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# Abundance and distribution of microplastics in the surface sediments from the northern Bering and Chukchi Seas☆

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ABSTRACT

Worldwide the seafloor has been recognized as a major sink for microplastics. However, currently nothing is known about the sediment microplastic pollution in the North Pacific sector of the Arctic Ocean. Here, we present the first record of microplastic contamination in the surface sediment from the northern Bering and Chukchi Seas. The microplastics were extracted by the density separation method from collected samples. Each particle was identified using the microscopic Fourier transform infrared spectroscopy (μFTIR). The abundances of microplastics in sediments from all sites ranged from not detected (ND) to 68.78 items/kg dry weight (DW) of sediment. The highest level of microplastic contamination in the sediment was detected from the Chukchi Sea. A negative correlation between microplastic abundance and water depth was observed. Polypropylene (PP) accounted for the largest proportion (51.5%) of the identified microplastic particles, followed by polyethylene terephthalate (PET) (35.2%) and rayon (13.3%). Fibers constituted the most common shape of plastic particles. The range of polymer types, physical shapes and spatial distribution characteristics of the microplastics suggest that water masses from the Pacific and local coastal inputs are possible sources for the microplastics found in the study area. In overall, our results highlight the global distribution of these anthropogenic pollutants and the importance of management action to reduce marine debris worldwide.

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## 1. Introduction

Marine plastic debris pollution has been recognized as a global issue due to growing concerns over the amount of marine plastic debris and the impacts they have caused on marine ecosystems (Sussarellu et al., 2016). More than 300 million tones of plastics are produced per year globally (PlasticsEurope, 2016). Between 8 and 12 million tones of plastics enters the ocean as marine debris from mismanaged waste at coastlines annually (Jambeck et al., 2015). Due to their durability and high resistance to degradation, plastics tend to remain in the environment for a long time (Geyer et al., 2017), and the floating plastics may be transported from their point of release to remote areas (Ivar do Sul et al., 2013; Law et al., 2010). Approximately 5 trillion pieces of floating plastic is estimated to be in the ocean worldwide (Eriksen et al., 2014).

Microplastics, defined as < 5 mm in size, occur due to the release of manufactured plastic particles in various products (primary microplastics) and the fragmentation of larger plastic litters (secondary microplastics) (Cole et al., 2011). Microplastics are ubiquitous in the world's oceans and their distributions have been reported to be the surface (Zhao et al., 2015; Zhao et al., 2014) and sub-surface waters (Desforges et al., 2014), beaches (Yu et al., 2016), sediments (Martin et al., 2017; Peng et al., 2017; Vianello et al., 2013), deep-sea seafloor (Van Cauwenberghe et al., 2013) and marine organism (Courtene-Jones et al., 2017; Li et al., 2016; Taylor et al., 2016). The Arctic, though far from significant pollution sources, has not been immune to the entry of microplastics (Lusher et al., 2015; Kanhai et al., 2018). Previous studies have shown that high abundances of floating plastic debris in surface and sub-surface water in the northernmost and easternmost areas of the Greenland and Barents seas (Cózar et al., 2017). The amount of

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plastic debris collected from the Svalbard deep seafloor highlight the increasing numbers of plastic litter between 2002 and 2014 (Tekman et al., 2017). Recently, higher microplastic abundances were reported in deep-sea sediment from the Arctic at 2340–5570 m depth (Bergmann et al., 2017). In addition, Arctic sea ice contains vast quantities of microplastics (Obbard et al., 2014; Peeken et al., 2018). So far, the limited reports about debris and microplastics in deep-sea sediment from the Arctic have largely focused on the Northeastern Atlantic sector of the Arctic (Greenland and Barents seas); however, data for microplastic abundance in sediments from the North Pacific sector of the Arctic Ocean are still scarce.

Both the Chukchi Sea within the arctic region and the Bering Sea within the subarctic region belong to the marginal ice zone, which is covered with the sea ice each winter (Natsuike et al., 2013). The northern Bering and Chukchi shelves are strong connected by Pacific origin waters flowing northward through the Bering Strait (Sigler et al., 2017). The water properties of the Chukchi Sea are dominantly determined by the Pacific water properties entering through the Bering Strait (Woodgate et al., 2005). Occurrences of plastic debris and microplastics were confirmed in the Bering Sea (Doyle et al., 2011) and the Northeast Pacific Ocean (Goldstein et al., 2012). These facts suggest that a significant fraction of the microplastics in the Chukchi Sea most likely came from the Pacific Ocean, while its existence in the Chukchi Sea remains largely uncertain. High benthic standing stocks occurred in the northern Bering Sea, the Bering Strait, and the southern Chukchi Sea (Grebmeier et al., 1988). Currently, microplastics ingestion by benthic organism was reported from the Bering-Chukchi Sea shelf (Fang et al., 2018), however, the occurrence and distribution of microplastics in this area are unknown. In this study, in order to estimate the abundance and distribution of microplastics in sediments from the Bering-Chukchi Sea shelf, we collected 7 samples from the northern Bering Sea, Bering Strait, and the Chukchi Sea. The abundance, size, type, and composition of microplastics were determined and compared.

## 2. Material & methods

### 2.1. Sampling

The sampling was conducted at the 9th Chinese National Arctic Research Expedition of the research icebreaker R/V Xuelong during the summer of 2017. Sampling sites were located in the Bering Sea, the Chukchi Sea and Bering Strait. Seven representative sampling sites named B15, B17, R01, R06, R08, R11, and P01 were selected, which were located on the Bering-Chukchi Seas shelf, ranging from 61.6°N to 75.9°N. Sites B15 and B17 were located in the Bering Sea, site R01 was located in the Bering Strait, and sites R06, R08, R11 and P01 were located in the Chukchi Sea and Chukchi Basin. Detailed location information for every sampling site is shown in Fig. S1 and Table S1.

The sediment samples were collected using a $50 \times 50 \times 65\ cm^3$ stainless-steel box corer. At each site, after the box corer was retrieved and carefully opened the jaws on the bottom, the collected sediments were slowly released to a stainless steel box with minimal disturbance. Approximately 1 kg sediments from the top 5-cm depth were carefully collected using a pre-cleaned stainless steel scoop. These superficial samples were wrapped with prewashed aluminum foil and stored at −20 °C until further analysis.

### 2.2. Microplastics separation

The microplastic separation from the sediment was performed using modified NOAA laboratory methods and the analysis procedure described by Zobkov and Esiukova (2017), with modification adjusted according to Zhao et al. (2017). Briefly, in the laboratory, the collected superficial sample from each site was defrosted and dried in an oven at 60 °C to constant weight. Afterwards, a subsample of 200 g dry weight (ww) sediment was weighed and placed in a pre-rinsed glass beaker. Two hundred milliliter of a saturated potassium iodide (KI) separation solution (density: 1.7 g/ml) was added to the beaker and stirred for 1 min with a glass rod. After about 2 h of the settlement, the supernatant containing particles was carefully transferred to another breaker. The step using the KI separation solution was repeated for at least five times, and all supernatants were then mixed and passed through Whatman® GF/C filters (0.7 μm pore size, the diameter of 47 mm). The filters were placed in covered glass Petri dishes to allow drying overnight.

### 2.3. Microplastic detection and analysis

All particles were visually identified, counted, and measured under a light stereomicroscope (Leica M205FA, 50–160 ×). The polymer type of all particles suspected to be plastic was identified by Fourier transform infrared microscopy (μFTIR) (Thermo Fisher IN10 MX). Each particle's spectra were recorded as the average of 8 scans in the spectral wavenumber range of 4000–675 $cm^{-1}$ with a spectral resolution of 8 $cm^{-1}$. All obtained spectra were processed and evaluated using Thermo Scientific's OMNIC Picta Version 9.6 spectroscopy software. Prior to analyzing each sample, background scans were performed, and the sample spectra were automatically adjusted.

### 2.4. Method validation and contamination prevention

To assess the recovery rates of the proposed method, artificial reference particles of around 30–50 items were quantitatively spiked as an internal standard to a known mass of natural sediment before the extraction step. Artificial reference particles used were polyethylene terephthalate (PET) beads and polyvinyl chloride (PVC) beads both with a size of 0.5–1.5 mm (Table S2). Recoveries were estimated by subtracting the previously calculated total particle content of the material from the spiked amount. Clean Petri dishes and filter papers were left exposed to the air during vacuum filtration to determine if there was any airborne contamination. To determine whether there was any additional contamination during vacuum filtering, distilled water was passed through clean GF/C filter paper (same with the sediment treatment) under vacuum conditions. Standard non-plastic equipment was used wherever possible. The samples were kept covered to minimize the exposure risk. Lab coats, cotton clothing, and gloves were worn during sample processing in order to avoid contact with the external synthetic fibers.

Only $1.85 \pm 0.90$ items/filter of microplastics was found in the blanks for the field samples, and $0.67 \pm 0.58$ items/filter were found in the procedural blanks for the laboratory samples. The recovery rates of PET beads with 0.5–1.0 mm and 1.0–1.5 mm in size were $87.8 \pm 8.4\%$ and $98.3 \pm 1.8\%$, respectively. The recovery rates of PVC beads with 0.5–1.0 mm and 1.0–1.5 mm in size were $88.9 \pm 6.9\%$ and $98.3 \pm 2.4\%$, respectively (Table S2).

### 2.5. Statistical analysis

The nonparametric Kruskal-Wallis H test was used to test multiple comparisons of the variance on the mean of multiple comparisons among the sampling sites. If there was a significant difference ($p < 0.05$), a pairwise Mann-Whitney $U$ test was performed (SPSS 13). Maps and contour plots were created using the

Ocean Data View 4 software. Spearman's correlation was conducted to assess relationships between the microplastic abundance and environmental variables.

## 3. Results

### 3.1. Microplastic abundance

Most of the surface sediments collected in the survey area were slightly polluted with the plastics, with 6 out of the total 7 sites were detected containing microplastics. A total of 32 pieces of debris were confirmed as microplastics from the FTIR spectra. The abundance of microplastics in the sediment collected from each site varied from ND ~68.88 items/kg (Fig. 1 and Table S1). The maximum abundance of MPs in the sediment appeared at site R06 (68.88 items/kg), followed by R01 (39.27 items/kg), B17 (20.78 items/kg), R08 (17.69 items/kg), R11 (8.33 items/kg) and B15 (5.30 items/kg). It should be noted that microplastics were not detected in samples from the deepest station, P01, which was the northernmost station. Although the average abundances of microplastics in the Chukchi Sea were higher than those in the Bering Sea, no statistically significant differences were found between the sediments of the Bering Sea and the Chukchi Sea.

### 3.2. Microplastic shape

Two types of particles, fiber and film (Fig. 2), were identified with fibers being the most abundant (64.4%) followed by films (35.6%) (Fig. 1). The colors of particles were classified as white and black, which accounted for 52% and 48% of the total microplastic particles, respectively. The microplastics were 100% fibers at R08 and B15 sites (Fig. 1).

### 3.3. Microplastic composition

Of those particles subjected to μFTIR analysis, polymers identified included polypropylene (PP), polyethylene terephthalate (PET) and rayon (Fig. S2), accounting for 51.5%, 35.2% and 13.3% (Fig. 3A). The highest proportion of PP was recorded at B15 (100.0%) and R 11 (100.0%), respectively, whereas the highest PET was recorded at R01 (100.0%). Rayon was only recorded at the Chukchi Sea (R06 and R08), accounting for 54.5% and 25%, respectively (Fig. 3B).

### 3.4. Microplastic size

Particle size ranged between 0.10 mm and 4.86 mm with an average length of 1.63 ± 1.12 mm. The most common lengths were in the interval from 0.10 to 2.0 mm, accounting for 78.2% of all the particles (Fig. 4A). The average sizes of microplastics were 1.34 ± 0.37 mm, 1.02 ± 0.19 mm, 1.73 ± 0.85 mm, 2.18 ± 1.48 mm, 1.14 ± 0.72 mm and 0.44 ± 0.06 mm in the sediment from sites B15, B17, R01, R06, R08 and R11, respectively (Fig. 4B). Overall, the mean size was 1.46 ± 0.73 mm and 1.31 ± 0.97 mm from the sub-Arctic region and Arctic region, respectively.

## 4. Discussion

This study presents the first report of microplastics in sediments from the northern Pacific sector of the Arctic Ocean, highlighting the global distribution of plastic debris. As there is no cohesive and standardized approaches for collecting, fractionating, characterizing, and quantifying microplastics in various marine matrices (Zhao et al., 2018b), it was difficult to directly compare the abundances of microplastics in our study with all the existing studies (Zhao et al., 2018a). However, we can compare our results with other published results that used similar sampling methods and quantification units. The results from studies of microplastic abundances in sediments worldwide, which used the same unit (particles per kg of dry weight) are summarized in Table 1. In comparison with other studies across different coastal and Open Ocean areas, the microplastic abundances in the sediment of this study were relatively low (Table 1). Most studies of coastal sediments from other regions of the world have reported higher abundances of microplastic particles than those in this study. For example, reported microplastic abundances were several orders of magnitude higher in the Northwest Pacific (Eo et al., 2018; Matsuguma et al., 2017) and Asian Seas (Lo et al., 2018; Qiu et al., 2015). Sediments from the Belgium coast (390 items/kg)

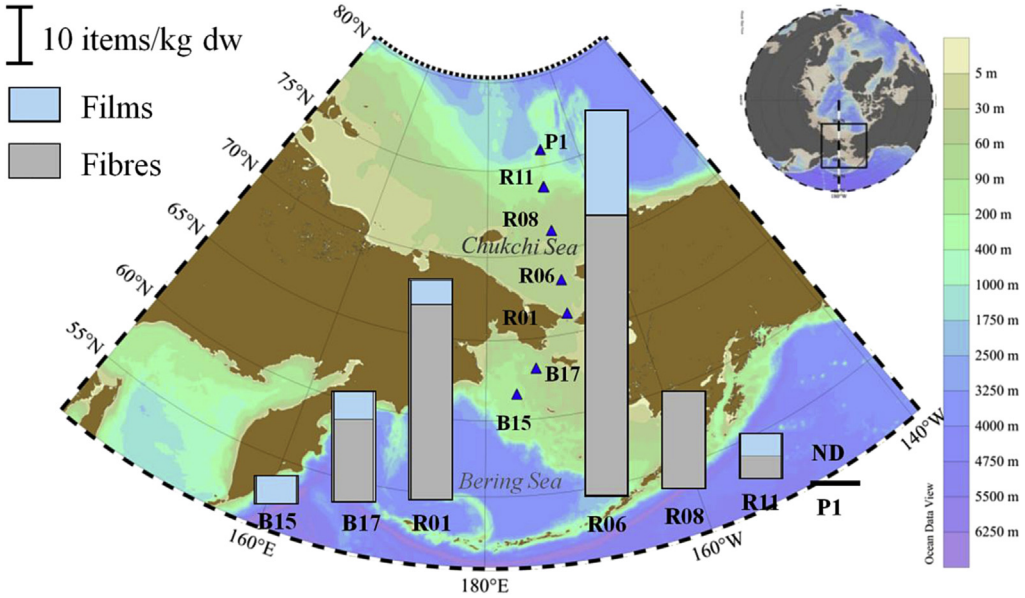


**Fig. 1.** Abundance and types of microplastics detected in sediments from the Bering Sea – Chukchi Sea shelf (Polymer abundance in the samples refers to number/kg dry sediment of the sample, abundance data shown in Table S1.). ND: not detected.

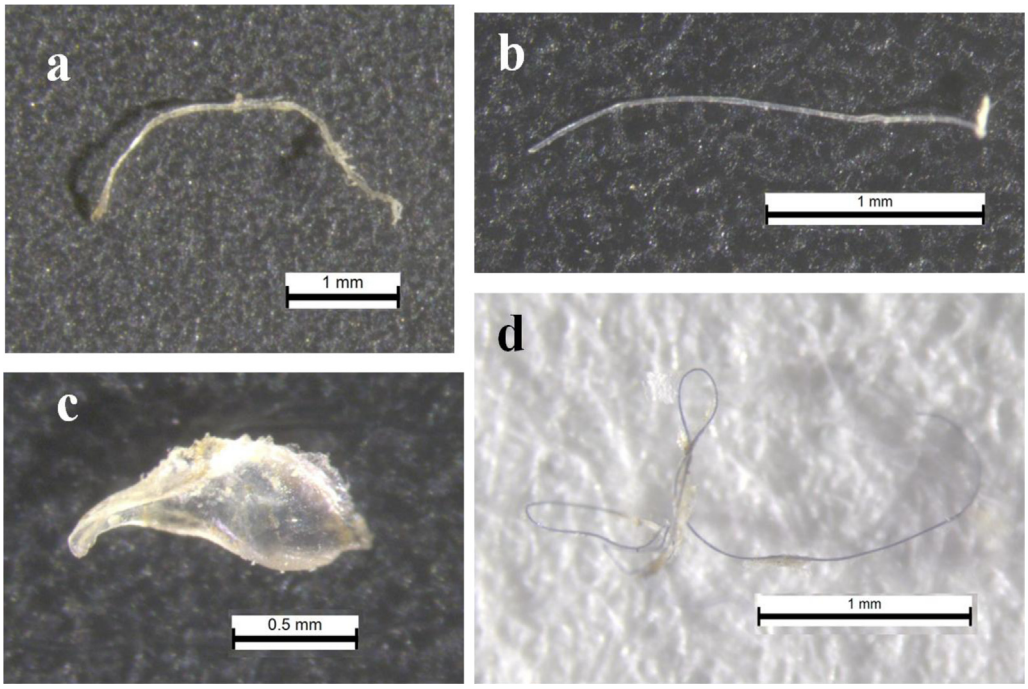


**Fig. 2.** Representative photographs of microplastic particles in sediment samples from the Bering Sea – Chukchi Sea shelf. (a) fibre, polypropylene (PP); (b) fibre, polyethylene terephthalate (PET); (c) film, PP; (d) fibre, PET.

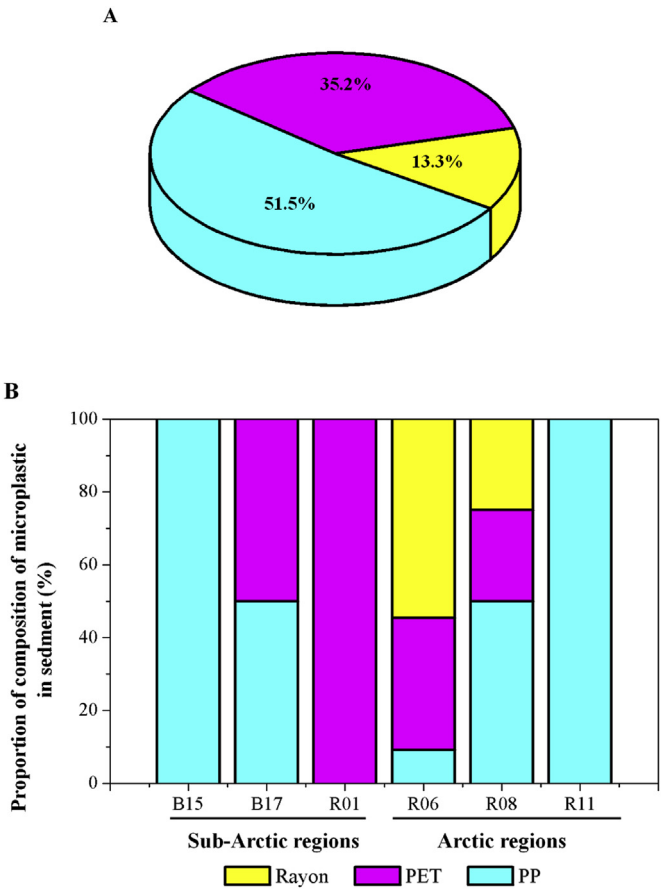


**Fig. 3.** The composition of microplastics detected in sediments from the Bering Sea – Chukchi Sea shelf. (A) The proportion of each composition to the total microplastics from all sites; (B) The proportion of each composition to the total microplastics from each site. PP: polypropylene; PET: polyethylene terephthalate.

(Claessens et al., 2011), Dutch North Sea coast (421 items/kg) (Maes et al., 2017) and Venice Lagoon in Italy (1512 items/kg) (Vianello et al., 2013) also demonstrated higher microplastic abundances than those reported in this study. Nevertheless, fewer microplastics were detected in sediments from the deep Northeast Atlantic, Mediterranean, and Southwest Indian Ocean, although only fibers were considered (Woodall et al., 2014). The data from the Greater Canterbury region sediment (21.2 items/kg) were comparable to the range reported in this study (Clunies-Ross et al., 2016). Unexpectedly high abundances of microplastics (42–6595 items/kg) were recorded in Arctic deep-sea sediment from the northern Atlantic sector (Bergmann et al., 2017). It should be noted that smaller-size microplastics (less than 25 μm) were more abundant in the Arctic deep-sea sediments (Bergmann et al., 2017). However, in the present study, 78.2% of all detected microplastics were in the 100–200 μm size range. As mentioned above, some of the observed differences in quantified microplastic abundances may attribute to a variety of extraction, identification and quantification methods used for microplastics. Bergmann et al. (2017) used MicroPlastic Sediment Separator to extract particles and applied an automated analysis approach to identify particle composition and extrapolate particle number. To better comparison of microplastics contamination across environments, it is important to develop reproducible methodologies for identifying nano-sized plastic particles (Mai et al., 2018).

Sediments are proposed as the final destination of microplastics and other pollutants in aquatic environment (Woodall et al., 2014). This outcome is due to natural processes, and buoyancy and density changes which eventually can lead to the deposition of microplastics in sediments (Bergmann et al., 2017; Galloway et al., 2017). In this study, the greatest abundance of microplastic was found in the Chukchi Sea, especially near the Bering Strait (R01 and R06). Likewise, the microplastic abundances in the surface and subsurface waters at sites from the Chukchi Sea ($0.23 \pm 0.07$ items/$m^3$ in surface water and $3.85 \pm 2.14$ items/$m^3$ in sub-surface waters) and the Bering Strait (0.25 items/$m^3$ in surface water and 3.33

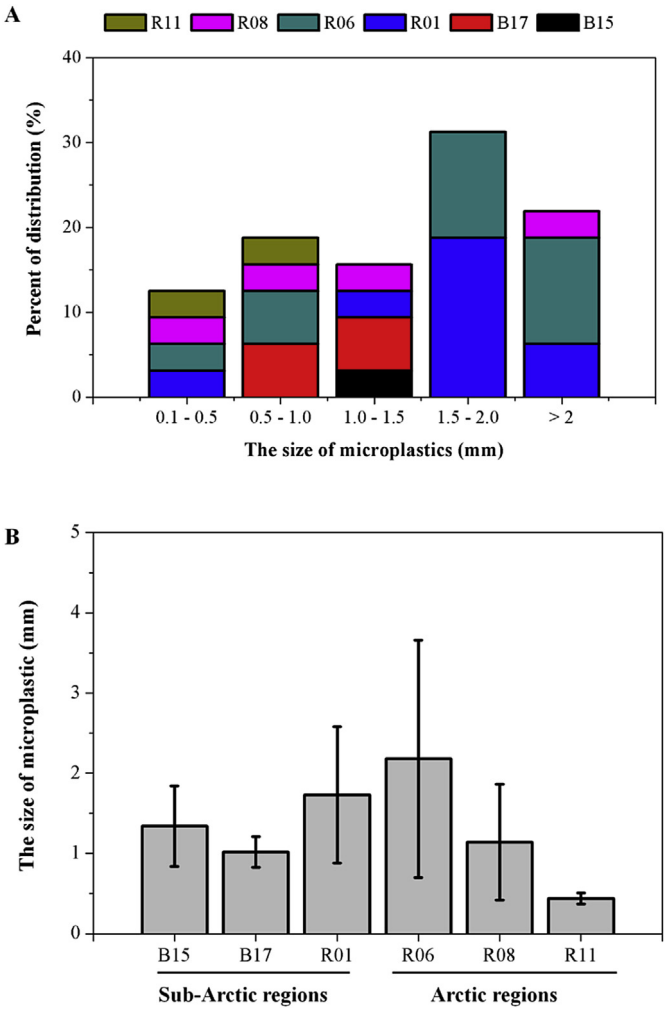


**Fig. 4.** Size of microplastics detected in sediments from the Bering Sea – Chukchi Sea shelf. (A) The distribution proportion of every size from all particles; (B) The average size from each site.

items/$m^3$ in sub-surface waters) were also relatively higher than those from the Bering Sea ($0.05 \pm 0.02$ items/$m^3$ in surface water and $2.28 \pm 1.79$ items/$m^3$ in sub-surface waters) (our unpublished data). Although there is extremely limited information available concerning the source of microplastics in the Chukchi Sea, the results from this study suggest that inputs from the North Pacific may increasingly contribute to this. A previous study showed that currents from the Pacific Ocean and the Arctic coast may be responsible for the transport of up to 16 200 to 1.9 million tons of plastics to the Arctic Ocean each year (Zarfl and Matthies, 2010). Data from the cores from Canadian Basin indicated high microplastic concentrations might reflect remains from the so-called North Pacific Garbage Patch (van Sebille et al., 2012), and transported with the incoming Pacific inflow. High quantities of microplastic in the northeast Pacific highlight the role of oceanographic conditions for the accumulation patterns of microplastics (Desforges et al., 2014). Besides, local pollution sources may also contribute to the amounts of microplastics in the Chukchi Sea. The accumulation of freshwater has been concentrated in the Canada Basin and especially to the Beaufort Gyre (Andrey et al., 2009). The station with the highest abundance of microplastics (R06) received currents from Barrow Point and the Prudhoe Bay offshore area, close to the mouth of the Mackenzie and Colville Rivers. As the distance from the polluted area increased, microplastic abundances gradually decreased, showing a spatial pattern that is consistent with the findings of polycyclic aromatic hydrocarbon (PAH) contamination (Zhao et al., 2016). Otherwise, the release of microplastics entrained in Arctic sea ice during melting processes in the region may also contribute to the number of microplastics on the Chukchi Sea shelf (Obbard et al., 2014; Peeken et al., 2018).

PP is often the most common polymer reported in some other microplastic studies (Andrady, 2011; Martin et al., 2017; Lots et al., 2017). This is in accordance with the scale of its global manufacture and use worldwide (Abidli et al., 2018; Browne et al., 2011). PP constituted the major portion of microplastics from surface water of NE Pacific Ocean (Desforges et al., 2014). The density of individual microplastic pieces was a major contributor to their distribution and eventual settlement into the natural sediment (Ling et al., 2017). PP density (approximately 0.95 g/cm) is less than that of seawater (approximately 1.03 g/cm). Thus, the largest proportion of PP (51.5%) in the Bering-Chukchi Sea shelf supports the hypothesis that a significant fraction of microplastics likely originated from the North Pacific inputs. Low density plastics float on seawater and facilitate long-distance dispersal (Ryan, 2015). Residence time and removal of floating plastic particles in water column were influenced by particle size (Ryan, 2015), biofouling (Kooi et al., 2017), wind mixing (Kukulka et al., 2012), ingestion by marine organisms (Cózar et al., 2017), and water flow (Nel et al., 2018). Our results indicated that biofouling and ingestion by marine organisms could play important roles in sinking of floating particles in arctic waters. A positive correlation ($\rho = 0.832$; $p = 0.040$) between microplastic abundance in sediment and chlorophyll α content in water was observed in this study (Table S3). The correlation has also been found in the study of Bergmann et al. (2017). Microplastics could potentially be incorporated into marine aggregates (Wright et al., 2013; Long et al., 2015), which would be an important pathway for the transport of microplastics from the surface to deeper layers of the ocean. The ice algal diatom (*Melosira arctica*) aggregates may entrain microplastics and accelerate the sinking rate of microplastics (Bergmann et al., 2107). Different algae species have been demonstrated in lab studies to incorporate and concentrate microplastics, greatly increasing the sinking rates of microplastics (Long et al., 2015). Further studies are needed to assess the potential role of aggregates in both transporting microplastics and marine animals in the environment.

Since the density of PET (1.37 g/cm) and rayon (1.53 g/$cm^3$) exceeds the density of seawater (1.02–1.03 g/$cm^3$), these microplastics will sink to the seafloor inevitably (Bergmann et al., 2017). Rayon has been widely used in personal hygiene products and clothing and is introduced to the marine environment through sewage (Barnes et al., 2009; Obbard et al., 2014). PET and Rayon are also often found in the arctic environments. PET was the most prevalent synthetic polymer in the water around Svalbard (Lusher et al., 2015), in sub-surface water of the Arctic Central Basin (Kanhai et al., 2018), in sea ice (Obbard et al., 2014) and in sediment from the Fram Strait (Bergmann et al., 2017). Rayon was reported as an important share of microplastics in deep-sea sediment (Comnea-Stancu et al., 2017) and arctic sea ice (Obbard et al., 2014). Of note, the highest proportion of PET and Rayon has been recorded from the nearby the Bering Strait. One possibility is that high flow rate and strong currents do not facilitate the deposition of low density plastic particles (Nel et al., 2018). Another possibility is that the microplastics came from the local inputs.

In general, the pollutant content of marine sediments is believed to be related with the TOC content and grain size (Macdonald et al., 1998). The larger the sediment grain size is the lower the TOC content and the smaller the amount of adsorbed pollutants (Zhao et al., 2016). Yet, surprisingly, no significant correlation was found between the microplastic abundance and TOC content in the

**Table 1**
Abundances, major types, sizes and major compositions of microplastics in sediments around the world.

| Location | Substrate | items/kg DW | Major types | size (mm) | Major composition | Reference |
|---|---|---|---|---|---|---|
| **Pacific** | | | | | | |
| **North West Pacific** | | | | | | |
| Japan | Tokyo Bay Canal sediment | 1845 [a] | Fragments | 0.315–5 | PE and PEP | Matsuguma et al. (2017) |
| South Korea | Sand beach | 199.7 [b] | Foam | 0.1–5 | PS | Eo et al. (2018) |
| **South Pacific** | | | | | | |
| Chile | Continental coast sediment | 1–805 | Fragments | 1–4.75 | – | Hidalgo-Ruz and Thiel (2013) |
| New Zealand | Greater Canterbury region | 21.2 [a] | Fragments | 0.03–5.6 | PS | Clunies-Ross et al. (2016) |
| **Asian Seas** | | | | | | |
| Singapore | Coatal sediment | 37 [b] | Fibres | 0.02–5 | PE and PP | Mohamed Nor and Obbard (2014) |
| Malaysia | Straight of Johor coastal sediment | 300 [a] | Fragments | 0.315–5 | PS and PP | Matsuguma et al. (2017) |
| China | Changjiang Estuary sediment | 121 [a] | Fibres | 0.3–5 | Rayon | Peng et al. (2017) |
| Thailand | Gulf of Thailand sediment | 248 [b] | Fragments | 0.315–5 | PE | Matsuguma et al. (2017) |
| Hong Kong | Shore sediment | 161 [a] | Fibres | 0.25–5 | PE | Lo et al. (2018) |
| China | Bohai Sea Beach | 127 [b] | Fragments | 0.01–5 | PEVA | Yu et al. (2016) |
| China | Beibu Gulf beach | 6912 [b] | Fibres | 0.1 - 5 | PET | Qiu et al. (2015) |
| **Atlantic** | | | | | | |
| **North Atlantic** | | | | | | |
| Canada | Nova Scotia, sediment | 105–800 | Fibres | 1–5 | – | Mathalon and Hill (2014) |
| Dutch | North sea coast sediment | 421 [b] | | | – | Maes et al. (2017) |
| Norway | Tromsø | 72 [a] | Fibres | 0.045–5 | Polyester and PE | Lots et al. (2017) |
| Germany | Isle of Rügen, Beach sediment | 88.1[c] | Fibres | 0.2–5.0 | – | Hengstmann et al. (2018) |
| Belgium | Belgain Coast sediment | 390 [a] | Fibres | <1 | PS | Claessens et al. (2011) |
| **South Atlantic** | | | | | | |
| South West Atlantic | Sediment | 0.73–9.63 | Fragment | 2–20 | – | Ivar do Sul et al. (2009) |
| South Africa | Durban bay sediment | 1750 [a] | Fragments | 0.315–5 | PE and PEP | Matsuguma et al. (2017) |
| **Baltic and the Mediterranean** | | | | | | |
| Russia | Kaliningrad, beach | 1.3–36.2 | Foam | 0.5–5 | PS | Esiukova (2017) |
| Tunisia | Coastal sediment | 316 [a] | Fibres | 0.1–5 | PP | Abidli et al. (2018) |
| Mediterranean zone | Coastal sediment | 291 [a] | Fibres | 0.045–5 | Polyester and PE | Lots et al. (2017) |
| France | Brest bay sediment | 0.97 [a] | Fragments | 0.3–5 | PE | Frère et al. (2017) |
| Spain | Mallorca Island and Cabrera Island sediment | 100–900 | Fragments | 0.5–2 | – | Alomar et al. (2016) |
| Italy | Lido Di Dante sediment | 1512 [b] | Fragments | 0.007–1 | PE and PP | Vianello et al. (2013) |
| **Arctic** | | | | | | |
| Fram Strait | Seafloor | 4356 [a] | Fibres | 0.01–1 | Polyethylene chlorinated and PTFE | Bergmann et al. (2017) |
| Bering Sea-Chukchi Seas shelf | Sediment | 22.8 [b] | Fibres | 0.1–5 | PP and PET | This study |

— means not reported in the article. PE: polyethylene; PEP: polyethylene-polypropylene; PS: Polystyrene; PEVA: Polyethylene vinyl acetate; PTFE: polytetrafluoroethylene.
[a] means the mean abundance of microplastic.
[b] means the average abundance of microplastic.
[c] means the median value of microplastic.

sediment (Table S3), which disagreed with the previous study. Vianello et al. (2013) have detected the highest microplastic concentration in the outer lagoon, which was characterized by higher proportion of organic and fine fraction content. Here, a positive correlation was found between the sand content and microplastic abundance in the sediment (Table S3). Therefore, apart from aggregation with organic matter, suspended sand in water may play an important effect on the routes of transport for microplastics to deep-sea sediments. This result suggests that migration and deposition of microplastic in sediment is different from those of chemical pollutants. Further research is required to study how the grain size of sediment affects the microplastic deposition rates.

Microplastics from our study were mainly fibers, which was consistent with most of the previous studies in other regions (Table 1). The dominance of fibers in seawater was reported in (i) the northeast Pacific Ocean (75%) (Desforges et al., 2014), (ii) the northeast Atlantic Ocean (96%) (Kanhai et al., 2017), (iii) south/southwest of Svalbard (95%) (Lusher et al., 2015), and (iv) the Arctic Central Basin (>90%) (Kanhai et al., 2018). Fibrous microplastics in the marine environment most likely originate from two types of materials, namely textile materials and fishing gear. As indicated by the studies of Napper and Thompson (2016), washing clothes may lead to the release of fibrous materials on the order of >1900 fibers per wash or as much as 700 000 fibers per 6 kg load of acrylic fabric. High abundances of fibers in the sediment heighten the probability that marine organisms inhabiting the same area will encounter microplastic particles. Our previous study found that fibers constituted the major type of microplastics identified in the benthic organisms from the same stations (Fang et al., 2018). Microfibers within *Nephrops norvegicus* from the Clyde Sea have been reported as linked to fishing gear materials (Welden and Cowie, 2016). PET and acrylic fibers have also been found within the gut contents of starfish (*Hymenaster pellucidus*) and hermit crabs from the North Atlantic (Courtene-Jones et al., 2017) and South West Indian Ocean (Taylor et al., 2016). These plastics are known to have impacts on terrestrial and marine ecosystems both at the macro- and micro-scale, although the effects on marine organisms in the wild are understudied and not yet conclusive. A recent study indicated that microfibers pose a greater risk to *Ceriodaphnia dubia* than microbeads (Ziajahromi et al., 2017). Further studies are necessary to compare the kinetics of fibers with other shapes of microplastics in the benthos in order to understand whether particle shape is a cause for the greater biological effects of fibers.

It is important to highlight that the size of microplastics is a critical factor influencing their distribution and detrimental effects (Ziajahromi et al., 2017). The most common sizes of the

microplastics detected in the sediments of this study fell into the smallest size groups (<2.0 mm) and were within the size ranges observed in other studies (Table 1). In addition, the positive correlation between average size and abundance of microplastics and the negative correlation between the size of microplastics and water depth in this study may support other recent findings that smaller microplastics sink more easily than larger ones do, which likely increases the possibility of the ingestion of smaller microplastics by the benthos (Katija et al., 2017). Another study of arctic sediment showed that 80% of microplastics were ≤25 μm and these smaller-sized microplastic particles have steadily increased in numbers with no sign of saturation. This finding may suggest that deep-sea sediments contain more plastic particles that are very small in size (Bergmann et al., 2017) and that evaded the detection methods applied in this study. Therefore, small microplastics (≤250 μm) in environmental samples should be analyzed in future studies.

## 5. Conclusion

In the present study, we reported microplastic pollution in the surface sediment of the Bering Sea–Chukchi Sea shelf for the first time. We found that microplastic pollution was ubiquitous and high numbers of micrplastics were present in the Chukchi Sea, especially near the Bering Strait. Fibers constituted the most common shape of the microplastic particles. PP, PET and rayon are the most common polymers in study area. PP likely came from the North Pacific inputs by ocean currents. The potential effects of microplastic contamination on benthic organisms might become more pronounced as the exploitation of the Arctic Ocean and the ice melts. Great efforts are needed to identify the sources of microplastics in the Arctic sediments and its potential risk for Polar ecosystem. Importantly, concerned countries should take actions and establish an international plastic pollution agreement to prevent and mitigate plastic pollution.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2018.10.097.

## References

Abidli, S., Antunes, J.C., Ferreira, J.L., Lahbib, Y., Sobral, P., Trigui El Menif, N., 2018. Microplastics in sediments from the littoral zone of the north Tunisian coast (Mediterranean Sea). Estuar. Coast Shelf Sci. 205, 1–9. https://doi.org/10.1016/j.ecss.2018.03.006.

Alomar, C., Estarellas, F., Deudero, S., 2016. Microplastics in the Mediterranean Sea: deposition in coastal shallow sediments, spatial variation, and preferential grain size. Mar. Environ. Res. 115, 1–10. https://doi.org/10.1016/j.marenvres.2016.01.005.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Andrey, P., Richard, K., Mary-Louise, T., John, T., Eddy, C., Fiona, M., J., W, W., Sarah, Z., Motoyo, I., Koji, S., 2009. Beaufort Gyre freshwater reservoir: state and variability from observations. J. Geophys. Res. 114, C00A10. https://doi.org/10.1029/2008JC005104.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. Lond. B Biol. Sci. 364, 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., Gerdts, G., 2017. High quantities of microplastic in arctic deep-sea sediments from the HAUSGARTEN observatory. Environ. Sci. Technol. 51, 11000–11010. https://doi.org/10.1021/acs.est.7b03331.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179. https://doi.org/10.1021/es201811s.

Cózar, A., Martí, E., Duarte, C.M., García-de-Lomas, J., van Sebille, E., Ballatore, T.J., Eguíluz, V.M., González-Gordillo, J.I., Pedrotti, M.L., Echevarría, F., Troublè, R., Irigoien, X., 2017. The Arctic Ocean as a dead end for floating plastics in the north atlantic branch of the thermohaline circulation. Science Advances 3, e1600582. https://doi.org/10.1126/sciadv.1600582.

Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204. https://doi.org/10.1016/j.marpolbul.2011.06.030.

Clunies-Ross, P.J., Smith, G.P.S., Gordon, K.C., Gaw, S., 2016. Synthetic shorelines in New Zealand? Quantification and characterization of microplastic pollution on Canterbury's coastlines. New Zeal. J Mar. Fresh. 50, 317–325. https://doi.org/10.1080/00288330.2015.1132747.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.

Comnea-Stancu, I.R., Wieland, K., Ramer, G., Schwaighofer, A., Lendl, B., 2017. On the identification of rayon/viscose as a major fraction of microplastics in the marine environment: discrimination between natural and manmade cellulosic fibers using fourier transform infrared spectroscopy. Appl. Spectrosc. 71, 939–950. https://doi.org/10.1177/0003702816660725.

Courtene-Jones, W., Quinn, B., Gary, S.F., Mogg, A.O.M., Narayanaswamy, B.E., 2017. Microplastic pollution identified in deep-sea water and ingested by benthic invertebrates in the Rockall Trough, North Atlantic Ocean. Environ. Pollut. 231, 271–280. https://doi.org/10.1016/j.envpol.2017.08.026.

Doyle, M.J., Watson, W., Bowlin, N.M., Sheavly, S.B., 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Mar. Environ. Res. 71, 41–52.

Desforges, J.P., Galbraith, M., Dangerfield, N., Ross, P., 2014. The widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. Mar. Pollut. Bull. 79, 94–99. https://doi.org/10.1016/j.marpolbul.2013.12.035.

Eo, S., Hong, S.H., Song, Y.K., Lee, J., Lee, J., Shim, W.J., 2018. Abundance, composition, and distribution of microplastics larger than 20 μm in sand beaches of South Korea. Environ. Pollut. 238, 894–902. https://doi.org/10.1016/j.envpol.2018.03.096.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PloS One 9, e111913. https://doi.org/10.1371/journal.pone.0111913.

Esiukova, E., 2017. Plastic pollution on the Baltic beaches of Kaliningrad region, Russia. Mar. Pollut. Bull. 114, 1072–1080. https://doi.org/10.1016/j.marpolbul.2016.10.001.

Fang, C., Zheng, R., Zhang, Y., Hong, F., Mu, J., Chen, M., Song, P., Lin, L., Lin, H., Le, F., Bo, J., 2018. Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. Chemosphere 209, 298–306.

Frère, L., Paul-Pont, I., Rinnert, E., Petton, S., Jaffré, J., Bihannic, I., Soudant, P., Lambert, C., Huvet, A., 2017. Influence of environmental and anthropogenic factors on the composition, concentration and spatial distribution of microplastics: a case study of the Bay of Brest (Brittany, France). Environ. Pollut. 225, 211–222. https://doi.org/10.1016/j.envpol.2017.03.023.

Galloway, T., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1, 0116. https://doi.org/10.1038/s41559-017-0116.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Science Advances 3, e1700782. https://doi.org/10.1126/sciadv.1700782.

Goldstein, M.C., Rosenberg, M., Cheng, L., 2012. Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. Biol. Lett. 8, 817–820. https://doi.org/10.1098/rsbl.2012.0298.

Grebmeier, J.M., McRoy, C.P., Feder, H.M., 1988. Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas.I. Food supply source and benthic biomass. Mar. Ecol. Prog. Ser. 48, 57–67. https://doi.org/10.3354/meps048057.

Hengstmann, E., Tamminga, M., vom Bruch, C., Fischer, E.K., 2018. Microplastic in beach sediments of the Isle of Rügen (Baltic Sea) - implementing a novel glass elutriation column. Mar. Pollut. Bull. 126, 263–274. https://doi.org/10.1016/j.marpolbul.2017.11.010.

Hidalgo-Ruz, V., Thiel, M., 2013. Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. Mar. Environ. Res. 87–88, 12–18. https://doi.org/10.1016/j.marenvres.2013.02.015.

Ivar do Sul, J.A., Costa, M.F., Barletta, M., Cysneiros, F.J.A., 2013. Pelagic microplastics around an archipelago of the Equatorial Atlantic. Mar. Pollut. Bull. 75, 305–309. https://doi.org/10.1016/j.marpolbul.2013.07.040.

Ivar do Sul, J.A., Spengler, Â., Costa, M.F., 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar. Pollut. Bull. 58, 1236–1238. https://doi.org/10.1016/j.marpolbul.2009.05.004.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771. https://doi.org/10.1126/science.1260352.

Kanhai, L.D.K., Gårdfeldt, K., Lyashevska, O., Hassellöv, M., Thompson, R.C., O'Connor, I., 2018. Microplastics in sub-surface waters of the arctic Central Basin. Mar. Pollut. Bull. 130, 8–18. https://doi.org/10.1016/j.marpolbul.2018.03.011.

Kanhai, L.D.K., Officer, R., Lyashevska, O., Thompson, R.C., O'Connor, I., 2017. Microplastic abundance, distribution, and composition along a latitudinal gradient in the Atlantic Ocean. Mar. Pollut. Bull. 115, 307–314. https://doi.org/10.1016/j.marpolbul.2016.12.025.

Katija, K., Choy, C.A., Sherlock, R.E., Sherman, A.D., Robison, B.H., 2017. From the surface to the seafloor: how giant larvaceans transport microplastics into the deep sea. Science Advances 3, e1700715. https://doi.org/10.1126/sciadv.1700715.

Kooi, M., van Nes, E.H., Scheffer, M., Koelmans, A.A., 2017. Ups and downs in the Ocean: effects of biofouling on vertical transport of microplastics. Environ. Sci. Technol. 51, 7963–7971. https://doi.org/10.1021/acs.est.6b04702.

Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D.W., Law, K.L., 2012. The effect of wind mixing on the vertical distribution of buoyant plastic debris. Geophys. Res. Lett. 39, L07601. https://doi.org/10.1029/2012GL051116.

Law, K.L., Morét-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the north atlantic subtropical Gyre. Science 329, 1185–1188. https://doi.org/10.1126/science.1192321.

Li, J., Qu, X., Su, L., Zhang, W., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016. Microplastics in mussels along the coastal waters of China. Environ. Pollut. 214, 177–184. https://doi.org/10.1016/j.envpol.2016.04.012.

Ling, S.D., Sinclair, M., Levi, C.J., Reeves, S.E., Edgar, G.J., 2017. Ubiquity of microplastics in coastal seafloor sediments. Mar. Pollut. Bull. 121, 104–110. https://doi.org/10.1016/j.marpolbul.2017.05.038.

Lo, H.S., Xu, X., Wong, C.Y., Cheung, S.G., 2018. Comparisons of microplastic pollution between mudflats and sandy beaches in Hong Kong. Environ. Pollut. 236, 208–217. https://doi.org/10.1016/j.envpol.2018.01.031.

Long, M., Moriceau, B., Gallinari, M., Lambert, C., Huvet, A., Raffray, J., Soudant, P., 2015. Interaction between microplastics and phytoplankton aggregates: impacts on their respective fates. Mar. Chem. 175, 39–46. https://doi.org/10.1016/j.marchem.2015.04.003.

Lots, F.A.E., Behrens, P., Vijver, M.G., Horton, A.A., Bosker, T., 2017. A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment. Mar. Pollut. Bull. 123, 219–226. https://doi.org/10.1016/j.marpolbul.2017.08.057.

Lusher, A.L., Tirelli, V., O'Connor, I., Officer, R., 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Rep. 5, 14947. https://doi.org/10.1038/srep14947.

Macdonald, R.W., Solomon, S.M., Cranston, R.E., Welch, H.E., Yunker, M.B., Gobeil, C., 1998. A sediment and organic carbon budget for the Canadian Beaufort Shelf. Mar. Geol. 144, 255–273. https://doi.org/10.1016/S0025-3227(97)00106-0.

Maes, T., Van der Meulen, M.D., Devriese, L.I., Leslie, H.A., Huvet, A., Frère, L., Robbens, J., Vethaak, A.D., 2017. Microplastics baseline surveys at the water surface and in sediments of the north-east Atlantic. Fron. Mar. Sci. 4, 135. https://doi.org/10.3389/fmars.2017.00135.

Mai, L., Bao, L.J., Shi, L., Wong, C.S., Zeng, E.Y., 2018. A review of methods for measuring microplastics in aquatic environments. Environ. Sci. Pollut. Res. 25, 11319–11332. https://doi.org/10.1007/s11356-018-1692-0.

Martin, J., Lusher, A., Thompson, R.C., Morley, A., 2017. The deposition and accumulation of microplastics in marine sediments and bottom water from the Irish continental shelf. Sci. Rep. 7, 10772. https://doi.org/10.1038/s41598-017-11079-2.

Mathalon, A., Hill, P., 2014. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova scotia. Mar. Pollut. Bull. 81, 69–79. https://doi.org/10.1016/j.marpolbul.2014.02.018.

Matsuguma, Y., takada, H., Kumata, H., Kanke, H., Sakurai, S., Suzuki, T., Maki, I., Okazaki, Y., Boonyatumanond, R., Zakaria, M.P., Weerts, S., Newman, B., 2017. Microplastics in sediment cores from Asia and Africa as indicators of temporal trends in plastic pollution. Arch. Environ. Contam. Toxicol. 73, 230–239. https://doi.org/10.1007/s00244-017-0414-9.

Mohamed Nor, N.H., Obbard, J.P., 2014. Microplastics in Singapore's coastal mangrove ecosystems. Mar. Pollut. Bull. 79, 278–283. https://doi.org/10.1016/j.marpolbul.2013.11.025.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112, 39–45. https://doi.org/10.1016/j.marpolbul.2016.09.025.

Natsuike, M., Nagai, S., Matsuno, K., Saito, R., Tsukazaki, C., Yamaguchi, A., Imai, I., 2013. Abundance and distribution of toxic *Alexandrium tamarense* resting cysts in the sediments of the Chukchi Sea and the eastern Bering Sea. Harmful Algae 27, 52–59. https://doi.org/10.1016/j.hal.2013.04.006.

Nel, H.A., Dalu, T., Wasserman, R.J., 2018. Sinks and sources: assessing microplastic abundance in river sediment and deposit feeders in an Austral temperate urban river system. Sci. Total Environ. 612, 950–956. https://doi.org/10.1016/j.scitotenv.2017.08.298.

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future. 2, 315–320. https://doi.org/10.1002/2014EF000240.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. 9, 1505. https://doi.org/10.1038/s41467-018-03825-5.

Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., Li, D., 2017. Microplastics in sediments of the changjiang estuary, China. Environ. Pollut. 225, 283–290. https://doi.org/10.1016/j.envpol.2016.12.064.

PlasticsEurope, 2016. In: PlasticsEurope (Ed.), Plastics - the Facts 2016: an Analysis of European Plastics Production, Demand and Waste Data. Brussels.

Qiu, Q., Peng, J., Yu, X., Chen, F., Wang, J., Dong, F., 2015. Occurrence of microplastics in the coastal marine environment: first observation on sediment of China. Mar. Pollut. Bull. 98, 274–280. https://doi.org/10.1016/j.marpolbul.2015.07.028.

Ryan, P.G., 2015. Does size and buoyancy affect the long-distance transport of floating debris. Environ. Res. Lett. 10, 084019. https://doi.org/10.1088/1748-9326/10/8/084019.

Sigler, M.F., Mueter, F.J., Bluhm, B.A., Busby, M.S., Cokelet, E.D., Danielson, S.L., Robertis, A.D., Eisner, L.B., Farley, E.V., Iken, K., Kuletz, K.J., Lauth, R.R., Logerwell, E.A., Pinchuk, A.I., 2017. Late summer zoogeography of the northern Bering and Chukchi seas. Deep-Sea Res. Part II 125, 168–189. https://doi.org/10.1016/j.dsr2.2016.03.005.

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E., Le Goïc, N., Quillien, V., Mingant, C., Epelboin, Y., Corporeau, C., Guyomarch, J., Robbens, J., Paul-Pont, I., Soudant, P., Huvet, A., 2016. Oyster reproduction is affected by exposure to polystyrene microplastics. P. Natl. Acad. Sci. USA. 113, 2430–2435. https://doi.org/10.1073/pnas.1519019113.

Taylor, M.L., Gwinnett, C., Robinson, L.F., Woodall, L.C., 2016. Plastic microfibre ingestion by deep-sea organisms. Sci. Rep. 6, 33997. https://doi.org/10.1038/srep33997.

Tekman, M.B., Krumpen, T., Bergmann, M., 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. Deep Sea Res Part 1. Oceanogr Res Pap. 120, 88–99. https://doi.org/10.1016/j.dsr.2016.12.011.

Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495–499. https://doi.org/10.1016/j.envpol.2013.08.013.

van Sebille, E., England, M.H., Froyland, G., 2012. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environ. Res. Lett. 7, 044040. https://doi.org/10.1088/1748-9326/7/4/044040.

Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. Microplastic particles in sediments of Lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. Estuar. Coast Shelf Sci. 130, 54–61. https://doi.org/10.1016/j.ecss.2013.03.022.

Welden, N.A.C., Cowie, P.R., 2016. Long-term microplastic retention causes reduced body condition in the langoustine, Nephrops norvegicus. Environ. Pollut. 218, 895–900. https://doi.org/10.1016/j.envpol. 2016.08.020.

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.J., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. Roy. Soc. Open Sci. 1 (4), 140317. https://doi.org/10.1098/rsos.140317.

Woodgate, R.A., Aagaard, K., Weingartner, T.J., 2005. A year in the physical oceanography of the Chukchi Sea: moored measurements from autumn 1990–1991. Deep-Sea Res. Part II 52, 3116–3149. https://doi.org/10.1016/j.dsr2.2005.10.016.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492. https://doi.org/10.1016/j.envpol.2013.02.031.

Yu, X., Peng, J., Wang, J., Wang, K., Bao, S., 2016. Occurrence of microplastics in the beach sand of the Chinese inner sea: the Bohai Sea. Environ. Pollut. 214, 722–730. https://doi.org/10.1016/j.envpol. 2016.04.080.

Zarfl, C., Matthies, M., 2010. Are marine plastic particles transport vectors for organic pollutants to the Arctic? Mar. Pollut. Bull. 60, 1810–1814. https://doi.org/10.1016/j.marpolbul.2010.05.026.

Zhao, S., Danley, M., Ward, J.E., Li, D., Mincer, T.J., 2017. An approach for extraction, characterization and quantitation of microplastic in natural marine snow using Raman microscopy. Anal. Methods 9. http://doi.org/10.1039/C6AY02302A.

Zhao, M., Wang, W., Liu, Y., Dong, L., Jiao, L., Hu, L., Fan, D., 2016. Distribution and sources of polycyclic aromatic hydrocarbons in surface sediments from the Bering Sea and western Arctic Ocean. Mar. Pollut. Bull. 104, 379–385. https://doi.org/10.1016/j.marpolbul.2016.01.016.

Zhao, S., Zhu, L., Li, D., 2015. Microplastic in three urban estuaries, China. Environ. Pollut. 206, 597–604. https://doi.org/10.1016/j.envpol.2015.08.027.

Zhao, J.M., Ran, W., Teng, J., Liu, Y.L., Liu, H., Yin, X.N., Wang, Q., 2018a. Microplastic pollution in sediment from the bohai Sea and the yellow sea, China. Sci. Total Environ. 640–641, 637–645. https://doi.org/10.1016/j.scitotenv.2018.05.346.

Zhao, S., Zhu, L., Gao, L., Li, D., 2018b. Chapter 2 - limitations for microplastic quantification in the ocean and recommendations for improvement and standardization. In: Zeng, E.Y. (Ed.), Microplastic Contamination in Aquatic Environments. Elsevier, pp. 27–49.

Zhao, S., Zhu, L., Wang, T., Li, D., 2014. Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence,

distribution. Mar. Pollut. Bull. 86, 562–568. https://doi.org/10.1016/j.marpolbul.2014.06.032.
Ziajahromi, S., Kumar, A., Neale, P.A., Leusch, F.D.L., 2017. Impact of microplastic beads and fibers on waterflea (Ceriodaphnia dubia) survival, growth, and reproduction: implications of single and mixture exposures. Environ. Sci. Technol. 51, 13397–13406. https://doi.org/10.1021/acs.est.7b03574.
Zobkov, M., Esiukova, E., 2017. Microplastics in Baltic bottom sediments: quantification procedures and first results. Mar. Pollut. Bull. 114, 724–732. https://doi.org/10.1016/j.marpolbul.2016.10.060.