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Composition and distribution of diatom assemblages in the surface sediments of the Bering Sea

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Abstract Diatoms collected from the top 1 cm of the surface sediment layer at seven Bering Sea stations during the Fourth Chinese National Arctic Research Expedition (4th CHINARE-Arctic) in 2010 were studied. In total, 101 taxa belonging to 38 genera were found. The species were divided into four groups: eurythermal species, boreal-temperate species, polar species, and sea-ice species. The diatom assemblages at the stations in the southwestern basin area were primarily composed of boreal-temperate species, such as *Neodenticula seminae*, *Thalassiosira trifulta*, *Rhizosolenia hebetata* f. *hiemalis*, and *Actinocyclus curvatulus*. The northeastern shelf stations were dominated by polar species, including *Fragilariopsis oceanica*, *Thalassiosira antarctica* spora, *Thalassiosira nordenskioeldii*, and *Thalassiosira hyalina*. The overall abundance was highest at the basin stations with 3.7×10^6 cells·g^{-1} of wet sediment, whereas the eastern shelf stations had the lowest abundance of 0.7×10^6 cells·g^{-1} of wet sediment (excluding the resting spores of *Chaetoceros* spp.). The relationship between the distribution of the surface sediment diatom assemblages and the environment is discussed.

Keywords **Bering Sea, surface sediment, diatom, species composition, distribution**

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1 Introduction

The Bering Sea is the largest marginal sea of the North Pacific Ocean, and its waters are highly productive and rich in diatoms. Diatoms are readily preserved in sediments because of their silicon frustules, therefore large deposits of diatoms are found in the sediments of the Bering Sea. Few studies have been conducted on these sedimentary assemblages. Semina and Jousé[1] were the first researchers to study diatoms from the western Bering Sea and they compared the deposited assemblages and living communities. Jousé[2] analyzed the diatom assemblage structure in vertical sections of sediment from the western Bering Sea. Sancetta[3-4] conducted a large-scale study of diatom assemblages in the surface sediments of the Bering Sea, classified the assemblages, and explored the relationship between the distribution of the diatom assemblages and the environment.

Rapid changes in the marine communities of the northern polar region related to global climate change have been the focus of much scientific research in recent years. China has conducted four scientific surveys in the Arctic (CHINARE-Arctic), and these surveys have included studies of diatoms in the water column and in the surface sediment. Yang et al.[5] studied the composition and distribution of diatom communities in the waters of the Bering and Chukchi Seas. Wang and Chen[6] analyzed diatom assemblages in the top 3 cm of sediments in the Bering Sea and found that the depth, temperature, and salinity of the water column were the major factors affecting the abundance and distribution of the diatoms. Ran et al.[7] investigated the distribution of diatom assemblages in the top sediment layer (0–2 cm) of the Bering and Chukchi Seas, and divided them into four major assemblages.

In the present study, we focused on the identification

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and categorization of diatom species collected from the surface sediment of seven stations surveyed in the Bering Sea during 2010. The distribution of the dominant species and the abundance of these assemblages were also studied. The findings of our study will improve understanding of the composition and distribution characteristics of diatom assemblages in the sediments of the Bering Sea, and will also provide baseline data for the investigation of environmental changes in the region.

2 Materials and methods

Three samples of the top 1 cm of surface sediment were collected from the seven stations in the Bering Sea using a multi-corer, and were preserved in 5% formalin. The details and locations of the sampling stations are shown in Table 1 and Figure 1. The diatom samples were processed according to the modified methods of Håkansson[8]. For each sample, 2 g of surface sediment were added to 100 mL of distilled water and mixed well, then 1 mL of this solution was collected, and 2 mL of 30% hydrogen chloride and 2 mL of 30% hydrogen peroxide were added. This solution was heated for 2 h at 60℃ to remove calcium and organic matter and then the remaining acid was removed by washing with distilled water. A 100-μL sample of the wet sediment was placed under a light microscope (Olympus BH-2) and diatoms were counted and identified. Each sample was counted three times and the average was calculated and converted to a number of diatom cells·g^{-1} of wet sediment. The cells that could not be identified under the light microscope were further examined using a scanning electronic microscope. The identification was based on the published literature[9-33]. The formula used to calculate diatom abundance is as follows:

$$\text{Diatom abundance}(\text{cells}\cdot \text{g}^{-1}) = \frac{(X1+X2+X3)/3}{2\text{ g wet sediment}}\times 1000, \quad (1)$$

where X1, X2, X3 denote the number of diatom cells in each of the three 100 μL sample replicates.

Table 1 Details of the seven sampling stations in the Bering Sea

Station	Longitude	Latitude	Depth /m	Sediment type	Sampling date (YYYY-MM-DD)
B06	174.49°E	57.01°N	3 780	gray clay	2010-07-12
B07	176.20°E	58.00°N	3 743	brown clay	2010-07-12
B14	177.69°W	60.92°N	130	gray muddy silt	2010-07-15
B15	176.37°W	61.07°N	110	brown muddy silt	2010-07-15
BB05	175.33°W	62.54°N	79	light gray clay	2010-07-16
NB01	175.08°W	61.23°N	92	light gray clay	2010-07-16
NB08	167.34°W	62.66°N	35	light gray silty sand	2010-07-18

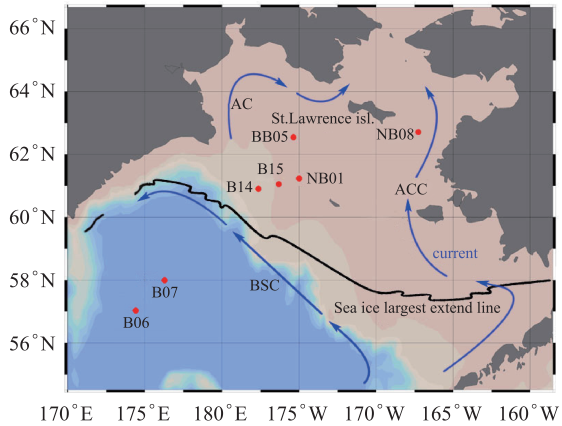

Figure 1 Locations of diatom sampling stations in the Bering Sea.

3 Results and discussion

3.1 Species composition

A total of 101 taxa, including varieties and forms, belonging to 38 genera were identified (Appendix 1).

The species were divided into four ecological groups:

(1) Eurythermal species: Species adapted to a range of temperatures and widely distributed, including *Thalassionema nitzschioides* and *Paralia sulcata*.

(2) Boreal-temperate species: Species found mainly at the basin stations B06 and B07, including *Neodenticula seminae*, *Thalassiosira trifulta*, *Rhizosolenia hebetata* f. *hiemalis*, and *Actinocyclus curvatulus*.

(3) Polar species: Species adapted to cold temperatures and widely distributed in polar and adjacent regions, including *Fragilariopsis oceanica*, *Thalassiosira antarctica* spora, *Thalassiosira nordenskioeldii*, *Thalassiosira hyalina*, and *Bacterosira fragilis*.

(4) Sea-ice species: Species mostly distributed on the northern shelf basin, including *Fragilariopsis cylindrus* and *Pauliella taeniata*.

3.2 Distribution of dominant species

3.2.1 Boreal-temperate species

The dominant diatom assemblages differed between the basin stations (B06 and B07) and the shelf stations (B14, B15, BB05, NB01, and NB08). At the basin stations, the dominant species was *Neodenticula seminae*, followed by other boreal-temperate species including *Thalassiosira trifulta*, *Rhizosolenia hebetata* f. *hiemalis*, and *Actinocyclus curvatulus*. These four species accounted for 70.7% of the total abundance at the basin stations and the polar species *Thalassiosira antarctica* spora accounted for 14.3% of the total abundance. There were very few sea-ice species found at the basin stations.

Neodenticula seminae is a boreal-temperate species found in the northern Pacific Ocean[30]. Sancetta[4] found that this species accounted for more than 50% of the total abundance of diatoms in the surface sediment of the north-eastern Pacific Ocean. In the present study, *Neodenticula seminae* accounted for 30.8% of the total abundance at the basin station B07 but its abundance was low at the shelf stations. Numbers of *Neodenticula seminae* decreased with increasing latitude, and it was not identified at the northern-most station NB08 (Figure 2a). Ran et al.[7] also found that this species was largely confined to the Bering Sea basin, and rarely found on the shallow shelf area or in the high latitude Chukchi Sea.

Thalassiosira trifulta accounted for 26.6% of the total abundance at the basin station B07 but for only 1.6% of the abundance at the shelf station B15. It was virtually absent at other shelf stations (Figure 2b). Sancetta[4] found that *Thalassiosira trifulta* accounted for 10%–20% of the total abundance in the Bering Sea basin but that numbers were much lower on the shelf, probably a consequence of the difference in salinity between the two areas.

Rhizosolenia hebetata f. *hiemalis* is a northern oceanic species, mainly distributed in temperate waters[18]. The species has thin silicon frustules that dissolve before it is deposited in the sediment, therefore only the base of the cell is preserved. It was widespread in the basin but virtually absent on the shelf (Figure 2c).

Actinocyclus curvatulus is widely distributed in the Okhotsk Sea. Sancetta[4] found that *Actinocyclus curvatulus* accounted for 10%–30% of the total abundance in the Okhotsk Sea, with the highest values in the central region. In the present study, *Actinocyclus curvatulus* accounted for only 5.7% of the total abundance at the basin station B07, and it was rarely found at the shelf stations (Figure 2d).

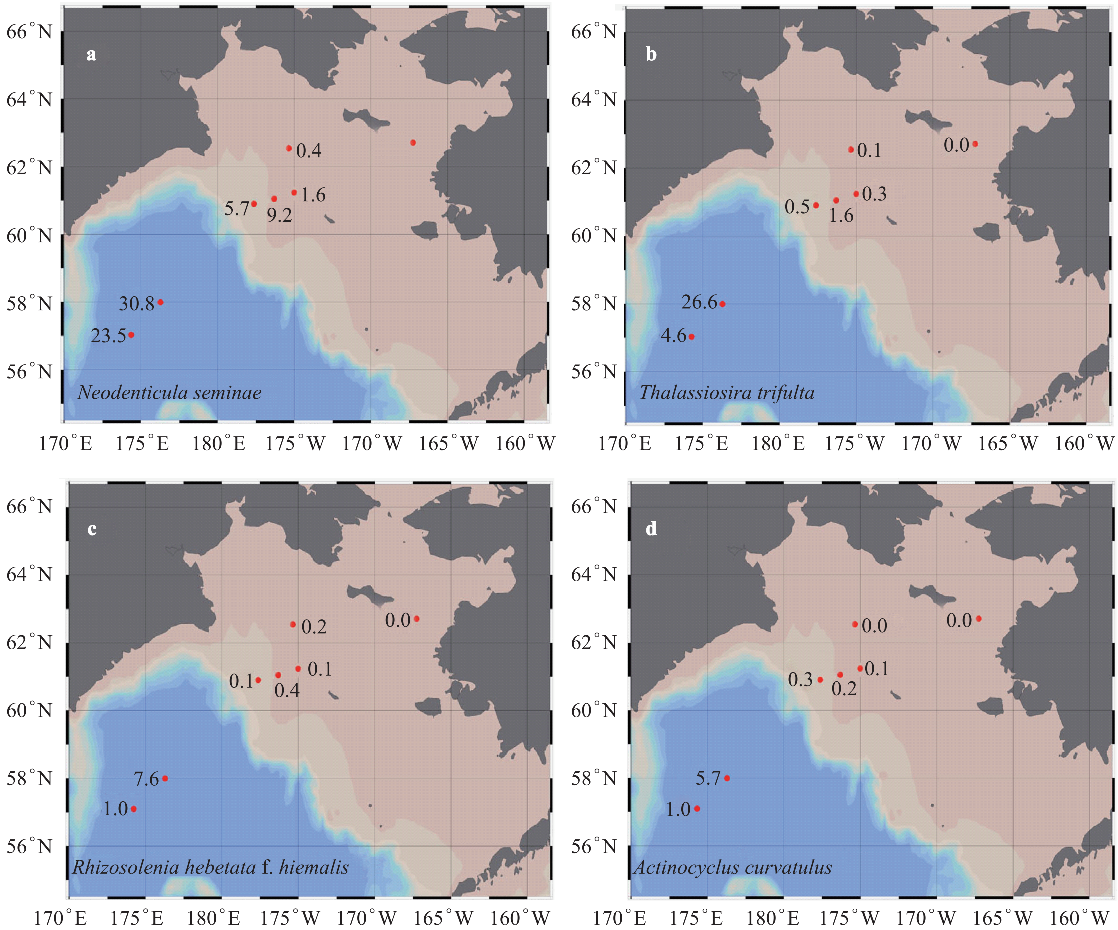

Figure 2 The distribution of the dominant boreal-temperate diatom species (% of total abundance).

3.2.2 Polar species

Fragilariopsis oceanica was the dominant species in the northern shelf region, followed by other polar species including *Thalassiosira antarctica* spora, *Thalassiosira nordenskioeldii*, and *Thalassiosira hyalina*. These four species accounted for 65.4% of the total abundance on the northern shelf. Sea-ice species were also found in the shelf region. For example, *Fragilariopsis cylindrus* accounted for 4.5% of the total abundance and the proportion of Pauliella taeniata increased with increasing latitude, to reach 6.2% of the total abundance at the northern-most station NB08.

Fragilariopsis oceanica is found in the high latitude northern polar regions, closely associated with sea-ice[16]. Sancetta[4] found that the species occurred throughout the Bering, Okhotsk, and Chukchi Seas. In the present study, it accounted for about 37.7% of the total abundance at the northern shelf stations, with the highest value of 50.9% at station BB05. On the western shelf, the proportion of *Fragilariopsis oceanica* increased with increasing latitude. At the eastern shelf station NB08, the species accounted for 36.7% of abundance, substantially lower than the abundance of 50.9% at station BB05, a western shelf station at a similar latitude. The species accounted for only 0.7% of the total abundance at the basin station B07 (Figure 3a).

Thalassiosira antarctica spora is a widely distributed polar species also found in sea-ice habitats[18]. In the Bering Sea surface sediment in this study, the species accounted for more than 10% of the total abundance at each station except for station NB08 (1.8%, Figure 3b).

Thalassiosira nordenskioeldii is a polar species mainly distributed in the Arctic region[18]. Jousé[2] reported that this species was common in the plankton community and sediment in Anadyr Bay and in the western Bering Sea. In the present study, it accounted for an average of 7.2% of the total abundance, making up more than 10% of the abundance at stations B15 and NB08, but at the basin station B07 it accounted for only 0.1% of total abundance (Figure 3c).

Thalassiosira hyalina is an Arctic shallow water species[19]. In the present study, it was found in low abundance at the deep basin stations where it accounted for an average of 1.6% of the total abundance, and it accounted for an average of 2.2% of abundance at the stations on the western shelf. At the northeastern shelf station NB08, the shallowest station, it accounted for 18.5% of the total abundance (Figure 3d).

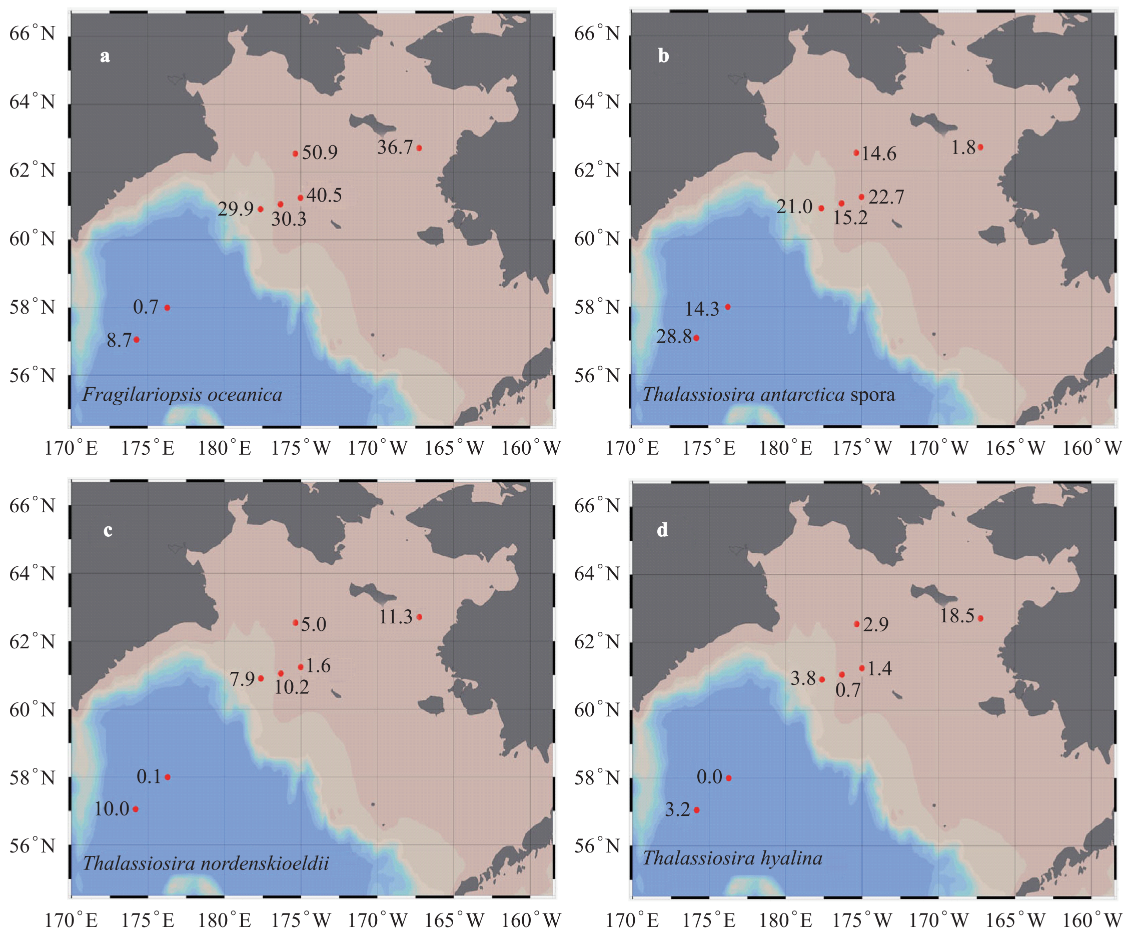

Figure 3 The distribution of the dominant polar diatom species (% of total abundance).

3.3 Abundance

The samples could be divided into three regions based on the total abundance. The southwestern basin stations B06 and B07 had the highest cell abundance of about 3.7 $\times10^6$ cells·g^{-1} of wet sediment, the northwestern shelf stations (B14, B15, NB01, and BB05) had an intermediate average abundance of 2.3$\times10^6$ cells·g^{-1} of wet sediment, while the northeastern shelf station NB08 had the lowest abundance of 0.7$\times10^6$ cells·g^{-1} of wet sediment. Therefore, the abundance decreased from the southwestern to the northeastern stations (Figure 4). Sancetta[4] found a similar distribution of abundance in the Bering Sea shelf area. Lisitzin[34] found that the abundance of diatom frustules in the southern sector of the Aleutian Basin was higher (15$\times10^6$–45$\times10^6$ cells·g^{-1} of dry sediment) than in the northern, eastern, and western sectors (5×10^6–15×10^6 cells·g^{-1} of dry sediment). Station B07 in the present study is within the region where Lisitzin[34] found an abundance of 5×10^6–15×10^6 cells·g^{-1} of dry sediment, but the abundance at station B07 was only 3.6×10^6 cells·g^{-1} of wet sediment. The main reason for this discrepancy is that we did not include the resting spores of *Chaetoceros* spp.

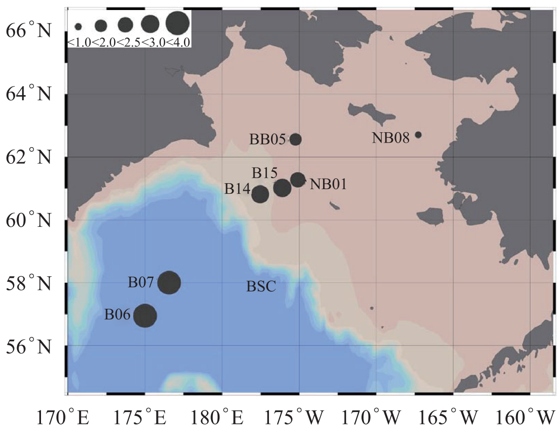

Figure 4 The horizontal distribution of total diatom abundance in the surface sediments of the Bering Sea ($\times10^6$ cells·g^{-1}).

3.4 Environmental factors influencing diatom distribution

3.4.1 Temperature, salinity, and water body

The warmer, saltier waters of the North Pacific enter the Bering Sea around the Komandor Archipelago, and the upper-layer water temperature and salinity decrease in a north to southeasterly direction as a result of mixing[35]. The total abundance of diatoms is affected by these changes in water temperature and salinity, and abundance at the basin stations was much higher than that at the northern shelf stations. The diatoms at basin stations were dominated by the boreal-temperate species, such as *Neodenticula seminae*, *Thalassiosira trifulta*, *Rhizosolenia hebetata* f. *hiemalis*, and *Thalassiothrix longissima*. The distribution of Neodenticula seminae, an indicator species of the North Pacific Ocean[5], also reflected the influence of the North Pacific Ocean water on the Bering Sea (Figure 2a).

The temperature and salinity in the northern shelf region are lower because of the influence of ice forming and melting in the winter and summer, respectively. The total abundance of diatoms in the northern shelf region was also lower than that at the basin stations, and was mainly dominated by polar water species and sea-ice species, such as *Fragilariopsis oceanica*, *Thalassiosira nordenskioeldii*, *Thalassiosira hyalina*, and *Fragilariopsis cylindrus*. The present study found that the diatom abundance at the eastern station NB08 was less than half of that at the western shelf station BB05, located at similar latitude, probably a result of the influence of the oligotrophic and low salinity Alaska Coastal Current[36] (Figure 1).

3.4.2 Water depth and sediment composition

Diatoms found at the deep water (>3 700 m) stations (B06, B07) were mostly planktonic species, while sporadic benthic pennate species, such as *Diploneis* spp. and *Gomphonema* spp., probably transported to the area from the continental shelf by ocean currents, accounted for only about 0.2% of the total abundance. Moderate numbers of benthic diatoms, such as *Nitzschia* spp. and *Navicula* spp., and small numbers of *Pleurosigma* spp. and *Amphora* spp. were found in the shelf region, at stations B14 and B15 where the average water depth was about 120 m. The pennate benthic diatoms accounted for an average of 8.3% of the total abundance, and the proportion of benthic diatoms increased with decreasing water depth. At station NB08 (water depth of 35 m), benthic pennate diatom species, such as *Nitzschia* spp., *Diploneis* spp., *Navicula* spp., *Pleurosigma* spp., *Amphora* spp., *Pinnularia* spp., and *Amphiprora* spp., accounted for 16.7% of the total abundance. Therefore, with a decrease in depth, there was a gradual increase in both taxa and numbers of benthic pennate diatoms. The abundance of sedimentary diatoms was highest at the deep-water basin stations, and the abundance decreased gradually as water depth decreased.

At the basin stations B06 and B07 the sediment was clay, with a fine grain size, and there were relatively weak hydrodynamic effects, favoring the sedimentation of diatoms. This resulted in much higher abundance compared with the continental shelf stations. Sediments at the shelf stations B14, B15, NB08, and BB05 were clay/silt and light gray clay, with coarser grain size and relatively low diatom abundance. The sediment at station NB08 was sandy and coarse, and the diatom abundance was the lowest among all stations, possibly a consequence of the stronger currents that flow over this station and carry sinking diatoms away.

3.4.3 Sea ice

The Bering Sea is seasonally covered by ice. During most of the winter, 75% of the shelf area is covered by sea-ice, with the largest extent occurring at the end of March[37] (Figure 1). Floe-ice occurs only occasionally in the basin waters, so the basin stations B06 and B07 are not significantly influenced by sea-ice and were dominated by temperate species, such as Neodenticula seminae and Thalassiosira trifulta, while cold water diatoms closely related to sea-ice environments, such as *Fragilariopsis oceanica*, *Thalassiosira nordenskioeldii*, *Thalassiosira hyalina*, *Fragilariopsis cylindrus*, and *Pauliella taeniata*, were rare. The five stations on the northern shelf were all located within the line of maximum sea-ice extent and the species associated with sea-ice, such as *Fragilariopsis oceanica*, *Fossula arctica*, *Thalassiosira nordenskioeldii*, *Thalassiosira hyalina*, *Fragilariopsis cylindrus*, and *Pauliella taeniata*, accounted for 57.1% of the total abundance on the shelf, while temperate species only accounted for 4.2%. Sea-ice not only affects the diatom composition, but also influences the abundance of diatoms. Ran et al.[7] found that diatoms were either very sparse or absent in the region permanently covered by sea-ice.

In recent decades, there has been a substantial reduction in sea-ice cover in the Arctic resulting from global warming and increasing surface water temperature. This reduction in ice cover is likely to affect the species composition and abundance of diatoms, and may lead to a decrease in sea-ice diatoms and cold water adapted diatoms, and an increase in temperate diatoms, in terms of both the variety of taxa and absolute numbers. The reduction in sea-ice cover and a northward shift of the minimum sea-ice extent line will expose areas previously covered by ice and will possibly favor the growth and reproduction of phytoplankton in the water column, in turn increasing the abundance of diatoms in the surface sediments.

4 Conclusion

A total of 101 diatom species belonging to 38 genera were identified in surface sediments collected from seven stations in the Bering Sea in 2010. The diatoms were sorted into four ecological assemblages. The composition of dominant surface sedimentary diatom species differed between stations in the basin area and on the shelf. Boreal-temperate diatom assemblages dominated the basin area, and *Neodenticula seminae* was the most abundant species. Sea-ice diatom assemblages and polar diatom assemblages dominated at the shelf stations, and the most abundant species on the shelf was *Fragilariopsis oceanica*. The highest diatom abundance was 3.7×10^6 cells·g^{-1} of wet sediment in the basin and the lowest abundance was 0.67×10^3 cells·g^{-1} of wet sediment on the eastern shelf (excluding resting spores of *Chaetoceros* spp.). The abundance decreased from the southwestern to the northeastern stations.

Temperature, salinity, currents, water depth, sediment composition and sea-ice extent all affected the distribution of diatoms in the surface sediments of the Bering Sea. The abundance of diatoms increased as temperature, salinity, and water depth increased, and locations where currents were weaker and sediments were finer were also associated with higher diatom abundance. Boreal-temperate diatoms were dominant in terms of number and species diversity in samples from basin stations influenced by the warmer, nutrient-rich waters from the Pacific Ocean. Samples from stations within the seasonal sea-ice zone were dominated by sea-ice diatoms, while the abundance of pennate benthic diatoms decreased in number and species diversity as water depth increased.

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Appendix 1 A list of diatom species found in the surface sediment samples from the Bering Sea in this study

Achnanthes sp.	*Navicula distans* (W. Sm.) Ralfs
Actinocyclus curvatulus Janisch	*Navicula* sp. 1
Actinocyclus ehrenbergi Ralfs	*Navicula* sp. 2
Actinocyclus oculatus Jousé	*Navicula* sp. 3
Actinocyclus subtilis Ralfs	*Navicula* sp. 4
Actinoptychus undulatus (Bailey) Ralfs	*Neodenticula seminae* (Simonsen and Kanaya) Akiba and Yanagisawa
Actinoptychus vulgaris Schumann	*Nitzschia closterium* (Ehrenberg) W. Sm.
Amphora angusta Gregory	*Nitzschia longissima* (Brébisson) Ralfs
Amphora sp.1	*Nitzschia lorenziana* (Grunow) Hustedt
Amphora sp.2	*Nitzschia sigmaformis* Hustedt
Amphora sp.3	*Nitzschia* sp. 1
Amphiprora sp.	*Nitzschia* sp. 2
Asteromphalus robustus Castracane	*Nitzschia* sp. 3
Bacterosira fragilis Gran spora	*Paralia sulcata* (Ehrenberg) Cleve
Chaetoceros decipiens Cleve	*Pauliella taeniata* Round and Basson
Chaetoceros didymus Ehrenberg spora	*Pinnularia* sp. 1
Chaetoceros furcellatus Bailey spora	*Pinnularia* sp. 2
Chaetoceros mitra (Bailey) Cleve Spora	*Pleurosigma tenuiforme* Hellum von Quillfeldt
Chaetoceros subsecundus (Grunow) Hustedt spora	*Pleurosigma* sp.
Coscinodiscus argus Ehrenberg	*Porosira glacialis* (Grunow) Jorgensen
Coscinodiscus asteromphalus Ehrenberg	*Pyxidicula weyprechtii* Grunow
Coscinodiscus centralis Ehrenberg	*Rhabdonema arcuatum* var. *ventricosa* Kützing
Coscinodiscus curvatulus Grunow	*Rhizosolenia hebetata* f. *hiemalis* (Bailey) Gran

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Coscinodiscus eccentricus var. *fasciculated* Hustedt	*Stephanodiscus lucens* Hustedt
Coscinodiscus lineatus Ehrenberg	*Stephanopyxis turris* Ralfs
Coscinodiscus marginatus Ehrenberg	*Synedra* sp.
Coscinodiscus oculus-iridis Ehrenberg	*Synedropsis hyperborea* (Grunow) Medlin et Syvertsen
Coscinodiscus pustulatus Mann	*Thalassionema nitzschioides* Grunow
Coscinodiscus radiatus Ehrenberg	*Thalassiosira anguste-lineata* (Schmidt) Fryxell et Hasle
Coscinodiscus subtilis Ehrenberg	*Thalassiosira antarctica* Comber spora
Coscinodiscus tabularis (Grunow) Fryxell and Sims	*Thalassiosira bulbosa* Syvertsen
Cymbella tumida (Brébisson) Grun	*Thalassiosira decipiens* (Grunow) Jørgensen
Delphineis kippae Sancetta	*Thalassiosira excentrica* (Ehrenberg) Cleve
Delphineis surirella (Ehrenberg) GW Andrews	*Thalassiosira frenguelli* Kozlova
Detonula confervacea Cleve	*Thalassiosira gravida* Cleve
Diploneis smithii (Brébisson) Cleve	*Thalassiosira hispida* Syvertsen
Diploneis subcincta Cleve	*Thalassiosira hyalina* (Grunow) Gran
Fossula arctica Hasle	*Thalassiosira hyperborea* (Gru+-now) Hasle
Fragilaria leptostauron (Ehrenberg) Hustedt	*Thalassiosira leptopus* (Grunow) Hasle et G. Fryxell
Fragilaria pinnata Ehrenberg	*Thalassiosira nordenskioeldii* Cleve
Fragilariopsis curta (Van Heurck) Hustedt	*Thalassiosira oestrupii* (Ostenfeld) Hasle
Fragilariopsis cylindrus (Grunow) Krieger	*Thalassiosira pacifica* Gran et Angst
Fragilariopsis oceanica (Cleve) Hasle	*Thalassiosira trifulta* Fryxell
Fragilariopsis reginae-jahniae Witkowski Lange-Bertalot	*Thalassiosira* sp. 1
and Metzeltin	*Thalassiosira* sp. 2
Fragilariopsis vanheurckii (M. Peragallo) Hustedt	*Thalassiosira* sp. 3
Gomphonema sp.	*Thalassiosira* sp. 4
Grammatophora angulosa Ehrenberg	*Thalassiothrix longissima* (Cleve) Cleve et Grunow
Gyrosigma fasciola (Ehrenberg) Cleve	*Trachyneis aspera* Cleve
Melosira arctica (Ehrenberg) Dickie	*Triceratium formosum* Brightwell
Navicula cancellata Donkin	
Navicula directa (W. Sm.) Ralfs	