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Profiling the Vertical Transport of Microplastics in the West Pacific Ocean and the East Indian Ocean with a Novel in Situ Filtration Technique

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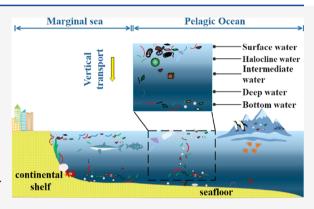
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ABSTRACT: A new technique involving large-volume (10 m³) samples of seawater was used to determine the abundance of microplastics (MPs) in the water column in the West Pacific Ocean and the East Indian Ocean. Compared to the conventional sampling methods based on smaller volumes of water, the new data yielded abundance values for the deep-water column that were at least 1–2 orders of magnitude lower. The data suggested that limited bulk volumes currently used for surface sampling are insufficient to obtain accurate estimates of MP abundance in deep water. Size distribution data indicated that the lateral movement of MPs into the water column contributed to their movement from the surface to the bottom. This study provides a reliable dataset for the water column to enable a better understanding of the transport and fate of plastic contamination in the deep-ocean ecosystem.



■ INTRODUCTION

Fueled by the consumption of oil, gas, and coal, the Anthropocene is characterized by problems such as climate change, environmental pollution, and biodiversity loss. Solid waste stands out among all the anthropogenic effects on the marine environment. The rising tide of plastic waste has caused a great alarm with the startling news of plastic accumulation in every corner of the planet. In light of the ever-increasing production of plastic materials,² these mismanaged plastics are being dispersed globally after improper disposal and could persist for centuries.3 Once they enter the ocean, some buoyant marine plastic debris initially accumulates with the currents in the ocean gyres.⁴ The Great Pacific Garbage Patch has increased 10-fold in size during the past decade, 5 indicating a rapid increase in the quantity of plastic debris at the ocean surface. Moreover, even on the deep-sea floor, all kinds of plastics have been found regardless of the density of these plastics.^{6–8} While it is commonly believed that the increasing load of microplastics (MPs) on the seafloor could be ascribed to the sinking of MPs from the surface, vertical transportation processes are poorly understood and rarely investigated. Therefore, the vertical distribution of MPs in the water column remains largely unknown, especially in the open ocean.

While there have been efforts made to investigate the distribution of MPs in the water column, 9-12 mechanisms of

transfer from the surface to the bottom have not been fully studied. The limited reports thus far are based mostly on the use of CTD (conductivity-temperature-depth) samplers to collect MPs from the water column. However, the CTD sampler is typically limited to a sample volume in the range of tens of liters per rosette.9 This sampling method cannot be used to collect a large enough volume (>1 m³) of water to represent reliable data from the deep sea. Furthermore, the heterogeneous distribution of MPs could lead to an overestimation or underestimation because of the small sample volume.¹³ In fact, the impact of sampling volume on MP quantification has been documented in previous studies, in which a higher volume of filtered water was recommended. 14-16 For instance, Tamminga et al. 13 observed inconsistent results for MP abundance with bulk sampling and manta trawl and concluded that bulk sampling, especially for low-volume samples, is insufficient for an accurate study of the abundance of MPs in the aquatic environment. In addition,

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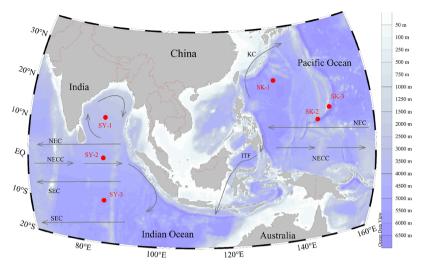


Figure 1. Geolocation of sampling stations in the IO and PO. In the figure, NEC, NECC, SEC, KC, and ITF represent the North Equatorial Current, North Equatorial Courter Current, South Equatorial Current, Kuroshio Current, and Indonesian Throughflow, respectively.

because much lower densities (number of plastic debris particles per unit volume of water) are expected in the water column relative to surface layers, as shown by Reisser et al. 17 and Tekman et al., 18 larger volumes of water are needed to obtain representative data. This vertical profile could be influenced by hydrographic conditions and sampling locations, but the scarcity of the available water column MP data makes it difficult to decipher vertical transport.

Two promising sampling devices (a multiple opening and closing net and a large volume water-transfer system) were used to collect MPs from the water column of the North Pacific Garbage Patch¹⁹ and the HAUSGARTEN Observatory. However, the multiple opening and closing net was unable to collect MP samples at the specified depth and the large volume water-transfer system could only be used to collect a limited volume (218–561 L) due to filtration efficiency and ship time. Overall, there have been few studies on the use of validated techniques for sampling MPs from the water column from the surface to the deeper environment. ^{14,15}

In our earlier study, in which we used a novel in situ filtration device (LVSF) to identify the transport mechanism of MPs from surface water to the seafloor, we validated the required volume (≥8000 L) of filtered seawater to obtain an accurate and precise quantification of MPs in the water column. ¹⁴ Based on this previous result, we sampled down to a depth of 4000 m in six water columns in the West Pacific Ocean (PO) and East Indian Ocean (IO). The sampling was done with an LVSF sampler with a sampling volume of 10,000 L per sample to obtain an accurate estimate of the abundance of MPs in the deep-water column.

■ MATERIALS AND METHODS

Sampling the Water Column in the PO and IO. From November 2018 to April 2019, we studied the vertical distribution of MPs in the water column of the PO and IO (Figure 1; Table 1). A plankton pump (KC Denmark A/S, Denmark) equipped with an external battery (24 V, 10 A/h) and pressure compensation was used to sample the water column. A schematic of the pump is shown in Figure S1. The pump takes up to $30 \text{ m}^3/\text{h}$ of seawater through a $60-\mu\text{m}$ screen that enables it to retain MPs present in the water (Table 2).

Table 1. Sampling Depth at Each Sampling Station

region	stations	sampling depth (m)
West Pacific Ocean	SK-1	2, 50, 400, 1000
	SK-2	2, 50, 200, 260, 500, 1000, 2000, 3000, 4000
	SK-3	2, 50, 100, 500, 1000, 2000
East Indian Ocean	SY-1	50, 100, 200, 500, 1000
	SY-2	50, 100, 200,500, 1000
	SY-3	50, 100, 200, 500, 1000

For every MP sample, 10,000 L of seawater was filtered during the sampling.

Based on the research by Sprintall et al., 20 ocean water layers can be divided into surface water (0-200 m), halocline water (200-600 m, within the halocline), intermediate water (600-1500 m, below the halocline), and deep water (1500-4000 m). We combined the thermohaline profile to categorize these sampled layers and detailed information is available in Table S2. Overall, we sampled a total of six stations (SK-1, SK-2, and SK-3) up to 4000 m depth in the PO and 2000 m in the IO (SY1, SY-2, and SY-3). The groupings of samples to assess MP abundances in different ocean layers are listed in Table S2. Replicate sampling was not conducted at every depth because of sea conditions and time constraints, which is common for pelagic MP investigation⁹ and other deep-sea research. However, our previous study confirmed the accuracy of the dataset when the sampling volume is higher than 8 m³ even without replicates. 14 Once retrieved, MPs collected in the net bag were thoroughly rinsed (Milli-Q water) into a collecting bottle with a stainless-steel water sprayer. The contents of the bottle were flushed with Milli-Q water into a clean container and stored at 4 °C.

MP Identification and Verification. Prior to counting MPs visually and under a stereomicroscope (Leica M165 FC, Germany), samples from the water column were pretreated by wet peroxide oxidation (WPO), as described by Masura et al. The MP samples were then filtered through a GF/A filter (1.60 μ m pore size, Whatman, UK) and stored in a glass desiccator for drying.

All the suspected MPs were tested using a micro-Fourier-transform infrared spectrometer (μ -FT-IR) instrument (Thermo Nicolet iN10, USA) by Liu et al. ¹⁶ and the spectra were analyzed using OMNIC 9 software with the associated

Table 2. Detailed Summaries (Sampling Methods, Sampled Depth, and Size) of MPs from Water Columns From the Literature and the Present Study

area division	sampling regions	methods	depth (m)	volume/sample (L)	mesh size of nets ^a or filters (sieves) ^b (μ m)	MP abundance (n/m^3)	MPs size (mm)
Coastal seas	Bohai sea, China ²⁵	CTD sampler	0-30	5	5 ^b	0-23,000	$0.10-3.00 \text{ (mostly)}^c$
	South China Sea, China ²⁶	CTD sampler/plexiglass water sampler	10-40	5	0.45 ^b	200-45,200	$0.02-0.33 (mostly)^c$
	Sumba coastal waters, Indonesia ²⁷	CTD sampler	5-300	10	0.45 ^b	0-120	0.30-1.00(mostly) ^c
	Baltic Sea, Russia ²⁸	Modified submersible pump	0.5-91	2500-3500	174 ^b	32.20 (mean) ± 50.40 (SD)	0.17-1.00(mostly) ^c
	Korean coastal waters ²⁹	submersible pump	3-58	100	20^b	10-2000	0.02-5.00
	HAUSGARTEN observatory ¹⁸	in situ filtration device	1-5350	218-561	32 ^b	0-1287	0.01-0.15
Pelagic ocean	Arctic Central Basin ¹⁰	CTD sampler	8-4369	7-48	250 ^b ; 1.20 ^b	0-375	0.25-5.00
	Mariana Trench ¹²	CTD sampler/lander system	2673-10,903	35-180	0.22^b ; 0.30^b	2060-13,510	$1.00-3.00 (mostly)^c$
	West Pacific and East Indian Ocean (present study)	in situ filtration device	2-4000	10,000	60 ^b ; 1.60 ^b	0.2-3.5	0.03-6.33

[&]quot;Mesh size of the net used in the reference. ^bMesh size of the filter or sieve used in the filtering process. ^cOnly the size range of MPs was included in the literature.

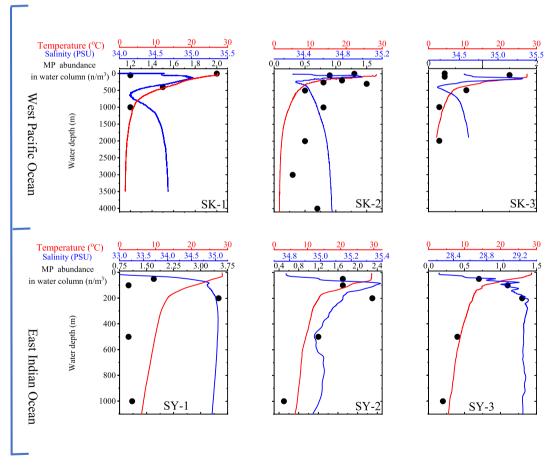


Figure 2. Vertical distribution of MPs in the water column of PO (SK-1, SK-2, and SK-3) and IO (SY-1, SY-2, and SY-3).

OMNIC spectra library. Samples were considered plastic only where the matching value to a plastic in the database was higher than 60%.

Contamination Control. *Purification of Filters, Glass-ware, and Experiment Vessels.* All the filters, stainless-steel tweezers, and glass vessels were wrapped with an aluminum foil

and heated at 450 °C overnight before use. Sample bottles were immersed in acid media (HCl/H₂O, volume ratio: 1:10) overnight and then washed with distilled water (resistivity: 9.5 M Ω ·cm, 25 °C) to neutrality. Afterward, the bottles were thoroughly rinsed 5–7 times with Milli-Q water (resistivity: 18.2 M Ω ·cm, 25 °C). All the solutions used in the study were

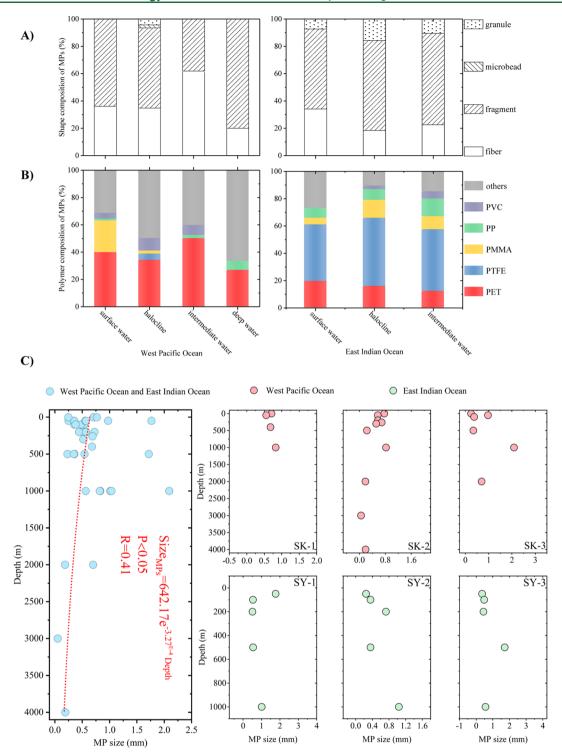


Figure 3. Shape (A), polymer (B), and size (C) compositions in different water layers of PO and IO. In (B), only the top five polymers of MPs by quantity are displayed. In (C), colored dots represent the average size of the MPs.

filtered with a GF/A glass microfiber membrane (Whatman, UK) prior to use. The net bag and collecting bottles for the plankton pump were carefully washed in the lab and dried on an SW-CJ-1FB-type ultraclean worktable (Sujing, Shaoxing, China).

Field and Procedural Blank during the Analysis. In the field, before every sampling, we thoroughly flushed the net on the plankton pump using a high-pressure stainless-steel sprayer containing prefiltered Milli-Q water. The residue in the

collecting bottle was preserved in a bottle similar to those containing the MP samples. The residue could be considered as the field blank and the following pretreatment (WPO) was identical to the analysis of MP samples. When MP samples were analyzed, the procedural blank was also performed using Milli-Q water to calibrate the potential contamination during indoor analysis.

Prevention and Assessment of Airborne Contamination. Once the samples were transferred to the laboratory, the pretreatment, identification, and verification of MP samples were performed in an ultraclean stainless-steel room with 24 h of air filtration (with an air shower before every entrance). Constant filtered clean air (0.22 μ m) was continuously blown in from the roof and this room was under positive pressure (around 14 Pa). Experimenters wore 100% cotton and nitrile gloves to prevent external contamination during the pretreatment and analysis procedures.

To assess contamination by airborne MPs, air samples were collected at the same time as the water samples using methods described by Liu et al.²² In addition, when the suspected MPs were examined and marked under the stereomicroscope, a blank filter was directly exposed to air to assess airborne contamination. In the end, only a number of pieces of orange-colored plastic microfibers were verified in the field blank, which was consistent with our observations of the air samples. However, no plastic contamination was found on the blank filter during laboratory analysis.

Statistical Analyses. The Kruskal–Wallis test was performed to compare the abundance of MPs in different layers and stations. Statistical significance and extreme difference were indicated with P < 0.05 and P < 0.01, respectively.

RESULTS

Mapping the Vertical Distribution of MPs in the Water Column. Analysis of field blanks revealed that the abundance of airborne MPs averaged 0.06 n/m³. These airborne MPs were all orange-colored PET [poly(ethylene terephthalate)] fibers, which were probably from the labor suits and life vests worn during the sampling effort. These fibrous MPs had smooth surfaces with relatively high transparency, which made them quite different from the oceanic MPs collected. Overall, a total of 136 orange-colored microfibers were excluded from the MP counts of the water samples.

Samples were collected using large-volume in situ filtration at various depths covering the eutrophic zone and the deep sea up to a depth of 4000 m from the surface. The abundances of MPs in SK-1, SK-2, and SK-3 were 1.2–2, 0.3–1.5, and 0.2–1.5 $\rm n/m^3$, with means of 1.48, 0.84, and 0.53 $\rm n/m^3$, respectively. The water-column MP abundances of SY-1, SY-2, and SY-3 were 1.0–3.5, 0.5–2.3, and 0.2–1.3 $\rm n/m^3$, respectively (Figure 2; Table S3).

The mean (± SD) value for the surface water of PO was 1.20 ± 0.57 n/m³; for the halocline water, it was 0.88 ± 0.45 n/m^3 ; for the intermediate water, it was 0.84 ± 0.52 n/m³, and for the deep water, it was 0.43 ± 0.22 n/m³ (see Table S2 for the layer category). The mean (± SD) value for the surface water at the IO site was $1.37 \pm 0.58 \text{ n/m}^3$; for the intermediate water, it was $1.28 \pm 1.04 \text{ n/m}^3$; and for the halocline water, it was 1.27 ± 0.38 n/m³. At both sampling regions, the highest abundance of MPs was detected in the surface waters. In general, no significant variation was found between different layers (surface water, halocline water, intermediate water, and deep water) by the Kruskal–Wallis test ($\chi^2 = 6.58$, df = 3, P >0.05). A similar trend of MP distribution was found in the water columns of PO (Kruskal–Wallis test, $\chi^2 = 5.58$, df = 3, P > 0.05) and IO (Kruskal–Wallis test, $\chi^2 = 0.43$, df = 2, P >0.05). In addition, there was no significant difference in MP abundance between the two sampled regions (Kruskal-Wallis test, $\chi^2 = 2.31$, df = 2, P > 0.05), but in PO, this vertical pattern varied greatly with the geolocation (Kruskal–Wallis test, χ^2 =

7.64, df = 2, P < 0.05). In general, the abundance of MPs decreased exponentially with increasing depth [MP abundance $(n/m^3) = 1.27e^{-depth(m)/1110} + 0.29$, r = 0.52, P = 0.006 < 0.01]. However, in a separate analysis of MPs, this pattern was observed in only half of the sampled water columns (SK-2, SY-2, and SY-3) (Table S4). In addition, a weak logarithmic relationship was statistically found between the water temperature (T, °C) and the MP abundance [MP abundance $(n/m^3) = 0.27 + 0.33 \log T$, r = 0.43, P < 0.01].

Morphological Characteristics. A total of 367 pieces of MPs was found in samples from the two regions (173 pieces from PO and 194 pieces from IO), as shown in Figure S3. Of these, fragments and fiber-shaped MPs comprised 61 and 25%, respectively. Fragment MPs dominated the samples at both sites, comprising 57 and 64% of the microdebris collected at PO and IO, respectively. Microbeads made up a minor fraction of the MPs (amounting to 1% in PO). Overall, in both regions, the abundance of fibrous MPs decreased with depth from surface water to halocline water, but then showed an increase in the intermediate water layer (Figure 3A). A higher proportion of MP fragments was found in deeper water compared to the upper layers. This pattern was also seen in IO.

The size range of MP particles in PO was $30.12-4559.73~\mu$ m with an average size of $668.36~\mu$ m. At IO, MPs ranged from $38-6330~\mu$ m with an average size of $645.14~\mu$ m (Figure 3C). The surface water at each location had a higher average size of MPs (711.51 \pm 616.15 μ m for PO and 826.46 \pm 1284.19 μ m for IO) compared to that in the deeper layers in the water column (PO: 482.20 \pm 285.15 μ m; IO: 589.54 \pm 794.53 μ m). Overall, the size of MPs decreased significantly as the sampling depth increased [size_{MPs} = 642.17 \times 10^{-3.27E⁻⁴} depth, r = 0.41, P < 0.05], and larger MPs were typically detected in the surface water (Figure 3C).

Polymer Composition of MPs. Overall, there were 25 MP polymer types identified (Table S5). PET, polytetrafluoroethylene (PTFE), poly(methyl methacrylate) (PMMA), polypropylene (PP), and polyvinyl chloride (PVC) comprised 72% of the total MPs from the six water columns. PET particles were prevalent in all water layers from PO to IO, but were less common in deep-ocean water (Figure 3B).

In the Pacific region, a higher amount of PVC microdebris was found in the halocline (9%) water and intermediate water (7%) compared to that in surface water (4%). The PMMA fragments were found only within the upper water environment of surface and halocline layers—23% in the surface layer and 2% in the halocline layer. In addition, PP particles were pervasive in surface (1%), intermediate (2%), and deep (7%) layers of the water column, with the exception of the halocline layer. A similar distribution of PVC and PP synthetic microdebris was found in the water column of IO. A relatively high amount of PVC and PP fragments was observed in the deep water of PO (7%) and the intermediate water of IO (23%). However, a different distribution of PMMA particles was found between PO and IO. Although high amounts (13%) of PMMA plastic microdebris were observed in the halocline water of IO, abundant PMMA fragments (23%) were verified in the surface water of PO.

DISCUSSION

Sampling and Analysis Methodology in the Water Column. Surface trawls (i.e., manta trawls and neuston trawls) can efficiently filter out MPs from hundreds of cubic meters of

water, providing a sufficient estimation of MPs (size: from 330 μ m to 5 mm) for further assessment. This sampling instrument has been widely used to collect neustonic MPs in the upper aquatic environment.²³ Even though MPs in the surface water have been well studied, little is known regarding their vertical distribution in the water column, especially for deeper environments. Although multinet trawls can collect MPs in the top 6 m of the water column, this method cannot be used in depths of thousands of meters.²⁴ In fact, there is little information on the vertical distribution of MPs in the ocean and their transport patterns due to the limitations of sampling methodologies and the amount of ship time required for sampling.

Recently, several researchers have attempted to collect MPs in the water column with CTD samplers. They reported exceptionally high values for MP abundance with high variation in these samples (Table 2), which yielded inconsistent results that cannot be compared with data from surface trawling. The huge differences in the abundance of collected MPs among sampling devices are shown in Figure 4 and summarized in Table S1. Sampling relatively low

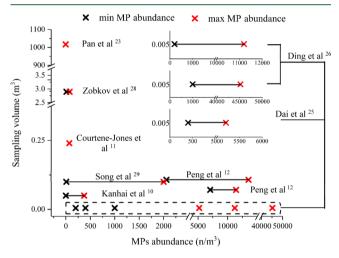


Figure 4. Comparison of the sampling volume and the MP abundance with bulk sampling in the water column. The x- and y-axes represent the MP abundance and the sampling volume, respectively. MP abundance in Pan et al.¹⁷ was investigated with a manta trawl. In the research by Courtene-Jones et al.,¹⁰ there was no replication and the black and red cross marks overlapped.

volumes of water using CTD samplers with Niskin bottles will yield highly variable estimates of MP abundance. The impact of sampling volume on MP quantification was pointed out in an earlier study that suggested that a sufficient volume of sampling water is critical to obtaining accurate estimates of MP abundance. Similarly, a recent study that investigated the vertical distribution of MPs in the water column of Monterey Bay stressed the importance of sampling volume. In that study, an in situ filtration device with a 100 μm mesh size was installed on a remotely operated vehicle to collect MPs at the 5–1000 m depth by filtering 1.0–2.4 m³ water for every sampling.

Another recent study indicated that net mesh size could be important for capturing the greatest amount of MPs in an aquatic environment, and that a smaller mesh size (100 μ m) used with a surface trawl could collect 10 times the amount of MPs that could be collected with a 500 μ m net.³⁰ However, when using bulk sampling, there were no significant impacts on

MP quantification even with finer pore size $(20-63 \ \mu m)$.³¹ Therefore, in the present study, we used an even smaller mesh size $(60 \ \mu m)$ and filtered 10 m³ water for every sampling, which should provide precise and accurate measurements of MP abundance in the open ocean.

Polymeric identification of MPs could also be a significant factor for the accurate study of MPs. To date, μ -FT-IR spectrometers allow for the rapid verification of the presence of MPs, but typically, this instrument only enables the identification of the polymeric composition of MPs that are larger than 10 μ m in size. Smaller MPs could be underestimated because of technical limitations. Recently, a μ -FT-IR spectrometer with focal plane array sensors was applied to verify the polymer types of MPs^{18,32} This technique can automatically image most particles (typically with sizes >5 μ m, e.g., Bruker LUMOS II) retained on the filter. This promising technique could be an effective tool for a follow-up study and merits further evaluation.

Comparison of MP Distribution with Similar Research. The prevalence of MPs was observed throughout the water column (2-4000 m) of PO and IO and was found to range from 0.2 to 2.0 n/m³ (PO) and from 0.2 to 3.5 n/m³ (IO). Our data are consistent with previous findings in the greater Monterey Bay, where the abundance of MPs in the water column (5-1000 m) ranged from 0 to 15 n/m³ with a higher abundance of MPs also found within the upper layers. S This current investigation with the LVSF confirmed our expectation that the actual abundance of MPs in the water column is lower compared to that in the surface water. Table 2 shows the depth-dependent counts of MPs obtained in this study and those reported for the water column at different locations in previous reports. The disparity between our results and the published data on MP abundance in the water column is at least 1-2 orders of magnitude. The estimate for the Mariana Trench by Peng et al., ¹² for instance, was 2.06–13.51 n/L at a depth from 2673 to 6804 m, which is several orders of magnitude higher than our findings. Similarly, Kanhai et al. 10 reported MP abundance in the Arctic Central Basin (0–375 n/ m³) that is 2 orders of magnitude greater than that found in the present study. In their study, the highest MP abundance $(0-375 \text{ n/m}^3)$ was also reported in the polar mixed layers of the Arctic Ocean, followed by the deep and bottom waters (0– 104 n/m^3). However, Song et al.²⁹ found that more MPs were detected in the middle $(423 \pm 342 \text{ n/m}^3)$ and bottom $(394 \pm$ 443 n/m³) water layers of sampling sites in Korean coastal waters. A CTD sampler was used to collect deep-water (2220 m) samples in the Rockall Trough¹¹ and found microplastic abundance at 70.8 n/m³, which was also an order of magnitude higher than that in our study. Clearly, differences in sampling methodology, especially the sampling volume of filtered water, inevitably affects the abundance data. A validated, consistent, and reliable sampling protocol is urgently needed to accurately quantify MPs in the water column.

Characteristics of MPs in the Water Column. The physico-chemical properties of MPs in the water column are of great importance to determine their vertical distribution pattern. The sources of MPs found in deep water are not entirely clear, but they are likely derived from floating and beached debris. The fragmentation of plastic debris through exposure to solar ultraviolet radiation and mechanical abrasion generates MPs.³³ Fragmentation processes may be accelerated by organisms ingesting the MPs.³⁴ Significant amounts of fibers can reach ocean waters from inland environments via wind and

atmospheric deposition.²² The specific sources of observed polymers were hard to determine, but their origin can generally be traced according to their usage. Fibrous and fragmented MPs comprised the majority of total MPs in this investigation, which is consistent with previous findings.^{10,29} However, low-volume bulk sampling in previous studies reported the dominant shape of MPs in the water column to be fibrous.^{10,25–27} PTFE plastic has been widely applied to industrial products as an antiabrasive or a protective layer. Interestingly, we found a higher proportion of PTFE MPs in the water column of IO, which could be derived from the fragmentation of floating electronic debris or coatings applied on ships.

The diversity of polymers found in this study (25 different kinds) was higher than that published in previous literature. 9-12 The dominant polymers (PET, PTFE, PMMA, PP, and PVC) of MPs in our study were consistent with similar studies using an in situ filtration device in the water column of Monterey Bay. The numerical fraction of PET microdebris found in this study was higher than that reported by Choy et al.9 Forty percent of the total MP particles in the PO water column were assigned to the "others" category. These polymers [polyethylene, alkyd resin, polyacetal, polyamide, polyethylene-PP copolymer, epoxy resin, polystyrene, polybutylacrylate, poly(butyl methacrylate), polyester, poly(methyl acrylamide), phenoxy resin, phenol resin, PP-polyethylene copolymer, ethylene vinyl acetate, polyacrylamide, poly(ethyl/ acrylate), polyether polyurethane, poly(vinyl acetate/ethylene) and poly(vinylidene fluoride)] were detected individually in water samples in very small amounts. They were found as either only one piece or in a single layer of the water column, and for this reason were ascribed to "others" during the

Although the density of PP is lower than that of seawater, these particles were still identified within all the sampled water layers. A similar trend was also observed for the denser particles (PET, PMMA, PTFE, and PVC), so the MP trends appeared to have few connections with polymer density. This observation is consistent with the recent investigation conducted around the HAUSGARTEN Observatory. 18 It seems that the density of polymers has a limited influence on their vertical movement. This phenomenon was also observed by Dai et al., 25 who found that low-density plastic microdebris could still be identified in deeper environments. The vertical displacement of PP particles to deep-water layers is complex and likely influenced by multifactorial hydrodynamics (i.e., Ekman pumping, upwelling and downwelling, convection cells, and Langmuir circulations).³⁵ Moreover, fouling is also known to increase the density of plastics, facilitating the sinking process.³⁶

PET plastics were found at all depths in substantial quantities at the PO site, and a similar trend was found for PTFE at the IO site (Figure 3B). Generally, at both sites, the amount of MPs denser than seawater (usually 1.02 g/cm³), such as PVC (1.3–1.45 g/cm³) and PMMA (1.17–1.20 g/cm³), was higher in the halocline and intermediate water compared to the surface water layer. However, at the PO site, more PMMA plastics were found in the surface layer (23%) than the lower layers (2%). The composition of surface-water MP debris is very different from that in deep-water layers. This was expected because lateral currents may not allow direct vertical sinking of surface debris.

Transport Mechanism of MPs from the Surface to the Deep Ocean. The floating MPs in the surface layer are assumed to aggregate with debris and undergo fouling that increases their density.³⁶ They then gradually sink to the deep layers of the water column. Previous studies have proposed the selective removal of floating plastics and that larger pieces of plastic debris would sink to the seafloor more quickly than smaller pieces,³⁷ which, having a less surface area, would be suspended in the water column for an extended time and sink more slowly.³⁸ We found that the size of MPs decreased significantly as the sampling depth increased; larger MPs were typically detected in the surface water. This phenomenon could possibly result from the combined effect of hydraulic conditions, biofouling, and the properties of the MPs. This complex combination would be difficult to interpret. Some researchers have speculated that there is a vital contribution from physically based parameterizations of MPs. For instance, Chubarenko et al.³⁹ proposed that the increasing ratio of surface area to volume could be an important factor in the rapid sinking of smaller MPs (i.e., slightly buoyant MPs) due to the biofouling effect. He also proposed that the surface area of fibrous MPs meant they could be more easily attached by biofilms than spherical MPs. In addition, Kanhai et al. 10 reported that the abundance of MPs at a given depth in the water column could be affected by the temperature, salinity, and hydrostatic pressure. During their investigation, the latitude, temperature, and salinity at the sites were found to be closely related to the abundance of MPs at various sampling depths. Isobe et al. 40 described the vertical abundance of MPs in terms of an exponential distribution that was inferred from macroplastics in the surface water.⁴¹ However, the upper mixed layer above the halocline can often have a higher concentration of MPs than the surface layer.

The MPs sampled in the water column could include not only particles moving downward from the surface but also particles from other regions laterally transported by underwater circulation. A Lagrangian particle-tracking algorithm has been applied to trace the origin of MPs from different layers. Their polymer composition could influence their pathway to deeper environments. Although this complicated scenario is too complex to model, it still merits further investigation.

Size distribution also suggested that the abundance of MPs in deep-water layers is not derived entirely from the direct settling of MPs from the surface layers of water via simple vertical movement of surface MPs in the water column. We believed that the pycnocline could be another significant factor influencing the MP distribution in the water column because most of the MPs would be temporally intercepted in this layer. Smaller MPs could be subjected to hydraulic force and more easily penetrate the density barrier of salinity and thermal variation. This theory can be confirmed by data from five water columns (SK-2, SK-3, SY-1, SY-2, and SY-3) sampled in the current investigation, in which the abundance of MPs above the halocline was higher than at the surface. A similar finding was also observed in the water columns of the Baltic Sea, where the vertical pattern of MPs was influenced by the thermohaline structure and pycnocline layers, which could hinder the sinking of MPs from surface water.²

This study pioneered the use of a novel and tested sampling technique to investigate MP abundance in the deep-water column (up to 4000 m) of the PO and IO. A total of 350 m³ water (10 m³ per sample) was sampled in this study, which is the largest volume sampled in any study of the ocean water

column. Given the high variability in the abundance of MPs in the water column, the present study estimated MP abundances that are at least 1–2 orders lower than those previously reported. This study is expected to provide a reliable dataset on MP abundance that can assist global policy makers in ecological risk assessments related to MPs in the marine environment.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c02374.

Function diagram of the plankton pump used in the study; relationship between the sample volume and MP abundance in the study; photos of representative MPs observed in this study; sampling volume and numerical proportion of the fibrous MPs in the water column; sampling layer categories in the study; raw dataset of MPs in every sampled water column; vertical profiles of MP abundance $(A, n/m^3)$ with sampling depth (depth, m); and abbreviation, quantity, and density of detected MPs in the water column and benthic sediments (PDF)

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Author Contributions

D.J.L., K.L., C.J.L., and G.Y.P. equally contributed to this work and all ranked the first author of this manuscript. This research and manuscript writing were conceived and instructed by D.J.L.; K.L. analyzed MPs in the water column of West Pacific Ocean and wrote the major part of manuscript in discussion with D.J.L.; C.J.L. helped analyze MPs in the water column of East Indian Ocean; G.Y.P. reviewed and revised the initial draft; A.A. provided the linguistic improvement and invaluable suggestions on this manuscript; analytical modeling was established with the help of W.T., Z.Z., and W.H.; M.Y.B., L.Z., and J.P.X. helped analyze the partial samples; X.H.W., Z.Y.S., F.Z., C.X.Z., F.Z., J.Y.X., and W.N. provided essential aid to the field work in the East China Sea; L.W. and S.Y.C. helped contact and rent the scientific ship in the East China Sea. W.Z. provided some suggestions on this study.

Notes

The authors declare no competing financial interest.

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