2013; Ren et al. 2014) and indicates the presence of Bering Sea waters in the Chukchi Sea. *P. sulcata* (12.7–15.3%), *B. bathyomphala* (8.3–12.7%), *Chaetoceros* RS (8.3–15.6%), *T. antarctica* (12%), and various cryophiles (4.8–14.7%) were also abundant. The sediments of the zone of influence of the Bering Sea waters (stations 77–2–77–7) were dominated by *Chaetoceros* RS (13–49.8%), *P. sulcata* (11–23.6%) and subdominated by various cryophiles (2.7–21.8%), *T. antarctica* (7.3–18.3%), *B. bathyomphala* (1.8–9.1%), *T. nordenskioeldii* (0–6%), and *Pauliella taeniata* (~ 1%). Permanent constituents of the diatom assemblages in the sediments of the Chukchi Sea included *Stephanopyxis nipponica, Thalassiosira hyalina, Actinoptychus senarius, Odontella aurita, Thalassionema nitzchioides*, and *Thalassiothrix longissima*.

Discussion

The diatoms from the surface sediments of the Laptev, East Siberian and Chukchi seas are characterized by low abundance, poor species richness, and the predominance of one or two species. These properties are typical of diatom communities under extreme environmental conditions such as the low temperatures and constant ice cover of the Arctic. The low diatom abundance in the deep sea sediments of the Arctic Ocean is explained by dissolution of the siliceous valves because of the low silicic acid concentrations in the water column and sediment pore water of the Arctic Ocean (Polyakova 1997; März et al. 2015; Polyakova et al. 2019).

The diatom assemblages in the sediments of studied region significantly differ in terms of ecological structure (Fig. 3). The assemblages of the Arctic Ocean are characterized by the predominance of marine species (80–94.2%). By contrast, brackish-water species predominate in the Laptev Sea (32–99%). There is a noticeable admixture of freshwater species in the zone of influence of the Lena River runoff. In the ESS sediments, brackish-water diatoms predominate in the western part (52–100%), whereas marine diatoms predominate in the eastern part (66.4–95.7%). In the Chukchi

Sea, the diatom assemblages consist almost exclusively of marine species (92.4–100%).

The diatom distribution in the surface sediments of the Laptev, East Siberian, and Chukchi seas, sampled in 2016 and 2018, showed some differences from that in sediments at the end of the last century. Based on the sedimentation rate (Vonk et al. 2012; Tsoy et al. 2017; Astakhov et al. 2019; 2022), the upper layer (0–1 cm) of the studied surface sediments accumulated from 12.5 to 20 years, depending on from the region. The sediments used for comparison were sampled mainly in the 1990s (Polyakova 1997; Kremer 1999; Tsoy 2001; Matul et al. 2007; etc.). Therefore, we believe that the compared sediments accumulated at different times with a difference of 20–30 years.

In the Arctic Ocean and the continental slope of the Laptev Sea, the cold-water assemblage formerly predominated by *T. antarctica*, *Aulacoseira* spp., *P. sulcata*, and *Melosira* spp. (Cremer 1999) was transformed into a *P. sulcata* assemblage subdominated by the oceanic species *A. curvatulus* possibly because of the growing influence of the warm North Atlantic Current in recent decades (Polyakova et al. 2005).

The most significant changes in sedimentary diatom distribution were noted for the Laptev Sea. To the east of the Lena River Delta, the diatom assemblage formerly predominated by the freshwater *Aulacoseira* species (Cremer 1999; Matul et al. 2007; Obrezkova et al. 2014) was eventually predominated by the brackish-water species *T. hyperborea* over three decades. One possible explanation is the change in the direction of the Lena River flow during that time. In low-water years, the water volume decreases in the eastern Bykovskaya Channel while the water runoff increases in the northern Trofimovskaya and western Olenekskaya Channels (Alekseevskii et al. 2014; Magritsky et al. 2018).

To the east of the Lena River Delta in the Dm. Laptev Strait and near the mouth of the Indigirka River, the brackish-water species *T. hyperborea* predominates (41–81.5%) (Fig. 4d) and the abundance of *M. arctica* is high (11–38%). Previous studies characterized the sediments to the east of the Lena River Delta as freshwater diatom assemblages dominated by *Aulacoseira* spp. (Cremer 1999; Matul et al. 2007; Obrezkova et al. 2014). Similar findings were reported for the phytoplankton assemblages (Sukhanova et al. 2017). In the present study, the total freshwater species content was ≤ 25% and no single species predominated. In the Dm. Laptev Strait, a high content of the brackish-water species *T. baltica* (≤ 67%) was previously noted (Polyakova 1997; Tsoy 2001; Obrezkova et al. 2014). For the samples obtained in 2018, *T. baltica* did not surpass 6% of the total.

In the coastal shelf sediments of the ESS, the assemblage was formerly dominated by the brackish-water species *T. hyperborea* and was later dominated by the marine ice-neritic species *M. arctica* possibly because of local transformations in the hydrochemical regime.

Here, the diatom distributions in the surface sediments of the Chukchi Sea corresponded to those previously reported (Polyakova 1997; Obrezkova et al. 2014, 2023; Ran et al. 2013; Astakhov et al. 2015; Obrezkova and Pospelova 2019). *T. antarctica* predominated in the western part of the sea (Fig. 8a), *Chaetoceros* RS predominated in the Herald Canyon area (Fig. 8b), and the neritic *T. nordenskioeldii* predominated in the southern part (Fig. 8d).

Thus the more noticeable changes in the composition of diatoms in the Laptev and East Siberian seas that we have established are probably associated with a greater influence of river runoff (e.g., Dong et al. 2022) and warm Atlantic waters (Polyakova et al. 2005), while in the Chukchi Sea the river runoff is particularly absent, and the influence of Pacific waters did not change dramatically last decades (Astakhov et al. 2020), so changes in diatom flora are minimal.

Eight reworked extinct Upper Cretaceous and Cenozoic diatom species were found sporadically in the sediments of the Laptev and East Siberian seas and the Arctic Ocean. They included the marine species *P. gracilis*, *P. oligocaenica* var. *tenuis*, *H. frigidus*, *Eupyxidicula* spp., and *Hemiaulus* spp. typical of the Upper Cretaceous and Lower Paleogene deposits of Western Siberia and the Ural Mountains (Strelnikova 1974, 1992), which are eroded by rivers and carried into the seas. These diatom species were detected mainly in sediments on the shelf edge, the continental slope, and in the Arctic Ocean (stations 83–7–83–12). Reworked marine Cretaceous-Paleogene diatoms occurred earlier in the surface and Quaternary sediments of the Eastern Arctic seas and the Arctic Ocean (Polyakova 1997; Tapia and Harwood 2002; Tsoy and Obrezkova 2017; Obrezkova et al. 2019). The freshwater Miocene species *Alveolophora robusta* and *Aulacoseira praegranulata* var. *praeislandica* f. *praeislandica* were located in the sediments of the Laptev Sea at stations 83–6, 83–16, 83–17, 83–21, 83–22, and 83–28 in the zone of freshened surface water flow including the Lena River water from the northeastern part of the delta in a northwestern direction (Dmitrenko et al. 2001; Wegner et al. 2017; Osadchiev et al. 2021). These diatoms were probably transported by river runoff from the adjacent land where continental Miocene deposits containing ancient freshwater diatoms commonly occur (Usoltseva and Khursevich 2013). These species were previously recorded in reworked form in the Pleistocene-Holocene deposits of Buor-Khaya Bay obtained from core No. 1D-11 (Obrezkova et al. 2019).

Conclusions

As of 2016 and 2018, the diatom assemblages in the surface sediments of the Laptev and East Siberian seas had significantly changed in terms of species composition and quantitative ratio compared with those analyzed nearly 30 years ago. By contrast, the diatom assemblages in the surface sediments of the Chukchi Sea had not significantly changed over this time period. The most significant changes in diatom assemblage had occurred in the Laptev Sea over the past three decades. To the east of the Lena River Delta, the freshwater assemblage *Aulacoseira* spp. had transformed to the brackish-water assemblage *T. hyperborea* presumably because of a change in the direction of the Lena River flow. In the vicinity of the continental slope of the Laptev Sea, the cold-water assemblage *T. antarctica* was replaced by the warm-water and brackish-water assemblage *P. sulcata* and the oceanic species *A. curvatulus* possibly because of an increase in the influence of the warm North Atlantic Current. In the coastal shelf sediments of the ESS, the brackish-water assemblage *T. hyperborea* had transformed to the marine planktonic ice-neritic assemblage *M. arctica* probably because of ice melting and a prolonged ice-free period associated with global warming in recent decades. Further research should be directed to the study of diatoms in the sediments of the Great Siberian Polynya and the zone of influence of the North Atlantic Current and Pacific waters to assess changes in these unique natural phenomena due to climate changes in recent decades.

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Author contributions AK analyzed the diatom samples, MO and IT analyzed the diatom samples and prepared the manuscript, XS and YL organized the expeditions and critically revised the manuscript. All authors read and approved the manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available in supplementary information or from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare that they have no conflict of interest.

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