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Microplastics abundance and characteristics in surface waters from the Northwest Pacific, the Bering Sea, and the Chukchi Sea

Jingli Mu[a,b,*], Shoufeng Zhang[a], Ling Qu[a], Fei Jin[a], Chao Fang[c], Xindong Ma[a], Weiwei Zhang[a], Juying Wang[a,**]

[a] National Marine Environmental Monitoring Center, No. 42, Linghe Street, Dalian 116023, China
[b] Institute of Oceanography, Minjiang University, No. 200, Wenxian Road, Fuzhou 350108, China
[c] Laboratory of Marine Biology and Ecology, Third Institute of Oceanography, State Oceanic Administration, No. 178, Daxue Road, Xiamen 361005, China

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ABSTRACT

Microplastics (MPs) in the Arctic Ocean have gained considerable attention due to its ubiquity and impacts within ecosystems. However, little information is available on MPs in the Pacific section of the Arctic Ocean. The present study determined the abundance, distribution, and composition of MPs in surface waters from the Northwestern Pacific, the Bering Sea, and the Chukchi Sea. The MPs abundances varied from 0.018 items/m^3 to 0.31 items/m^3, with a mean abundance of 0.13 ± 0.11 items/m^3. The highest level of MPs was found in the Chukchi Sea. Of all of the detected MPs, polyethylene terephthalate (PET) accounted for the largest proportion of MPs, and fiber was predominant with regard to the total amount. Our results highlighted that the Arctic Ocean is becoming a hotspot for plastic pollution, and the risks posed by MPs need to be paid closer attention in future investigations.

1. Introduction

Due to its ubiquity in marine environments and its potential harm to marine organisms and ecosystems (Sussarellu et al., 2016), marine plastic pollution is currently considered one of the most important global environmental issues of our time (Barnes et al., 2009; Cózar et al., 2014; UNEP, 2016). According to PlasticsEurope, the annual global plastic production has increased exponentially since the 1950s, and reached 335 million tons in 2016 (PlasticsEurope, 2018). As a result of mismanagement and accidental release, approximate 10% of all plastics will end up as waste in marine environments (Jambeck et al., 2015). It was estimated that the accumulated number of floating plastic particles in the global ocean surface is at least 5 trillion pieces (Eriksen et al., 2014). By 2050, plastic in the marine environment is expected to be more abundant (by weight) than fish in the oceans (Neufeld et al., 2016).

In the marine environment, large plastic items degrade into smaller fragments via different pathways such as weathering (Andrady, 2017; Li, 2018), photodegradation (Barnes et al., 2009), and biodegradation (O'Brine and Thompson, 2010), and thus become “microplastics (MPs)” (< 5 mm) (Cole et al., 2011). To data, MPs are ubiquitous in a global scale and they have been found in surface water (Zhao et al., 2015; Zhao et al., 2014), sub-surface water (Desforges et al., 2014), water column (Dai et al., 2018), sediments (Peng et al., 2017), deep-sea floor (Bergmann et al., 2017; Van Cauwenberghe et al., 2013), and even in remote regions (Bergmann et al., 2017; Cózar et al., 2017; Kanhai et al., 2018; Lusher et al., 2015; Cincinelli et al., 2017; Isobe et al., 2017). As an emerging global pollutant, MPs are growing concerns about potential effects in biota and marine ecosystem (Anderson et al., 2016).

The Arctic Ocean is tightly connected to the northern Pacific through the Bering Strait and to the Atlantic through the Canadian Archipelago, the Barents Sea, and the Fram Strait (Schlosser et al., 1995). The Arctic Ocean is divided into the Eurasian and Amerasian (Canadian) Basins by the Lomonosov Ridge (Rudels, 2015). It is now well established that persistent organic pollutants in the Arctic are largely transported from the mid-latitudes by the water column and the atmosphere (Muir and de Wit, 2010). MPs have been found in surface and subsurface waters (Kanhai et al., 2018; Lusher et al., 2015), sediments (Bergmann et al., 2017), sea ice (Obbard et al., 2014; Peeken et al., 2018), benthic organisms (Fang et al., 2018), fish (Kühn et al., 2018), and seabirds (Amélineau et al., 2016) of the Arctic Ocean. Five plastic gyres in the open ocean have been confirmed to date (van Sebille et al., 2012; van Sebille et al., 2015), and the suspected presence of further accumulation zones in the Arctic was recently corroborated

* Correspondence to: J. Mu, Institute of Oceanography, Minjiang University, Fuzhou 350108, China.
** Correspondence to: J. Wang, National Marine Environmental Monitoring Center, Dalian 116023, China.
E-mail addresses: jlmu@mju.edu.cn (J. Mu), jywang@nmemc.org.cn (J. Wang).

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(Bergmann et al., 2017). Since the significant transport of plastic debris occurs into the Arctic Ocean by the global Thermohaline Circulation (THC), the Northeastern Atlantic sector of the Arctic Ocean has appeared as a dead end for buoyant plastic (Cózar et al., 2017; Morgana et al., 2018). To date, the majority of existing studies on MPs in the Arctic Ocean have focused on the Atlantic sector of the Arctic Ocean, while little information is available on MPs in the Pacific section of the Arctic Ocean, where MPs on sediment (Mu et al., 2019) and benthic organisms (Fang et al., 2018) have been reported. However, MPs in waters from the Western Bering Sea and the Chukchi Sea are almost unknown.

The Bering and Chukchi Seas are linked by the Bering Strait, through which the North Pacific communicates with the Arctic Ocean (Danielson et al., 2014). As a major source of oceanic nutrients (Woodgate, 2018), the net northward transport of Pacific water through the Bering Strait profoundly affects the Bering-Chukchi ecosystem (Danielson et al., 2014). Hence, an understanding of MPs pollution in the Northwest Pacific, the Bering Sea, and the Chukchi Sea is essential to understanding the sources of MPs in the Arctic Ocean. Here, we analyzed the distribution, abundance, and characteristics of MPs in the surface waters from the Northwest Pacific, the Bering Sea, and the Chukchi Sea.

2. Methods

2.1. Sample collection

Samples were collected onboard the icebreaker R/*V Xuelong* or the Snow Dragon from July to October of 2017 during the 8th Chinese National Arctic Research Expedition. Surface trawling was performed according to our previously published methods, with some modifications (Zhang et al., 2017). Briefly, surface samples were collected using a Manta net (0.95 m wide × 0.45 m height, 330 μm mesh, 3 m long). The net was released from the stern of the vessel and towed horizontally on the surface for 20 min at approximately 3.0 knots. To minimize the influence of vessel movement, the distance between the net and the stern of the vessel was maintained at > 200 m. A calibrated flow meter (Hydrobios 438110, Hydrobios Inc., Germany) was fixed in the middle of the trawl frame to allow for the calculation of the amount of water filtered. At the end of the trawl, the cod-end was removed and taken to the laboratory, where it was rinsed using distilled water. Each sample was transferred into a 250 mL collecting jar and stored in formalin (4% final concentration) (Zhao et al., 2014) until analysis. Detailed sampling information is shown in Table S1, and the surface water sampling sites are shown in Fig. S1.

2.2. Method validation and contamination prevention

The preparation and analysis of all samples were carried out in an independent laboratory. Field blanks and controls were conducted to determine whether there was any contamination during sample processing and laboratory analyses. Before trawling began, the net was flushed from the outside with natural seawater onsite, and the water in the cod-end was collected as a field blank sample. In the laboratory, the method blanks and air contamination checks were conducted to determine whether there was any contamination during laboratory analyses. The precision and accuracy of the analytical methods were also verified by spiking particles with known amounts of polypropylene (PP) and polyethylene (PE) plastics (Mu et al., 2019). To determine whether there was any airborne contamination in the laboratory, clean petri dishes with filter papers were left exposed to the air during water filtration. Distilled water was passed through clean GF/C (0.7 μm, 47 mm diameter) filter paper to determine potential contamination from the water in contact with the sample. Standard nonplastic equipment was used wherever possible. All apparatuses were washed with distilled water prior to use, and equipment was inspected under a dissecting microscope (Courtene-Jones et al., 2017).

A total of 31 fibers were found in the field blank samples (number of blanks: $n = 13$); these fibers were considered to be residues of the trawl nets used for sampling. Two fibers were found in the laboratory procedural blanks (number of procedural blanks: $n = 5$). For the small particles with sizes of equal to or < 0.5 mm, the mean recovery rates of PP microbeads and PE microbeads were 91.7 ± 7.6% and 90.0 ± 5.0%, respectively. For the large particles, with sizes of 1–2 mm, the mean recovery rates were 96.7 ± 2.9% for PP microbeads, 98.3 ± 2.9% for PE microbeads, and 93.8 ± 6.3% for PE fragments (Table S2). No significant difference was found among recovery rates for either small or large microplastics ($p > 0.05$).

2.3. Sample preparation and analysis

The preparation of surface samples was conducted as previously described (Zhang et al., 2017). Briefly, each sample was poured through a 0.3 mm stainless steel mesh sieve and then transferred to a preweighed 500 mL glass beaker, in which the sample was oven-dried at 60 °C for approximately 24 h. To remove the natural material mixed into the sample, an aliquot of 20 mL of digestion solution, which contained a 0.05 M Fe(II) solution and 30% hydrogen peroxide (H_2O_2) (Masura et al., 2015), was added to the beaker containing the collected solids. The mixtures were heated at 60 °C and gently stirred for 30 min. If the natural organic material was still visible, additional H_2O_2 was added and heating was repeated as necessary. After rinsing with distilled water to remove residual H_2O_2, the sieved contents were rinsed using a hypersaline solution (300 g/L NaCl in distilled water) into glass funnels. After completion of the material separation, settled items were dried in 50 mL beakers, transferred to glass Petri dishes, and visually examined using a dissecting microscope at 8× magnification (SZ51, Olympus Inc., Japan). The remaining mixed solution was filtered through GF/C (0.7 μm, 47 mm diameter) filters. Each filter paper was placed into a clean glass Petri dish, covered and stored in a freezer (−20 °C) until further analysis.

Particles were examined and analyzed according to our previous published method (Mu et al., 2019). All particles were examined under a light stereomicroscope (M205FA, Leica Inc., Germany) and identified visually by their color and shape (Martin et al., 2017). Each particle was analyzed using a Fourier transform infra-red spectroscope equipped with a microscopy (μFTIR) (IN10 MX, Thermo Fisher Scientific Inc., USA). The spectral resolution of the spectrometer was ~8 cm^{-1}. Sample were A spectral wavenumber range of 4000–675 cm^{-1} was sued for measurements.

2.4. Statistical analysis

Regional comparisons were accomplished by grouping sites into the following oceanographic regions: the Northwestern Pacific (WP), the Bering Sea (BS), and the Chukchi Sea (CS). The abundance of each particle type at each site took airborne fiber contamination observed in the procedural blank into account. The mean number of observed fibers was subtracted from the observed samples in each sample (similar types of observed fibers) (Catarino et al., 2018). A non-parametric Kruskal-Wallis H test was performed to assess statistical differences between the three oceanographic regions. The correlation between microplastic abundance and environmental variables (temperature, salinity, chlorophyll α content, and latitude) was tested using Spearman's correlation coefficient. These analyses were conducted using SPSS 13.0 (IBM Corporation, NY, USA). p-value < 0.05 was considered statistically significant.

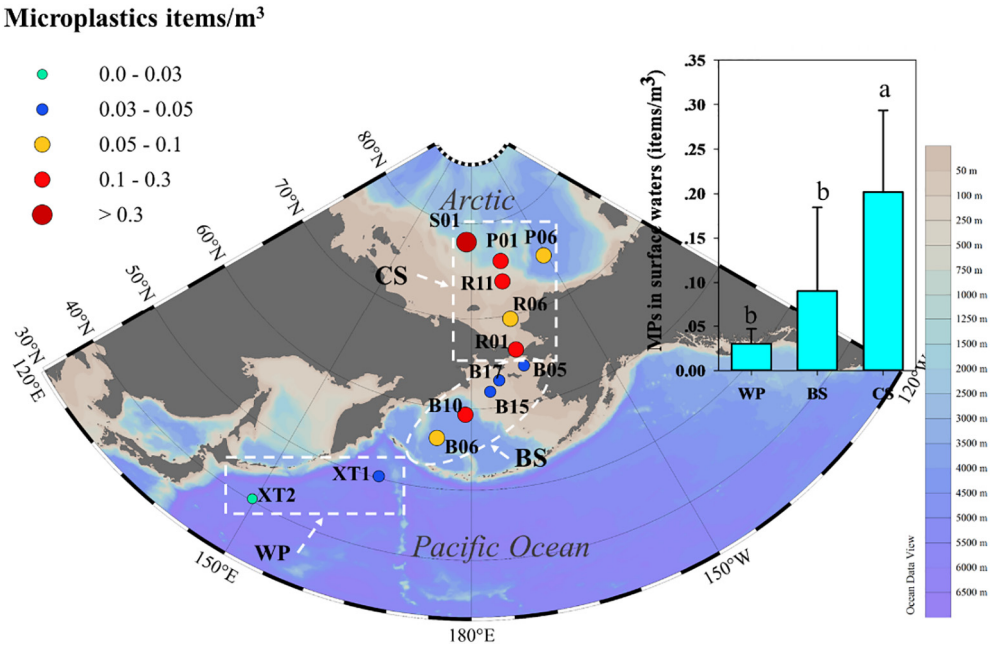

Fig. 1. Maps of the abundance and distribution of microplastic in the surface water. WP, West Pacific; BS, Bering Sea; CS, Chukchi Sea. If there is no common letter (a or b) between two entries, then a significant difference was detected ($p < 0.05$).

3. Results

3.1. Abundance

MP abundances in the surface water are shown in Fig. 1. After μFTIR analysis, 2110 particles were confirmed to be microplastics. There was a significant difference in the abundance of MPs among the 13 stations ($p < 0.001$). The abundance of MPs ranged between 0.018 and 0.31 items/m^3, with a mean abundance of 0.13 ± 0.11 items/m^3. The highest MP abundance was found in S01, located at northernmost site of the Chukchi Sea. The lowest MP abundance was found in XT2 from the northwestern Pacific Ocean. In the WP, MP abundance in the surface water ranged from 0.018 to 0.035 items/m^3, with a mean value of 0.030 ± 0.017 items/m^3 ($n = 2$). In the BS, MP abundance in the surface water ranged from 0.035 to 0.26 items/m^3, with a mean value of 0.091 ± 0.094 items/m^3 ($n = 5$). In the CS, MP abundance in the surface water ranged from 0.086 to 0.31 items/m^3, with a mean value of 0.23 ± 0.07 items/m^3 ($n = 6$). In regard to these three survey regions, MP abundance in the surface water from the CS was significantly higher than those from the WP ($p = 0.04$) and BS ($p = 0.006$) (Fig. 1).

3.2. Polymer composition

The analysis of MP polymer composition is important as it provides clues about their origins. All collected particles were analyzed using μFTIR. For all of the particles from the 13 stations, polyethylene terephthalate (PET) was the most common polymer type (67.5%), followed by 10.5% of polypropylene (PP), 7.4% of polyamide (PA) also called nylon, 5.9% of polyethylene (PE), 3.9% of acrylic (AC), 2.9% of rayon (possibly cellulose), and 1.9% of other types. There was a large variability in MP polymer compositions in the surface waters from different stations (Fig. 2). In regard to the three survey regions, the highest proportion of PA (26.3%) and the lowest proportion of PET were recorded in the WP. The highest proportion of PET (72.7%) and the lowest proportion of PA (1.0%) were recorded in the CS.

3.3. Type, color and size

Irregular shapes of MPs were classified into four types, including fiber, fragment, and film. Representative photographs of all types of MPs are shown in Fig. S2. Fiber was the most abundant (95.9%), followed by fragment (3.6%), and film (0.5%) (Fig. 3). White (70.5%), black (13.5%), and red (7.2%) were the most common colors (Fig. 4). Comparing the sites, the highest proportion of white fibers was detected in the CS.

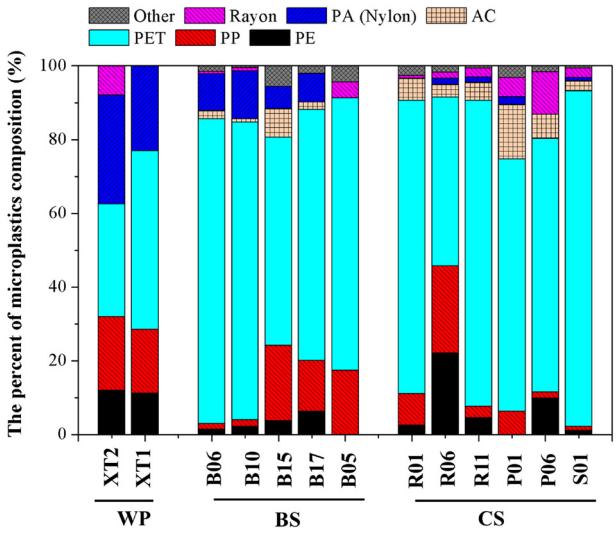

Fig. 2. The composition of MPs identified in surface water. WP, West Pacific; BS, Bering Sea; CS, Chukchi Sea.

The mean size of all detected MPs was 1.56 ± 0.89 mm, and the most common size recorded was < 1 mm, accounting for 52.5% of all of the sizes (Fig. 5A). In general, the mean sizes in the WP, BS and CS were 1.73 ± 1.06 mm, 1.57 ± 0.89 mm, and 1.39 ± 0.74 mm, respectively (Fig. 5B).

4. Discussion

The present study addressed the abundances and characteristics of MPs in surface waters from the Northwestern Pacific, the Bering Sea,

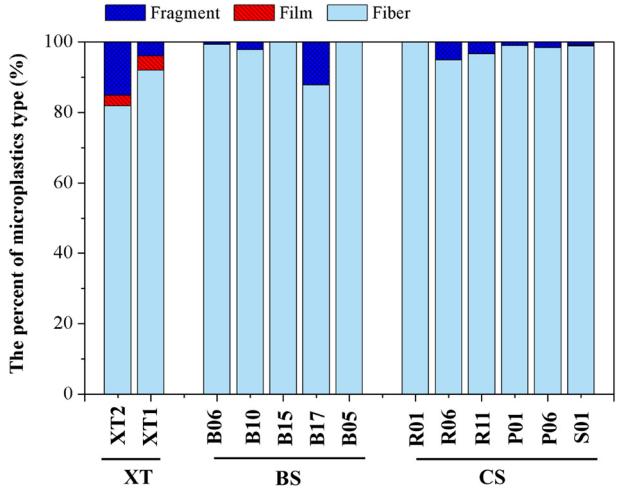

Fig. 3. The types of particles identified in surface water. WP, West Pacific; BS, Bering Sea; CS, Chukchi Sea.

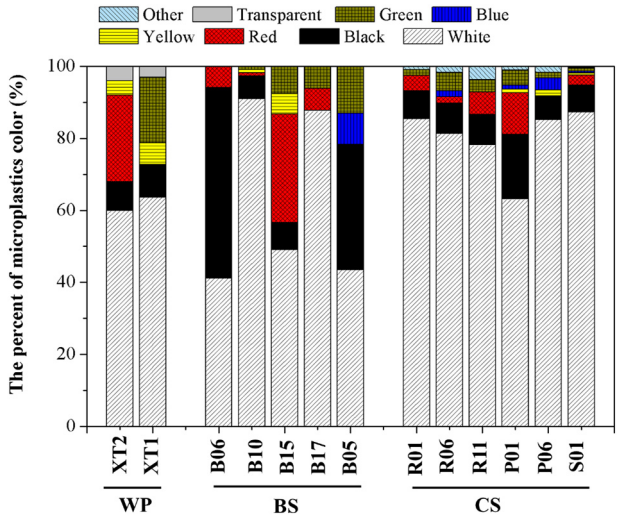

Fig. 4. Colors of particles identified in surface water. WP, West Pacific; BS, Bering Sea; CS, Chukchi Sea.

and the Chukchi Sea. The MPs data from the Chukchi Sea was the first to be reported. Our results highlighted the global distribution of marine plastics debris and suggested that the accumulation of floating MPs will likely occur in the Arctic Ocean.

4.1. Abundance and distribution

The present study confirmed the existence of MPs in the Western Bering Sea and the Chukchi Sea. Until now, there are no standardized sampling protocols for collecting MPs. Different sampling methods and sampling gears with various mesh sizes have been used to collect MPs in previous studies (Pan et al., 2019). Differences in sampling methods, mesh sizes, extraction techniques, and reporting units hamper the direct comparison of MPs levels. Thereby, the reported MPs abundances in surface waters from the Pacific and the Arctic found in other studies using similar sampling methods were summarized in Table 1. MPs abundances in the Northwestern Pacific in this study are similar to what was previously reported in the northwest Pacific by Pan et al. (2019) (0.01 items/m^3) and are similar to what was reported in the Northeast Pacific surface waters by Law et al. (2014) (0.06 items/m^3). Our observed MPs in the Northwestern Pacific, however, is at least one order of magnitude smaller than those in the East China Sea (Zhao et al., 2014) (0.17 ± 0.14 items/m^3), the Yellow Sea (Sun et al., 2018) (0.13 ± 0.2 items/m^3), the southeastern coast of Korea (Kang et al., 2015) (0.62 ± 0.81 items/m^3), and the southern California coast (Moore et al., 2002) (8.0 items/m^3). This might be due to those areas being closer to highly urbanized and industrialized land (Pan et al., 2019). Doyle et al. (2011) found that MPs were ubiquitous in the surface waters of the Southeastern Bering Sea, with the MP values ranging from 0.004 to 0.19 items/m^3, with the mean value being 0.064 items/m^3 (Doyle et al., 2011). MPs abundances from the Bering Sea in the present study are also similar to those data reported by Doyle et al. (2011). Compared to the high debris accumulation zones in the northeast Pacific, MP levels recorded in this study were relatively low compared to previous studies in the north Pacific subtropical gyre (Goldstein et al., 2012) and the central gyre in the northeast Pacific (Moore et al., 2001). Of note, however, the Bering Sea is a high-latitude, semi-enclosed body of water that supports a globally significant diversity and abundance of marine organisms (Aydin and Mueter, 2007). Our data and those of Doyle et al. (2011) suggest that MPs remain relatively low in this highly productive coastal ecosystem, where more organisms are likely to be affected, compared with the less productive open ecosystem in the North Pacific Central Gyre (Doyle et al., 2011).

In the present study, we revealed for the first time the abundances and distributions of MPs in surface waters of the Chukchi Sea. We found that the mean MPs in surface waters from the Chukchi Sea shelf were higher than those from the Bering Sea and the Northwestern Pacific and that the highest abundance of MPs was observed at the northernmost site (S01), which was close to the marginal ice zone and under the impact of a cold current (Fang et al., 2018). The association of high MPs levels in the Chukchi Sea reflects MP inputs from low latitudes and MP accumulation in high latitudes, especially in the Canadian Basin. The mean MP abundance in the Chukchi Sea is similar with those in the East

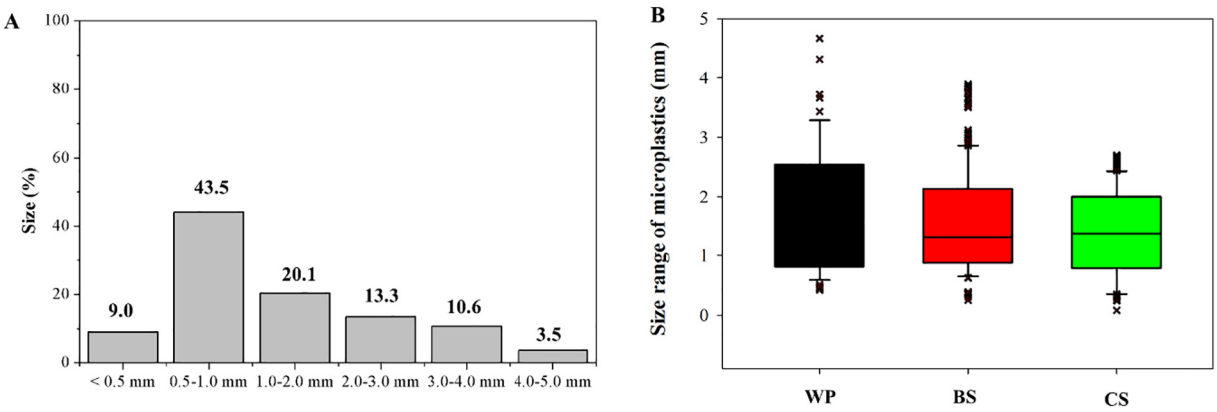

Fig. 5. Sizes of MPs identified in surface water. (A) Histogram distribution of size; (B) Size distribution in WP, BS, and CS.

Table 1
Summary data of MP abundances in surface waters from the Pacific Ocean and the Arctic.

Location	Time	Sampling methods	Size ranges	Abundance (items/m^3)	References
The East China Sea	July 2013	Surface, Neuston net	> 333 μm	0.17 ± 0.14	Zhao et al., 2014
Yellow Sea	August 2015	Surface, Bongo net	> 500 μm	0.13 ± 0.20	Sun et al., 2018
East Asian Seas, China	July to August 2014	Surface, Neuston net	> 350 μm	3.70 ± 10.40	Isobe et al., 2015
Kuroshio Current Area, Western North Pacific Ocean	April to October 2000 and March to April 2001	Surface, Neuston net	> 330 μm	0.70 ± 1.80	Yamashita and Tanimura, 2007 *
Southeastern coast of Korea	July 2012	Surface, Manta net	> 330 μm	0.62 ± 0.81	Kang et al., 2015
Northwestern Pacific Ocean	August 2017	Surface, Manta net	> 330 μm	0.01 (0.0006–0.04)	Pan et al., 2019 *
North Pacific Subtropical Gyre	2009–2010	Surface, Neuston net	> 330 μm	0.16 (Median)	Goldstein et al., 2012
Northeast Pacific	October 2001 to December 2012	Surface, Plankton net	> 335 μm	0.06	Law et al., 2014 *
Central gyre Northeast Pacific	August 1999	Surface, Manta net	> 330 μm	2.50	Moore et al., 2001 *
Southern California coast	October 2000	Surface, Manta net	> 330 μm	8.00	Moore et al., 2002
Southeast Bering Sea	May to September 2006	Surface, Neuston net	> 505 μm	0.064	Doyle et al., 2011
South and Southwest of Svalbard, Norway	June 2014	Surface, Manta net	> 333 μm	0.34 ± 0.31	Lusher et al., 2015
Greenland and Barents Seas	June to October 2013	Surface, Manta net	> 330 μm	0.049 (Median)	Cózar et al., 2017 *
Northwestern Pacific Ocean	July to October 2017	Surface, Manta net	> 333 μm	0.030 ± 0.017	This study
Bering Sea	July to October 2017	Surface, Manta net	> 333 μm	0.091 ± 0.094	This study
Chukchi Sea	July to October 2017	Surface, Manta net	> 333 μm	0.23 ± 0.07	This study

*The abundance was reported as items/km^2 in the original work. Here, the date were converted into items/m^3 by adding a third dimension (i.e., conversion of items per square kilometer to items per square and multiply by the height of trawl net) (Lusher, 2015).

China Sea (Zhao et al., 2014), the Yellow Sea (Sun et al., 2018), and the southeastern coast of Korea (Kang et al., 2015), and it is comparable to the abundance reported by Lusher et al. (2015) in the south and southwest of Svalbard. All of these areas are known to be hotspots for MP accumulation. Our findings support the hypothesis that the Chukchi Sea is indeed a hotspot for plastic pollution. MP contamination in sediments and benthic organisms from the Chukchi Sea has been reported in our previous study (Fang et al., 2018; Mu et al., 2019). More importantly, the trophic transfer of MPs through benthic food webs were observed in the Chukchi Sea (Fang et al., 2018) and high MP contamination levels were also found in the polar cod (*Boreogadus saida*) (Kühn et al., 2018) and bigeye sculpin (*Triglops nybelini*) (Morgana et al., 2018). Thereby, detailed investigations of MPs in the Chukchi Sea are required to better understand the potential impacts of plastic particles in the polar ecosystem.

4.2. Particle shape and polymer composition

Fibers are among the most prevalent types of MPs observed in the natural environment (Obbard, 2018). Fishing gear and textile are believed to be important source of microfibers in the marine environment (Kanhai et al., 2018; Mu et al., 2019), and washing clothes may release a large number of fibrous materials (Gago et al., 2018). Similar to existing reports, the main type of MPs found in the present study was also fiber. Fibers accounted for approximately 75% of the identified particles in the northeast Pacific Ocean (Desforges et al., 2014). 95% of particles was fibers in the south/southwest of Svalbard (95%) (Lusher et al., 2015). The majority of the identified particles were fibers (96%) (Kanhai et al., 2017). In the present study, higher levels of fibrous MPs were observed in the Chukchi Sea relative to those in the Northwestern Pacific and the Bering Sea. Fibrous MPs in the Arctic waters are likely a result of the breakdown products of larger plastic items transported over large distances by prevailing water mass currents or derived from local vessel activities (research, fishing, etc.) (Cincinelli et al., 2017; Lusher et al., 2015). Browne et al. (2011) showed that a single garment might produce > 1900 fibers per wash. Napper and Thompson (2016) found high amounts, e.g. 728,789 fibers from acrylic clothing for every 6 kg of laundry. The origins and pathways of MPs could be inferred based on their shapes (Cheung and Fok, 2016). Fibrous MPs occasionally appeared in the open sea after a long-distance migration from continents (Pan et al., 2019). The Chukchi Sea is not surrounded by dense urban populations, therefore, the input of MPs from urban areas would be less likely than the transport of MPs by ocean currents or the input from shipping and commercial activities (Cózar et al., 2017). The release of fibers entrained in Arctic sea ice during melting processes can be considered another reason for the high fiber numbers (Peeken et al., 2018).

The analyzed polymers in this study were identified as PP, PE, PS, PET (polyester), acrylic (AC), PA (nylon) and rayon. Of these, the most abundant polymer was PET (67.5%). PET is a category of polymers (Hernandez et al., 2017) that is often used in manufacturing beverage containers and packaging materials, and its fibrous forms are used in clothing (Andrady, 2017). Recent studies showed that a single garment made of PET can shed innumerable tiny fibers into the wash water, and these fibers are finding their way to the ocean (Hernandez et al., 2017). Overall, this finding of a high prevalence of PET in surface waters in the present study, especially in the Chukchi Sea, are consistent with those in the south/southwest of Svalbard (Lusher et al., 2015), the east Greenland Sea (Amélineau et al., 2016), the Arctic Central Basin (Kanhai et al., 2018), and in sea ice (Obbard et al., 2014). The present study is not first to report the high prevalence of PET in the Arctic Ocean regions. We were not able to conclusively identify the origins of the synthetic polymers we found, it was likely that they originated from textiles, fishing gear, beverage containers and packaging materials (Kanhai et al., 2018). A further anticipated risk is that PET easily attracts oily pollutants in seawater (Koelmans et al., 2016) and may act as a vehicle for the transfer of chemicals into the food web when the fibers are ingested by organisms (Andrady, 2017). Of note is the fact that the densities of rayon (1.5 g/cm^3) and AC (1.2 g/cm^3) (Peng et al., 2017) exceed the density of seawater. Thus, such polymer particles would be more likely to sink, and their presence means that the local pollution of MPs should be considered (Martin et al., 2017). Over the past two decades, activities of shipping and fisheries have remarkably increased in the Arctic (Miller and Ruiz, 2014). The input of both expanding shipping and fishing in the Arctic may also be a source. A recent study of sea ice cores revealed that high levels of MPs were observed in sea ice from the Arctic Ocean (Peeken et al., 2018). Given the ongoing decline in sea ice, the release of MPs might accelerate in the near future.

In the present study, higher proportions of PA, PE, and PP were recorded in the Northwestern Pacific relative to those in the Bering Sea

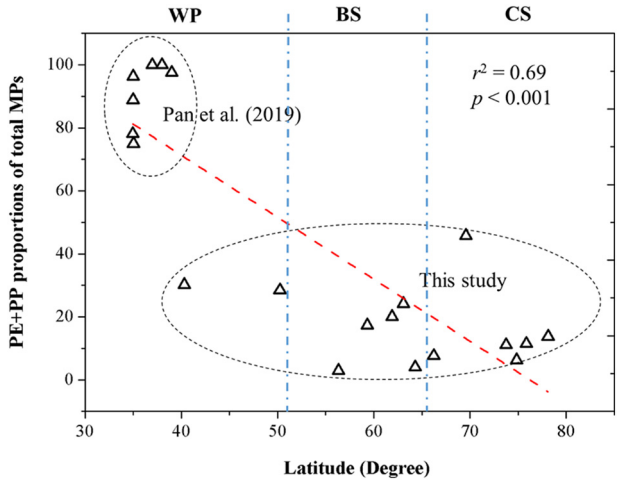

Fig. 6. Correlation between the percentages of PE and PP in total MPs numbers in surface waters from the Northwestern Pacific (WP), the Bering Sea (BS), and the Chukchi Sea (CS).

and the Chukchi Sea. It is comparable to the North Pacific Ocean, where PP and PE are the most abundant in the waters (Rios et al., 2007). Other studies have also reported PA (nylon), PP, and PE were the predominant polymer compositions of MPs from the northeast Pacific (Browne et al., 2011; Desforges et al., 2014), which may be due their high production, extensive use and global transportation (Fang et al., 2018). Recent data showed that PE and PP accounted for the largest proportion of MPs in surface water from the eight stations located closest to the Pacific coast of Japan, and it is possible that the marine debris off the Pacific coast of Japan may be a source of MPs in the Northwestern Pacific (Pan et al., 2019). Using the combination of our results and the data from Pan et al. (2019), we found that the percentages of PE and PP in total MP numbers in surface waters from the northwestern Pacific to the Chukchi Sea showed a remarkable decrease with increasing latitude ($p < 0.001$, as shown in Fig. 6). The cause of this variation is not clear, but it might be related to marine aggregates of these polymers. High amounts of MPs in marine-aggregate samples were recorded during the summer time (Zhao et al., 2018), and the marine aggregates, along with the primary polymers in the water are thought to be a pathway for the removal of small plastic particles from the ocean's upper layer (Zhao et al., 2017). Accordingly, we hypothesized that a relatively fast sinking of marine aggregates might occur at higher latitudes. Recently, a high proportion of PP was reported in sediments from the Bring-Chukchi Sea shelf (Mu et al., 2019) and the HAUSGARTEN Observatory in the Arctic (Bergmann et al., 2017). Further studies are needed to explore the potential role of aggregates in the long-distance transport and sinking of MPs from in the surface layer of the Polar Regions.

4.3. Size and color

This present study showed that more than half of the MPs were smaller than 1.0 mm, and nearly 25% of MPs were of a medium size (1.0–3.0 mm). Our results are consistent with the recent findings that were reported in the surface waters of open seas, including the northwest Pacific (Pan et al., 2019), northeast Pacific (Doyle et al., 2011), and the Southern Ocean (Isobe et al., 2017). Meanwhile, we should note that a relatively high percentage of small items was observed in the Chukchi Sea, which suggests that the cycles of freezing and melting at high latitudes could accelerate the fragmentation of large plastic debris (Cózar et al., 2017). The size of MPs is considered to be a critical factor influencing their distribution and detrimental effects (Ziajahromi et al., 2017). Smaller MPs may be more easily ingested by organisms than larger ones, which could cause a greater risk to the vulnerable Arctic ecosystem (Bergmann et al., 2017). The accumulation of small-sized MPs in zooplankton was also found in the Yellow Sea (Sun et al., 2018). The mean sizes of MPs in two species of Arctic fishes were 1.4 mm in Bigeye sculpin (*T. nybelini*) and 1.8 mm in Polar cod (*B. saida*), respectively (Morgana et al., 2018). Herein, the ingestion of MPs by species that prey on zooplankton and are consumed by top predators turns them into potential carriers of plastics in Arctic food webs (Morgana et al., 2018). Previous studies have reported elevated levels of ingested plastics in high Arctic seabirds such as the northern fulmars (*Fulmarus glacialis*) (Mallory, 2008) and the thick-billed murres (*Uria lomvia*) (Provencher et al., 2010). These findings suggested that trophic impacts may occur at higher trophic levels if the ingested MPs are transferred within the prey items of fish, birds, and mammals. Therefore, the high levels of MPs found in the Chukchi Sea highlight the importance of management actions to reduce marine litter globally, and the possibility that MPs affect the Arctic food web is worthy of further consideration. In addition, a high incidence of small-sized MPs (< 25 μm) was reported in Arctic sediments. This highlights that small-sized MPs in surface waters were mostly ignored in the present study due the mesh size of the sampling net (Sun et al., 2018). In future studies, it may be important to develop a small MPs observation technique.

White MPs account for nearly 70% of the observed MPs, whereas red and black are 20%. Our results are in agreement with the most recent study findings showing that translucent and light-colored floating plastic particles are the common colors observed in the Northwestern Pacific (Pan et al., 2019), the South Atlantic (Ryan et al., 2009), and the Mariana Trench (Peng et al., 2018). The diversity of MP colors may confuse natural prey and predatory behaviors and lead to specific colors being ingested by marine biota (Pan et al., 2019). For instance, Pacific fish (*Decapterus muroadsi*) may selectively ingest blue MPs, which resemble their natural prey (Ory et al., 2017). Some seabirds observed preferences for preying on certain colors of food, as well (Lavers and Bond, 2017). In addition, plastic color might indicate the residence time and degree of weathering of plastic debris in the ocean (Rodriguez-Seijo and Pereira, 2016). The light-colored MPs in this study show a discoloration of the plastic polymers, which indicates that they might be transported across the ocean and undergo weathering and degradation (Pan et al., 2019).

5. Conclusion

MPs were found in all surface waters from the Northwestern Pacific, the Bering Sea, and the Chukchi Sea. The abundance of MPs in this present survey area was 0.018 to 0.31 items/m^3 in surface waters, with a mean abundance of 0.13 ± 0.11 items/m^3. MPs abundance in the surface water from the Chukchi Sea was significantly higher than those from the Northwestern Pacific ($p = 0.04$) and the Bering Sea ($p = 0.006$). The highest MPs level was observed at northernmost site of the Chukchi Sea. PET and microfibers were dominated in the surface water samples. This study provides new evidence of MPs in the Arctic waters. There is a high abundance of MPs in the Chukchi Sea, suggesting that the Arctic is likely to be a sink for MPs. With the growth of human activity and the decrease of sea ice in the Arctic, high loads of plastic debris pollution may become prevalent in the future.

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Appendix A. Supplementary data

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