· Article ·
Advances in Polar Science
doi: 10.13679/j.advps.2014.3.00155
September 2014 Vol. 25 No. 3: 155-163

The distribution and characteristics of suspended particulate matter in the Chukchi Sea

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Received 1 June 2014; accepted 27 July 2014

Abstract Samples taken from the Chukchi Sea (CS) during the 4th Chinese National Arctic Research Expedition, 2010, were analyzed to determine the content and composition of suspended particulate matter (SPM) to improve our understanding of the distribution, sources and control factors of the SPM there. The results show that the SPM in the water column is highest in the middle and near the bottom in the south and central–north CS, followed by that off the Alaskan coast and in Barrow Canyon. The SPM content is lowest in the central CS. Scanning electron microscope (SEM) analysis shows that the SPM in the south and central–north CS is composed mainly of diatoms, but the dominant species in those two areas are different. The SPM off the Alaskan coast and in Barrow Canyon is composed mainly of terrigenous material with few bio-skeletal clasts. The distribution of temperature and salinity and the correlation between diatom species in SPM indicate that the diatom dominant SPM in the south CS is from the Pacific Ocean via the Bering Strait in summer. The diatom dominant SPM in the central–north CS is also from Pacific water, which reaches the CS in winter. The SPM in the middle and near the bottom of the water column off the Alaskan coast and in Barrow Canyon is from Alaskan coastal water and terrigenous material transported by rivers in Alaska.

Keywords **suspended particulate matter, content, distribution, origin, Chukchi Sea**

Citation: Wang W G, Fang J Y, Chen L L, et al. The distribution and characteristics of suspended particulate matter in the Chukchi Sea, Adv Polar Sci, 2014, 25: 155-163, doi: 10.13679/j.advps.2014.3.00155

1 Introduction

Suspended particulate matter (SPM) is commonly used to describe aquatic particles larger than 0.45 μm, including terrigenous and biogenic clasts, and a variety of aggregated flocs[1]. SPM in the water column is controlled by hydrodynamic conditions and by physical, chemical and biological processes[2-4]. SPM plays an important role in carrying nutrients and contaminants from land to sea[5-7], where they are a major source of sediments on continental shelves and in ocean basins. Research into the distribution, composition and origins of SPM is essential for comprehensive understanding of the deposition processes, pollutant transportation, material cycles, export productivity and ecosystems in bathyal and abyssal seas[3-14].

The Chukchi Sea (CS) lies in the western Arctic Ocean and connects with the Pacific Ocean via the Bering Strait to the south. The Pacific water flowing into the CS bifurcates into three branches as a result of the topography of the CS and flows northward though the CS to the High Arctic[15-16]. The terrigenous particles, nutrients and plankton transported by these northward-flowing currents may impact deposition and ecosystems on the CS shelf. Previous studies indicate that a regional difference exists between the terrigenous and biogenic components in the bottom sediments of the CS[17-21]. Research into the content distribution and sources of suspended particles should significantly improve our understanding of sedimentology and paleo-oceanography in the CS. The content distribution of SPM over the CS slope has been reported in research into the particulate organic carbon export and/or exported productivity, using radioactive methods, such as ^{210}Pb[22-25]. However, little is known about the content distribution and the composition of SPM on the CS shelf. The present study is based on the samples collected during the 4th Chinese National Arctic Research Expedition, 2010. We present the results on the distribution and composition of SPM on the CS shelf and discuss its origins.

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2 Materials and methods

During the 4th Chinese Arctic Research Expedition in July, 2010, water samples were collected with the CTD controlled SBE 911^{TM} water sampler on the R/V *XUE LONG* icebreaker from 23 stations and 91 discrete depths for SPM study in the CS (Figure 1). Four seawater samples were collected at nearly average discrete depths at most stations, including the surface and bottom water samples. The exceptions were stations 10R02 and 10CC8, where the seawater samples were collected at surface, middle and bottom depths (Table 1).

The seawater volume used for SPM filtering was generally 2 000 mL, although the volume of a few samples was 1 300 mL; all samples were measured with a graduated cylinder. The seawater at each depth was vacuum filtered through pre-weighed 47 mm diameter, 0.45 μm Millipore cellulose acetate filters. The filters were rinsed three times with deionized water to remove sea salt. After onboard sample processing, the filters were stored frozen at −20℃ in plastic boxes until analysis. At the laboratory, the frozen filters were dried to a constant weight with a vacuum-freeze dryer and weighed by electronic balance with a precision of 0.01 mg. The content of SPM (mg·L^{-1}) at each depth was calculated as:

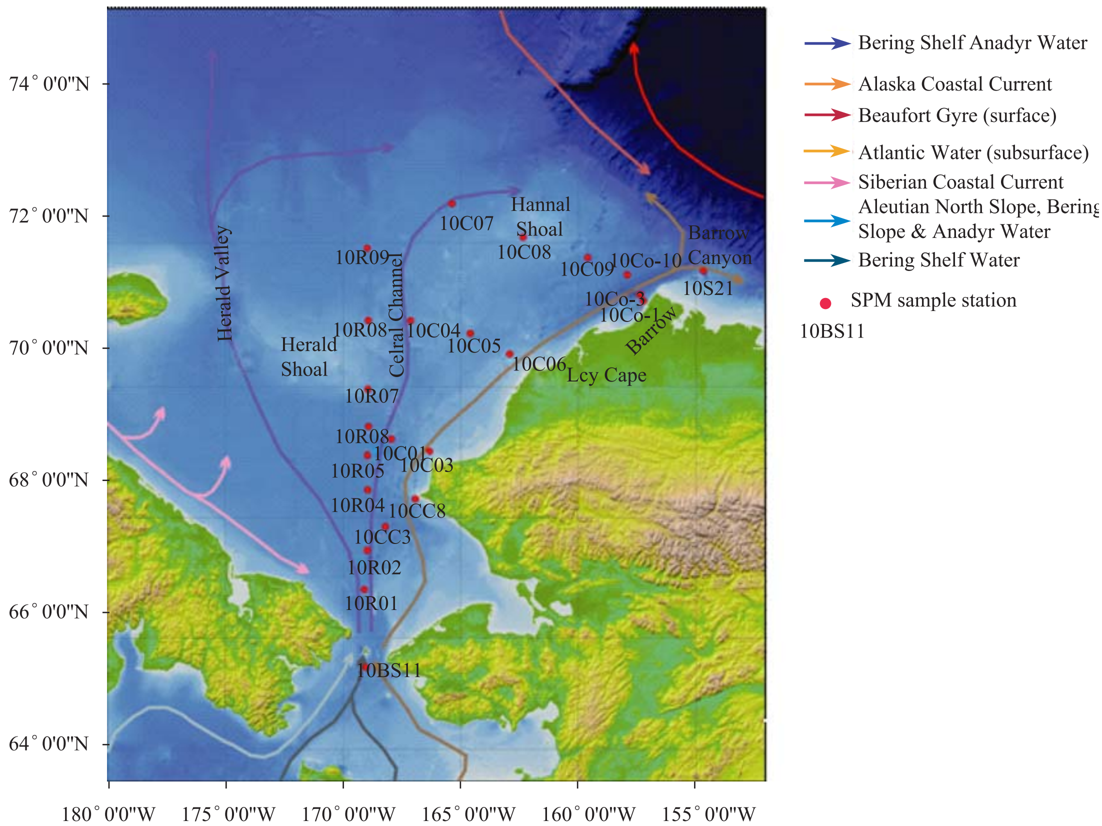

Figure 1 Topography, currents, and suspended particulate matter sample locations in the Chukchi Sea.

Table 1 The SPM content, temperature, and salinity at sample stations

Station	Longitude /(°)	Latitude /(°)	Depth /m	SPM /(mg·L^{-1})	Temperature /℃	Salinity /psu	Station	Longitude /(°)	Latitude /(°)	Depth /m	SPM /(mg·L^{-1})	Temperature /℃	Salinity /psu
10BS11	−168.971 50	65.503 83	3	0.33	4.59	32.33	10C05	−164.728 33	70.760 00	3	0.00	4.82	30.44
			17	1.07	3.88	32.51				10	0.00	4.43	30.73
			30	1.11	3.11	32.64				22	0.44	−0.08	32.38
			49	2.95	1.74	32.61				30	0.00	−0.49	32.44
10R01	−169.010 00	67.001 00	5	1.37	3.40	32.25	10R08	−168.980 17	71.003 17	3	0.59	0.86	30.35
			18	1.14	3.11	32.71				13	0.98	−1.59	31.91
			30	1.77	2.55	32.70				23	4.99	−1.64	32.33
			42	3.20	2.52	32.70				39	0.65	−1.72	32.94

(To be continued on the next page)

(Continued)

10R02	−169.007 67	67.501 33	3	0.00	5.01	31.99	10C04	−167.029 83	71.011 83	3	0.00	4.18	29.96
			20	1.86	2.19	32.19				10	0.00	4.39	31.53
			44	0.47	2.19	32.21				28	1.69	0.02	32.53
10CC3	−168.236 17	67.89 867	5	0.00	5.14	31.89				42	2.35	0.02	32.53
			15	0.00	5.13	31.88	10Co-1	−157.158 80	71.246 80	40	1.13	3.25	32.07
			30	0.06	0.84	32.10				5	0.00	2.69	30.39
			51	2.28	0.94	32.14				10	0.48	2.94	31.18
10CC8	−166.963 33	68.300 00	5	0.00	6.78	30.99				30	1.62	3.25	32.07
			20	0.38	4.14	31.67	10Co-03	−157.315 50	71.331 83	5	0.33	2.42	30.62
			30	0.48	3.98	31.71				20	0.59	1.72	32.26
10R04	−169.000 00	68.500 00	3	0.00	5.86	31.87				50	0.00	0.58	32.53
			10	0.10	5.98	31.87				87	1.06	0.12	32.70
			30	0.00	2.44	32.02	10Co-10	−157.926 83	71.620 17	5	0.91	3.48	29.21
			50	0.42	1.18	32.13				15	0.00	0.41	29.96
10R05	−169.000 00	69.000 00	3	0.13	4.98	31.78				30	0.77	−0.50	31.37
			20	0.00	4.83	31.75				50	0.22	−0.91	32.22
			30	0.00	1.36	32.03	10S21	−154.722 17	71.623 50	5	0.35	1.91	29.91
			48	0.15	0.21	32.33				15	1.06	4.35	31.65
10C03	−166.466 17	69.027 50	3	0.00	4.72	31.34				25	0.77	4.39	31.87
			10	0.00	4.18	31.60				42	0.93	3.48	32.26
			20	0.06	2.48	31.82	10C09	−159.714 67	71.813 83	3	2.74	−1.21	29.33
			30	1.03	2.16	31.85				10	0.00	−1.22	29.37
10C01	−168.126 00	69.222 00	15	0.13	2.40	31.92				20	0.00	−0.80	30.59
			5	0.00	5.83	30.98				46	2.69	−1.23	32.84
			25	0.00	1.38	31.95	10R09	−168.940 00	71.963 33	3	1.18	−1.21	29.98
			35	0.15	0.29	32.23				13	1.55	−1.43	31.06
			46	4.97	−0.30	32.44				30	1.59	−1.73	32.89
10R06	−168.983 33	69.500 00	3	0.00	5.21	31.06				47	1.34	−1.73	32.92
			10	0.00	3.82	31.92	10C08	−162.379 00	72.105 17	3	0.00	−0.82	28.14
			36	0.44	−0.71	32.66				10	2.78	−0.56	28.48
			48	0.00	−0.78	32.70				20	0.00	1.97	32.29
10R07	−168.983 00	69.978 83	3	0.01	0.23	27.69				30	1.52	−1.27	32.54
			10	1.44	−0.96	28.86	10C07	−165.325 67	72.541 17	5	0.42	−0.46	29.12
			20	0.85	−1.59	32.22				15	0.07	−1.63	32.77
			34	1.80	−1.68	32.78				26	3.70	−1.63	32.77
10C06	−162.763 33	70.516 67	3	0.03	5.33	32.09				46	1.37	−1.72	33.05
			13	0.00	5.33	32.09							
			20	0.17	5.24	32.16							
			30	6.73	2.90	32.68							

$$SPM = \frac{Mp - Ms - \Delta M}{V} \quad (1)$$

where *Mp* is the weight after filtering (mg), *Ms* is the weight before filtering (mg), ΔM is the weight variation of blank filter before and after filtering, and *V* is the volume of filtered water (L).

The temperature and salinity at each SPM sample depth was obtained from the records of the CTD[26]. To analyze the composition of the SPM, the dried filters were examined with a scanning electron microscope (SEM) to obtain images and information about the particle composition on the filters.

3 Research results

3.1 SPM distribution: horizons

According to the weights of filters before and after filtering, the result shows that the SPM content in all samples on the CS shelf ranges from 0.00 to 6.73 mg·L^{-1} (Table 1). The SPM content in surface seawater is generally less than in seawater close to the sea floor. In surface seawater, the SPM content ranges between 0.00 and 2.74 mg·L^{-1}, and is higher in the south CS near the Bering Strait, the central–north and northeast CS, is lower in the central CS. Close to the sea floor, the seawater SPM content ranges between 0.00 and 6.73 mg·L^{-1}; it is higher in the south CS, offshore of Icy Cape, Alaska, and in parts of the central CS.

3.2 SPM distribution: sections

Three sections were chosen from the sample stations for this study. Section 1 was mostly along longitude 169°W, and comprised nine stations: 10BS11, 10R01, 10R02, and 10R04–10R09 from south to north. Section 2 was in the northeast CS and comprised six stations: 10C07, 10C08, 10C09, 10Co-10, 10Co-3 and 10Co-1 from the northwest to the southeast. Section 3 was located in the east–central CS, extending northwest from Icy Cape to the central CS, and comprised four stations: 10R08 and 10C04–10C06 from west to east. We will now consider the distribution characteristics of SPM, temperature and salinity in the three sections.

The distribution of SPM in section 1 extending south–north is shown in Figure 2. There are two areas with higher SPM content in section 1. One is the south CS, the other is the central–north CS. The SPM content is markedly lower from the surface to the sea floor in the central CS, which partitions

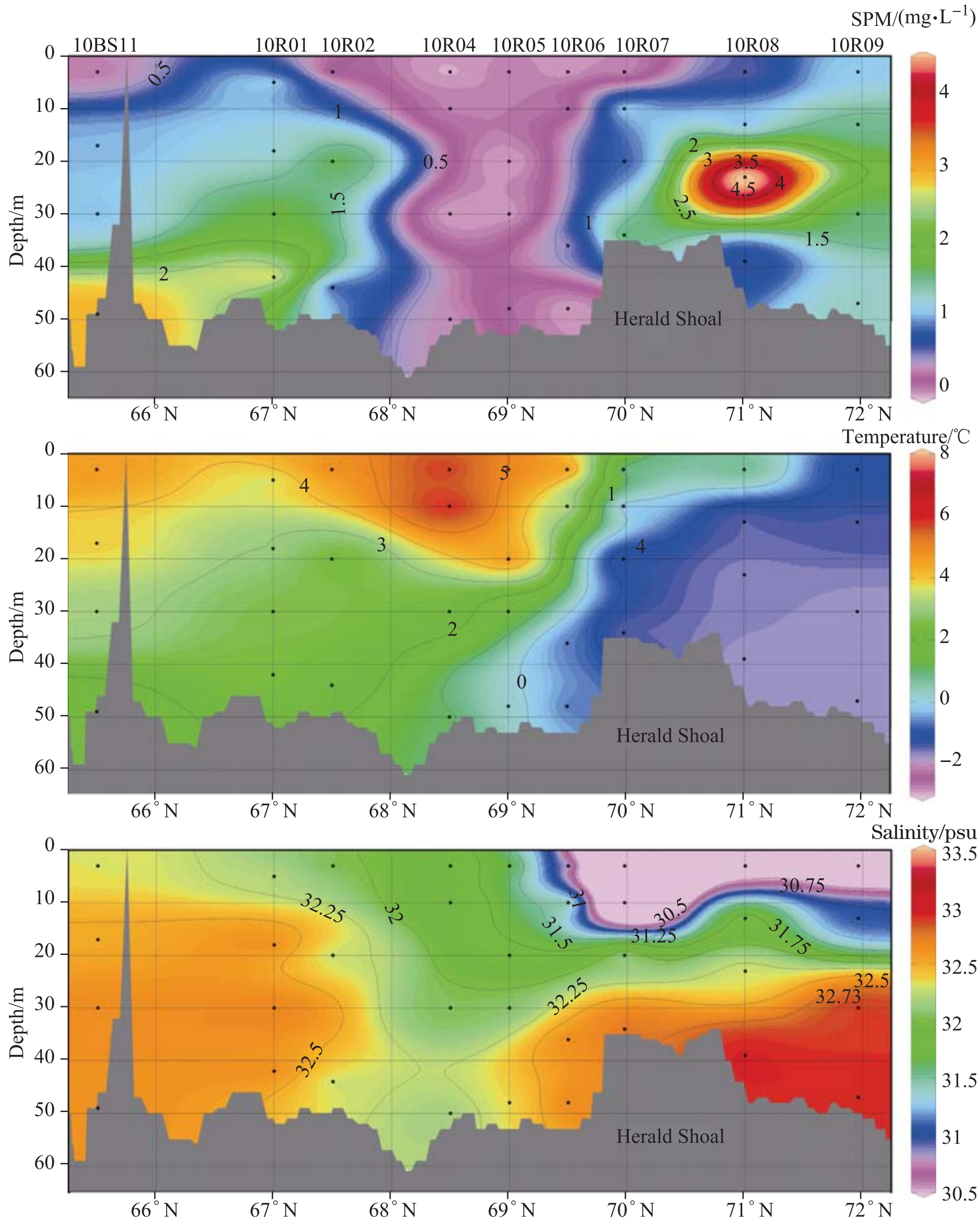

Figure 2 Distributions of suspended particulate matter content, temperature, and salinity along section 1 in the Chukchi Sea.

the two higher SPM content areas in section 1. For the two higher SPM areas in section 1, the SPM content in the Bering Strait (south CS) in section 1 decreases from the bottom to the top of the water column, and the highest SPM content is in seawater near the sea floor, where it is more than 2.5 mg·L^{-1}. The highest SPM content in the central–north CS of section 1 is found at depths of 15–35 m, and decreases above and below that. The temperature is higher in the upper water column than in the lower water column, and higher in the south than in the north of section 1. The variation in salinity in section 1 is similar to the variation in SPM, which is higher in the north and south of the section and lower in the middle, and higher in the lower water column than in the upper water column. The salinity of the upper 10 m in the north of the section is less than 31 psu (practical salinity unit), a result of the melting of sea ice there.

Section 2 crosses the Hannal Shoal and Barrow Canyon. The SPM content in section 2 shows layers of higher content alternating with layers of lower content at depth (Figure 3). There is a high SPM layer in the water column below 25 m on both sides of Hannal Shoal, and the SPM content is the highest at 26 m at the 10C07 sample station. The SPM content at 10R08 and 10R09 sample stations in section 1, near station 10C07 in section 2, are also relatively higher. This suggests that the higher SPM distribution is found regionally in the central–north CS. Results from 10Co-1 and 10Co-3 sample stations in Barrow Canyon show that the layers of high content SPM alternates with layers of low content SPM. The SPM content is higher in the water column below 70 m and between 20 and 40 m; and it is lower in the water column at depths above 20 m and between 40 and 70 m. The higher SPM content near the bottom of Barrow Canyon is not the result of eastward SPM diffusion from the east side of Hannal Shoal because the SPM content at sample station 10Co-

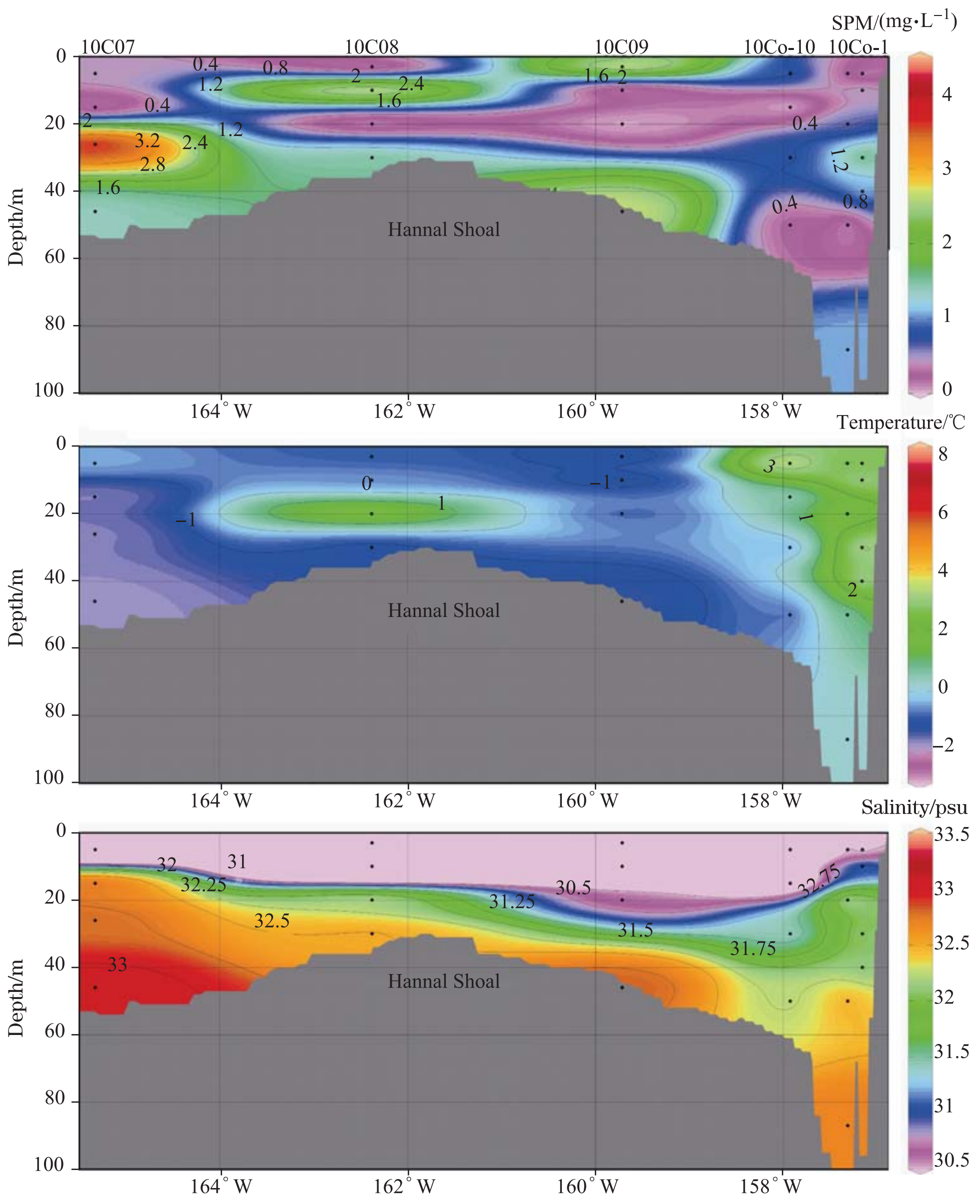

Figure 3 Distribution of suspended particulate matter, temperature, and salinity along section 2 in the Chukchi Sea.

10, located between Hannal Shoal and Barrow Canyon, is especially low. It also separates the two higher SPM areas near the bottom. The SPM content in the upper 20 m off the Alaskan coast is extremely low. The low content layer deepens westward and forms a low SPM layer at water depths of 15–25 m over the Hannal Shoal. Temperatures along section 2 show that the high-temperature mid-water layer with low SPM content over the Hannal Shoal is connected to the high-temperature upper-water layer off the Alaskan coast. The salinity at the lower water layer over the Hannal Shoal is higher than 32.5psu, less than that near the bottom of Barrow Canyon. Additionally, the salinity at sample station 10Co-10 is evidently lower than that over the Hannal Shoal and in Barrow Canyon, which means that the seawater at the lower layer in Barrow Canyon does not come from the central CS.

The SPM content in section 3 is higher at depths below 25 m near the Alaskan coast, and decreases sharply upward and westward. The SPM content falls to its lowest from the surface to the bottom of the water column toward sample station 10C05 in the middle of the section. Further westward, the SPM content in the mid-water column to the bottom water column increases again (Figure 4). The temperature in section 3 decreases at depth and westward, in contrast to the variation in salinity.

3.3 Composition of SPM

The SEM images of the SPM show a regional variation in the composition of SPM in the CS. The higher SPM samples from the southern CS and in the middle–bottom water layer of the central–north CS are composed mainly of diatoms, with terrigenous particles being subdominant. The SEM

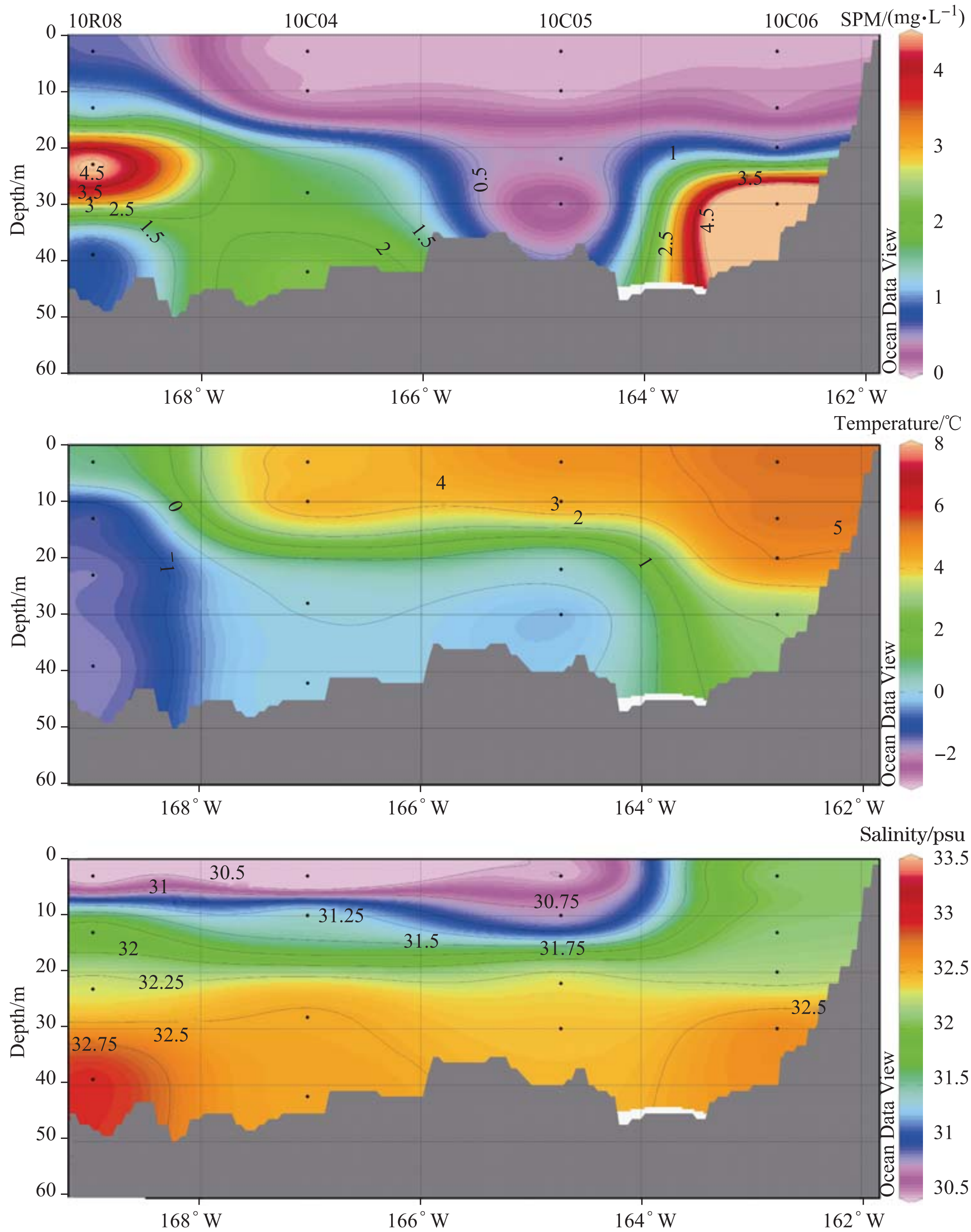

Figure 4 Distribution of suspended particulate matter, temperature, and salinity along section 3 in the Chukchi Sea.

images also show that the dominant species of diatoms in the two high SPM areas are different. The diatoms in the south CS are mainly Centricae (Figure 5a), whereas the diatoms in the central–north CS are both Centricae and Pennatae (Figure 5b). The SPM off the Alaskan coast and in Barrow Canyon is dominated by terrigenous minerals, with limited plankton and bio-skeletal clasts (Figure 5c). The SPM in the central CS, where the content is especially low, is dominated by bio-skeletal clasts and scattered plankton (Figure 5d).

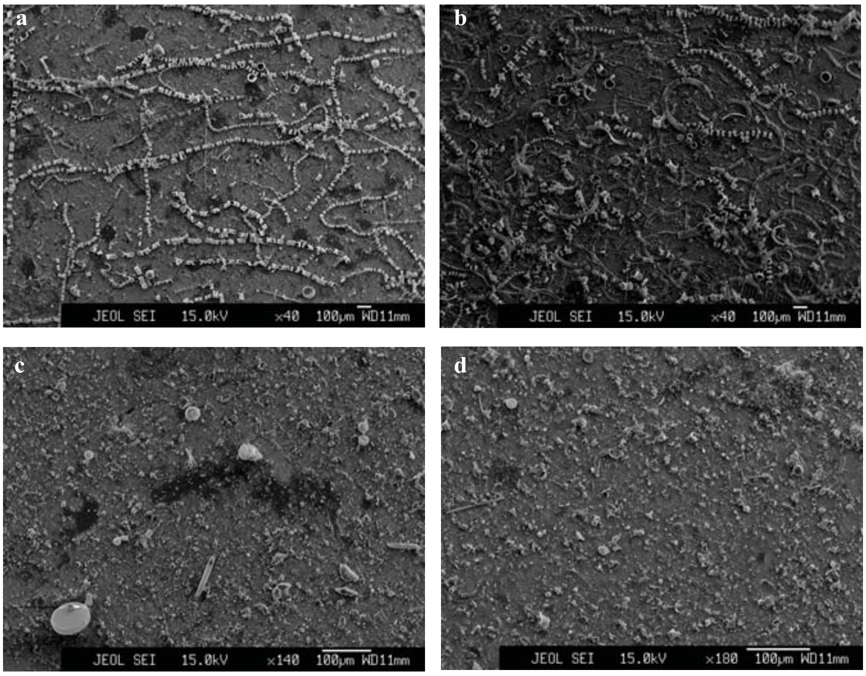

Figure 5 Scanning electron microscope of typical suspended particulate matter from the Chukchi Sea. **a**, 10R01, 5 m; **b**, 10R09, 30 m; **c**, 10Co-10, 15 m; **d**, 10R05, 48 m.

4 Discussion

The spatial distribution of SPM shows that its content is highest in the south CS near the Bering Strait and in the central–north CS. The SPM in both areas is dominated by diatoms. The high bio-Si content in the surface sediments of the two areas [19] indicates that it results from the high SPM composed of diatoms. The distribution of high SPM dominated by diatoms in summer should occur annually, because the 2nd Chinese National Arctic Research Expedition, 2003, revealed that the content of particulate biogenic silica along what is called section 1 for the present study showed a high–low–high variation from south to north [18], similar to the SPM content distribution that we observed.

There is a difference in dominant diatom species between the south CS and the central–north CS, and the two high SPM content areas are divided by low SPM content area. The temperature and salinity distributions in section 1 also imply that the two areas are affected by two water masses, so the diatom-dominant SPM in the two areas are controlled by the currents and water masses there, respectively.

The SPM in the south CS is dominated by Centricae diatoms. Temperature and salinity in section 1 of the south CS decrease gradually from south to north. This is because of the heat loss in sea water in the process of northward flowing. There are two Pacific seawater currents flowing into the CS via the Bering Strait: one is Anadyr water to the west and the other is Alaska Coastal water to the east. Compared with the Alaska Coastal water, the Anadyr water has a lower temperature, higher salinity and is richer in nutrients[16,19,27]. The dominant diatom species in the Anadyr water are similar to those in the south CS, indicating that planktonic diatoms in the south CS may be the result of the intrusion of the diatom-rich Anadyr water. Alterlatively, the temperature, salinity and nutrients of seawater both in the south CS and the northwest Bering Sea fit for the growth of Centricae diatoms.

The planktonic diatoms in the central–north CS are both Centricae and Pennatae. The distributions of temperature and salinity in section 1 show that the seawater in the south CS and the central–north CS belong to different water masses. Compared with the seawater in the south CS, temperature in the central–north CS is lower, but salinity is relatively higher. The Atlantic water, with higher subsurface salinity, might upwell along the slope and reach the north shelf of the CS when it flows southward and along the slpoe of the CS.[28]. However,the Atlantic water is nutrient-poor and below the upper halocline layer (>100 m)[29]. The water depth is about 50 m in the central–north CS and diatoms are abundant there, suggesting that the low-temperature, high-salinity and nutrient-rich seawater in the central–north CS is not of Atlantic origin. Previous studies indicated that the north-flowing Bering Shelf water and Anadyr water mix to form Bering Shelf–Anadyr water in the Bering Strait. In the south CS, Bering Shelf–Anadyr water bifurcates into two branches again because of sea floor topography and flows northward, separately, through Herald Valley and the Central Channel between Hanna and Herald shoals[27,30-31]. The two branches of the currents turn east and into the central–north CS after passing through the channels[15-16,30]. Consequently the nutrient-rich, high-salinity seawater in the central–north CS, suitable for planktonic diatom growth, is also from the Pacific water via the Bering Strait. The seawater in the central–north CS has a lower temperature and higher salinity than that in the south CS. That is because the seawater in the central–north CS receives an inflow of Pacific water in winter via the Bering Strait[29]; but seawater in the south CS receives the summer Pacific water inflow. The salinity of the Bering Sea increases in winter resulted from the decrease of river flux into the Bering Sea. Therefore, the inflow water via the Bering Strait in winter is of a higher salinity. Additionally, sea ice formation in winter in the Bering Sea increases the salinity beneath the ice. Cooper et al. suggested that it takes at least 3–4 months for the Pacific water to flow over the CS shelf[29]. The higher-salinity winter seawater in the Bering Sea flows to the central–north CS before the sea ice in the central–north CS melts in summer. The melting of the sea ice forms the upper lower-salinity water layer in the central–north CS, and this blocks the thermal conduction of the seawater. Therefore, the summer middle–bottom seawater in the central–north CS has a lower temperature, higher salinity and is richer in nutrients, which results in the difference in dominant diatom species between the south and central–north areas of the CS.

The SPM content close to the bottom of the water column off the Alaskan coast and in Barrow Canyon is lower than that in the south and central–north CS, and its composition is mainly terrigenous minerals, with few plankton and bio-skeletal clasts. The lower level of nutrients limits the growth of plankton in the Alaskan Coastal Current, which flows along the coast of Alaska and Barrow Canyon. Additionally, terrigenous materials are transported into the CS by northwest inflow rivers in Alaska and mixed with SPM in the Alaskan Coastal Current. The difference in composition and source results in different attributions of ^{210}Pb between the central–north CS and Barrow Canyon[23-24].

5 Conclusions

Through analysis of the water samples obtained during the 4th Chinese National Arctic Research Expedition, a number of conclusions can be drawn. SPM content is the highest in the south and central–north CS, followed by the Alaskan coast and Barrow Canyon. It is the lowest in the central CS. The SPM in both the south and central–north CS is composed mainly of diatoms; however diatom species in the south CS are almost all Centricae, and in the central–north CS they are both Centricae and Pennatae. SPM off the Alaskan coast and in Barrow Canyon is dominated by terrigenous minerals with few skeletal clasts. The diatom-dominated SPM in the south CS is associated with the nutrient-rich Anadyr water flowing into it via the west side of the Bering Strait. However, the diatom-dominated SPM in the central–north CS is affected by Pacific water inflow in winter. The low-plankton SPM off the Alaskan coast and in Barrow Canyon is the result of nutrient-poor Alaska Coastal water and terrigenous material transported by rivers flowing northwest into the CS.

Acknowledgments Work on this paper was supported by 4th Chinese National Arctic Research Expedition (Grant no. CHINARE-2010), Public Science and Technology Research Funds Projects of Ocean (Grant nos. 201105022-2 and 201205003), Chinese Polar Environment Comprehensive Investigation & Assessment Programms (Grant nos. CHINARE2014-03-02 and CHINARE2014-04-03-03). We are particularly grateful to Shi Jiuxin, Chen Hongxia and Jiao Yutian, who provided temperature and salinity data. Our thanks also to two anonymous reviewers for their constructive comments.

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