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Microplastics in the tropical Northwestern Pacific Ocean and the Indonesian seas

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ABSTRACT

The abundance of microplastics fragments with sizes larger than 0.30–0.35 mm is measured during two research cruises in the tropical Northwestern Pacific Ocean and inside the Indonesian seas. The fragments are confirmed to be primarily nylon, polyester, and polyethylene etc. microplastics in the western Pacific by Fourier transform infrared spectroscopy (FT-IR), whereas dominated by polyethylene in the Indonesian seas based on Raman spectrum analyses. The abundance of the microplastics is found to be very low (<0.018 particles m^{-3}) in the surface waters of the North Equatorial Current and the Kuroshio, suggesting no westward extension of the Great Pacific Garbage Belt and lack of microplastics accumulation due to mass convergence in the western boundary current. The abundances of the microplastics in the Makassar Strait of the Indonesian seas are found to be higher by an order of magnitude than those in the Northwestern Pacific, believed to be due to river run-offs carrying microplastics from nearby lands. The largest microplastics abundance is found in the northeastern Maluku Sea, where concurrent current measurements suggest a branch of the Indonesian Throughflow bringing accumulated microplastics from the eastern Indonesian seas into the convergent area of multiple strong currents. The study underlines the importance of ocean circulation in the microplastics distributions and transportation, and suggests the importance of high-resolution spatial mapping in the budget analysis of global microplastics distribution.

1. Introduction

The invention of plastics and the development of its industry have facilitated human lives tremendously. It also brings damage to the environment of the human being. Literally, every piece of plastic products produced by humans since the 1950s still exists in the earth environment today, since plastics last for 400 to 1000 years (Fowler, 1987). Many of them have come into the ocean in different ways (Carpenter et al., 1972; Carpenter and Smith, 1972). The situation has received intensive attention lately. The drifting plastic garbage in the North Pacific Ocean was reported first by Day et al. (1990). The Great Pacific Garbage Patch was named by Captain Charles Moore to refer to a zone of the size of the state of Texas in the Pacific Ocean between Hawaii and California that has a high concentration of plastic wastes (Moore et al., 2001, 2002; Moore, 2008). These plastic fragments are suggested to generate serious problems to the marine ecosystem (Derraik, 2002; Page et al., 2004; Arthur et al., 2009; Andrady, 2011; Tanaka and Takada, 2016).

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Microplastic fragments of 0.3–5 mm diameters have great influence on the ecosystem we are living in because of their similarity to zooplankton or young fish. Animals from zooplankton to giant blue whales in the ocean eat plastic fragments as baits, which will pass through the food chain to human's dining tables. The ratio between the floating microplastics and zooplankton mass has been reported as high as 6:1 in the North Pacific, and can be up to 30:1 in some areas of the ocean (Moore et al., 2001). However, the studies of microplastics in the oceans are based on very scarce data and are at the inventory level (Isobe et al., 2019). Very few processes of the microplastics distributions and concentrations are known at present.

To date, microplastics research in the western Pacific Ocean is limited to estuaries or nearshore areas, showing high concentrations of microplastics (Zhou et al., 2011; Zhao et al., 2014). In the open ocean, we hypothesize that leakage from the North Pacific Garbage Patch could be transported westward by the North Equatorial Current (NEC) so that the microplastics abundances in the western boundary currents could rise significantly due to mass and materials convergence. The accumulation of the microplastics due to surface Ekman current convergence in basin-scale gyres has been suggested by existing studies (see van Sebille et al., 2020 and the references therein). So far, only a few studies of the microplastics abundances in the western Pacific Ocean have been reported (Uchida et al., 2016; Isobe et al., 2019; Pan et al., 2019a; Liu et al., 2021). None of them has focused on the areas near the western boundary or inside the Indonesian seas.

The microplastics abundances inside the Indonesian seas are unknown to date. Existing microplastics measurements were mainly conducted in the Java Islands and has focused primarily on coastal waters, with most articles not carrying out the polymer identification (Manullang et al., 2023). The area is occupied by an important branch of the Great Ocean Conveyer Belt — the Indonesian Throughflow (ITF in abbreviation; Gordon, 1986; Sprintall et al., 2009, 2019; Gordon et al., 2019), which carries heat, freshwater, as well as affluences like microplastics, around the world oceans. It is important to measure the microplastics abundances in the far western Pacific Ocean and the Indonesian seas and investigate the roles of ocean circulation in redistributing the microplastics.

The ocean circulation in the northwestern Pacific Ocean is dominated by the NEC splitting off the east Philippine coasts, forming two strong western boundary currents, the northward Kuroshio and the southward Mindanao Current (MC) (Hu et al., 2015). The MC mainstream retroflects at the entrance of the Indonesian seas and meets with the New Guinea Coastal Current (NGCC) to form the beginning of the North Equatorial Counter Current (NECC) (Fig. 1). About 12–13 Sv (1 Sv = $10^{6}\ \mathrm{m}^{3}\ \mathrm{s}^{-1}$) of the MC leaks into the Indonesian seas and feeds into the main flow of the ITF in the Makassar Strait, which exits into the Indian Ocean through the straits in the Nusa Tenggara Island chain (Sprintall et al., 2009). In the Maluku Channel in the northeastern Indonesian seas, a recent study based on in situ mooring measurements has suggested that about 1.0 Sv of Indonesian sea waters is transported back to the Pacific to join the NECC in the upper 300 m (Yuan et al., 2018). The roles of these ocean currents in the distributions of the microplastics are not known at present.

In this study, we report the microplastics abundances in the NEC, the

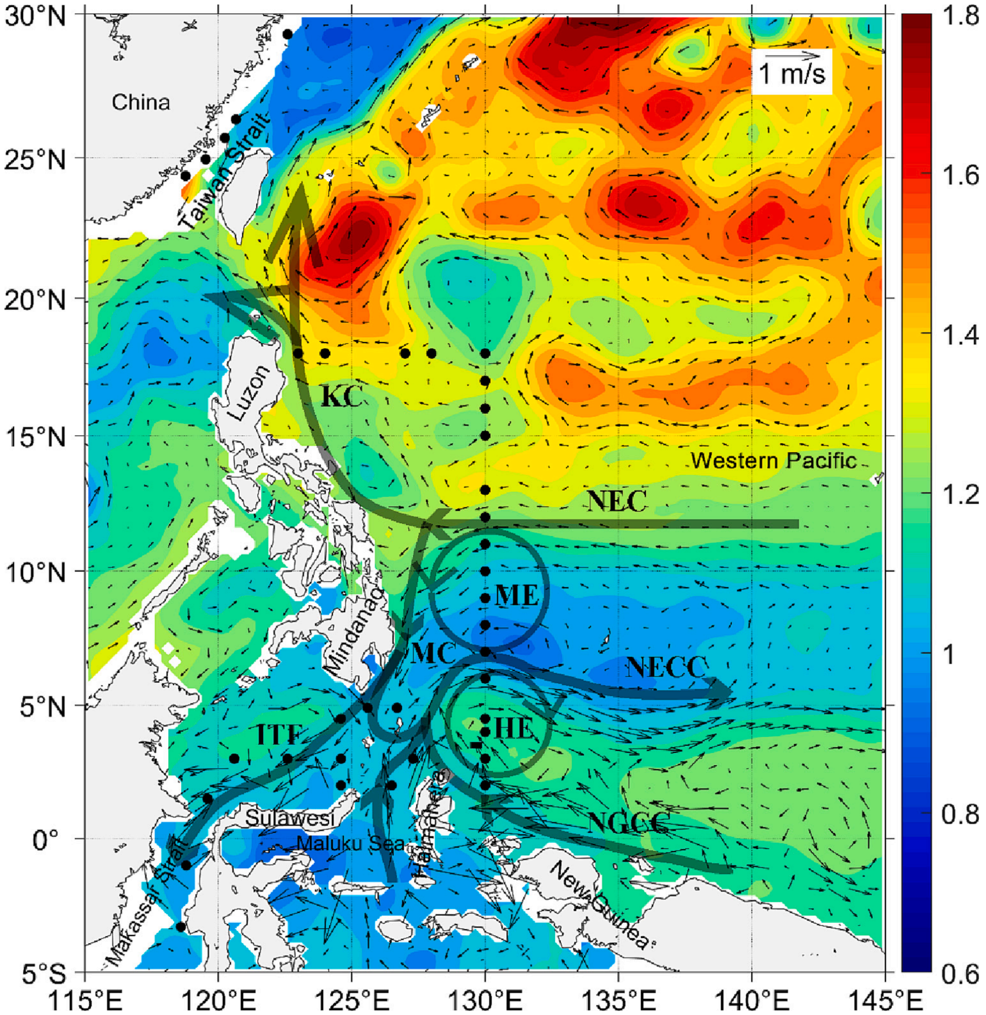

Fig. 1. Mean absolute dynamic topography (shading, unit: m) and OSCAR surface geostrophic velocity (vector) during the 2017 western Pacific cruise from October 17th to November 12th. Black dots denote the microplastics trawling stations. The curved arrows stand for the North Equatorial Current (NEC), North Equatorial Countercurrent (NECC), Kuroshio (KC), New Guinea Coastal Current (NGCC), Mindanao Current (MC), and Indonesian Throughflow (ITF). Two mesoscale eddies the Mindanao Eddy (ME) and Halmahera Eddy (HE) are also drawn in the schematic current system.

western boundary currents, and inside the Indonesian seas based on trawling measurements during two microplastics surveys in the western Pacific Ocean and inside the Indonesian Seas in the fall of 2017. The distribution dynamics of the areal microplastics abundance are investigated using synchronous measurements of ocean currents.

2. Material and methods

2.1. Microplastics sampling and analysis

The western Pacific Ocean cruise was conducted onboard the R/V "KEXUE" during October 15 through November 16 of 2017 by the Institute of Oceanology of the Chinese Academy of Sciences. The cruise is one of the annual expeditions of the western Pacific Open Research Cruises, funded by the National Natural Science Foundation of China. Conductivity-temperature-depth (CTD) profiles were measured along the 18°N and 130°E sections (Fig. 1). Microplastics samples were collected using a single Bongo zooplankton net with a mesh size of 0.2 mm and a round mouth of 80 cm diameter trawled on the sides of the vessel. The net has a Hydro-Bios current meter (type 438115) at the mouth to measure the volume of filtered waters and was trawled at the speed of 3 knots for 10–15 min. The upper net barely sticked out above the sea surface during the trawling so that the surface microplastics were collected with the volume of the sampling water estimated. On the same cruise, the microplastics was also sampled by another team using a Manta net trawled behind the research vessel, with a mesh size of 330 μm, a height of 0.5 m, and a width of 1 m (Liu et al., 2021). The Manta net sampling volume was estimated based on the ship speed, multiplied by the sampling time, width and averaged sampling height of the trawl. The microplastics abundances of the two sampling methods are similar (see later), suggesting the validity of our measurements.

Trawling was also conducted near the coasts of the southern China at the beginning of the cruise to collect data for comparisons. During the entire cruise, a Ship-board Acoustic Doppler Current Profiler (SADCP) is powered on to measure the upper ocean velocity profiles up to ~160 m depths.

The trawl net was rinsed from outside to wash everything inside the net to a collection tube attached to the end of the net, before the content in the collection tube was transferred to a glass bottle for further processing. The collected samples were immediately frozen in a refrigerator after the collection and were processed in the laboratory after the cruise. In the laboratory, they were filtered with a mesh of 0.35 mm size and washed with deionized waters for easy recognition. The microplastics were measured and visually examined under a Leica M125 stereomicroscope and were sent to a specialized laboratory in the Sun Yet-Sen University for Fourier transform infrared spectroscopy (FT-IR) analysis to identify their composition. Due to the small number of microplastics fragments left on the 0.35 mm mesh, the counting and processing of the samples were easily handled following the above procedure (Table 1).

In 2017, another cruise almost concurrent to the western Pacific cruise was conducted inside the Indonesian seas using the Indonesian R/V Baruna Jaya VIII during September 15 through November 15 of 2017. The cruise is one of the annual joint cruises between the Research Center for Oceanography of Indonesian Institute of Sciences (now belongs to BRIN) and the Institute of Oceanology of the Chinese Academy of Sciences, as an effort to maintain the Indonesian seas part of the WPOC-ITF mooring arrays constructed since 2014 (Fig. 2). Hydrography and SADCP measurements were conducted along the route of the cruise. The same trawling using the Bongo zooplankton net with a mesh size of 0.2 mm was also conducted along the main stream of the ITF, i.e., from the Sulawesi Sea and the northern Maluku Sea to the Makassar Strait.

Due to the high biomass concentrations in the marginal seas, the samples collected inside the Indonesian seas were processed slightly differently from those of the western Pacific. The sampling was processed by adapting the method from Lippiatt et al. (2013) and Michida et al. (2019). The samples were stored in 1000 ml sterile beaker glasses and filtered with a stainless steel filter with a mesh size of 0.5 mm and 0.3 mm, sequentially, which were then closed using a ParaFilm® sealing film stored at 4 ± 2 °C.

Table 1
Microplastics abundance for 2017 cruises.

No.	Station	Longitude	Latitude	Filtered water volume (m^3)	Total MPs	Abundances (particles m^{-3})
1	WP01	122.6° E	29.3° N	232.0	8	0.034
2	WP02	120.6° E	26.3° N	176.3	2	0.011
3	WP03	120.2° E	25.7° N	98.9	1	0.010
4	WP04	119.5° E	24.9° N	114.6	1	0.008
5	WP05	118.7° E	24.3° N	119.9	1	0.008
6	WP06	123.0° E	18.0° N	251.3	1	0.004
7	WP07	124.0° E	18.0° N	247.7	0	0.000
8	WP08	127.0° E	18.0° N	375.9	0	0.000
9	WP09	130.0° E	15.0° N	333.4	0	0.000
10	WP10	130.0° E	13.0° N	217.2	0	0.000
11	WP11	130.0° E	12.0° N	233.7	0	0.000
12	WP12	130.0° E	11.0° N	126.3	0	0.000
13	WP13	130.0° E	10.0° N	144.7	0	0.000
14	WP14	130.0° E	9.0° N	117.9	0	0.000
15	WP15	130.0° E	8.0° N	131.7	0	0.000
16	WP16	130.0° E	7.0° N	133.4	0	0.000
17	WP17	130.0° E	6.0° N	171.9	1	0.005
18	WP18	130.0° E	4.5° N	99.8	0	0.000
19	WP19	130.0° E	4.0° N	162.1	0	0.000
20	WP20	130.0° E	3.0° N	119.5	1	0.008
21	WP21	130.0° E	2.0° N	74.5	7	0.095
22	WP22	130.0° E	16.0° N	196.6	1	0.005
23	WP23	130.0° E	17.0° N	217.8	1	0.005
24	WP24	130.0° E	18.0° N	108.5	2	0.018
25	WP25	128.0° E	18.0° N	169.7	0	0.000
26	INA01	126.5° E	2.0° N	152.5	15	0.100
27	INA02	127.3° E	3.0° N	137.8	24	0.170
28	INA03	126.7° E	4.9° N	223.3	9	0.040
29	INA04	125.6° E	4.9° N	215.9	3	0.010
30	INA05	124.6° E	4.5° N	259.4	21	0.080
31	INA06	124.6° E	3.0° N	166.0	12	0.070
32	INA07	124.6° E	2.0° N	130.3	2	0.020
33	INA08	122.6° E	3.0° N	215.2	2	0.010
34	INA09	120.6° E	3.0° N	150.3	2	0.010
35	INA10	119.6° E	1.5° N	225.3	2	0.010
36	INA11	118.8° E	1.0° S	125.2	0	0.000
37	INA12	118.6° E	3.3° S	189.6	3	0.020

The laboratory analysis began with implementing a wet peroxide oxidation procedure for biological digestion (Lippiatt et al., 2013; Claessens et al., 2011; Mohamed Nor and Obbard, 2014; Masura et al., 2015; Suaria et al., 2017; Thompson et al., 2004; Zhang et al., 2015; Zhao et al., 2014; Cordova et al., 2019, 2020, 2021). In sterile conditions, the samples were dried at 60 °C for 24 h in an oven and were then heated with a water bath (B-One waterbath DWBC-30L6H) at 60 °C for 24–48 h after adding 3–5 ml of 30% H_2O_2 (Merck Millipore, Emprove® Essential Medical). This treatment aimed to digest organic materials while keeping the microplastics. The samples were then transferred to a filter paper (sterile cellulose nitrate Whatman filter paper Ø47 mm, pore

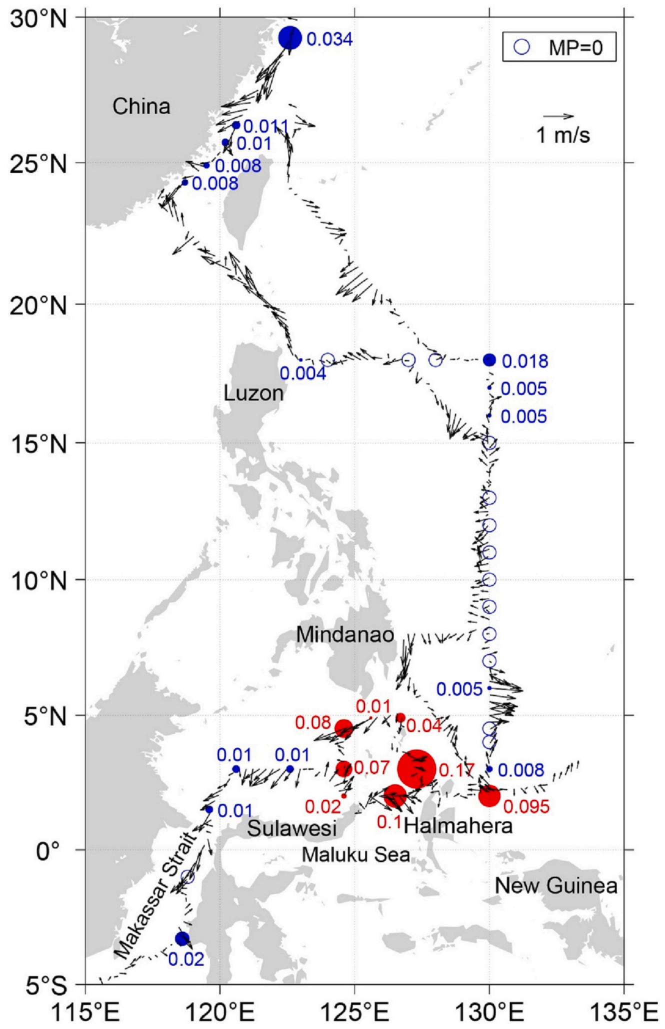

Fig. 2. Microplastic abundances in the western Pacific Ocean and the SADCP velocity at about 15–18 m depth of the ocean. Unit is particles m^{-3} for microplastics abundances. Notice the difference size scales of the blue and red dots, the former being enlarged by 3 times to enhance visibility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

size 0.45 μm) and were covered by a sterile petri dish at room temperature for shape, size, and polymer analysis (Table 1).

The shapes and sizes of microplastics were identified using a stereomicroscope (Leica M205C with a camera Leica IC90 E) to consist of fiber and fragments. The size category was divided into 300–500 μm and 500–1000 μm. No microplastics larger than 1000 μm were found in the filtered samples. After manual identification, micro-Raman (Renishaw inVia™ Qontor® confocal Raman microscope) analysis was applied to the microplastics randomly chosen (55.79%, $n = 53$ of the 95 recovered microplastic fragments) to obtain the functional group analysis of the particle polymer (Table 2). Our measurement procedures have met the requirements in the GESAMP (2019) guidelines (using a plankton net with a flowmeter for sampling and spectrometry such as FT-IR and Raman for ingredient analyses, http://www.gesamp.org/publications/guidelines-for-the-monitoring-and-assessment-of-plastic-litter-in-the-ocean).

Table 2
Functional group analysis result using micro-Raman (53 of the 95 fragments collected).

No.	Polymer type	Total	%
1	Polyethylene	32	60.38
2	Polyethylene terephthalate	15	28.30
3	Polypropylene	3	5.66
4	Polyvinyl chloride	2	3.77
5	Nylon 6/10	1	1.89
Total		53	100

Preventive methods suggested by Nuelle et al. (2014), Cordova et al. (2021), Nurhasanah et al. (2021), and Suteja et al. (2021) were employed to avoid contamination by airborne microplastics during the sampling and storage processes by wearing 100% cotton clothing, covering the container with aluminum foil whenever possible, avoid using plastics in the process and using all non-plastic equipment. The container and the film were rinsed thrice with double-distilled deionized water to control the potential release of microplastics from the sealing film. A procedural blank was also performed in the laboratory (Lusher et al., 2017; Cordova et al., 2019, 2020, 2021). No plastic fragments were found in the blank procedure, implying no airborne microplastics contamination during laboratory processes.

2.2. *Satellite altimeter sea level data and surface velocity data*

The satellite altimeter products are collected by the Data Unification and Altimeter Combination System (DUACS) and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS, http://marine.copernicus.eu/). The data cover the global ocean on a grid of 0.25° longitude by 0.25° latitude from January 1993 to present. The product is merged from all altimeter missions, including HY-2A, Jason-2, Topex/Poseidon, Envisat, ERS-1/2, etc.

The Ocean Surface Currents Analyses Real-time (OSCAR) provides ocean surface horizontal velocity which is directly estimated from satellite data and in situ observations (Bonjean and Lagerloef, 2002). The data is on global 1/3° grid with a 5-day resolution dating from 1992 to present day. The OSCAR velocity data can be accessed via http://apdrc.soest.hawaii.edu/datadoc/podaac_oscar.php.

2.3. *SADCP data*

The SADCP instrument fixed on the hull of R/V “KEXUE” is a 300 KHz WorkHorse Mariner product manufactured by the TRDI company of the U.S. It measured the upper ocean velocity profile for 80 bins with 2.0 m interval. Its first bin measured near-surface ocean current at about 8–11 m depth.

Hydrography profiles and upper ocean currents were measured by the Sea-Bird 911plus CTD and the U.S. TRDI 75 KHz SADCP during the Indonesian seas cruise. The SADCP measured ocean current profiles for 128 bins with 5.0 m intervals, and its first bin located at about 15–18 m depth.

The SADCP data were post-processed using Common Ocean Data Access System (COADS) software, including calibration and quality control (https://currents.soest.hawaii.edu/docs/adcp_doc/index.html), to compute the absolute current velocity relative to the ground. In this study, we use the velocity data at about 15–18 m to depict near-surface ocean circulation pattern along the route of the two cruises (Fig. 2).

2.4. *Surface drifter trajectories*

The surface drifters released during the 2017 western Pacific cruise were manufactured by the Chinese Xiaolong Instruments Co. Ltd., the design of which follows the World Ocean Circulation Experiment (WOCE) standards. The drifters return their locations at 8-h intervals.

The SADCP data and the drifter trajectory data are available online at http://itf.qdio.ac.cn/xzlxz/202103/t20210322_629720.html.

3. Results

3.1. Microplastics abundances in the western Pacific

A total of 25 stations have been chosen to conduct microplastics trawling. Except in the area near the China coasts, the microplastic fragments collected by the surface net are very few in the western Pacific (Table 1). Of the 20 stations in the 18°N and 130°E sections, only 7 stations have found fragments of microplastics larger than the 0.35 mm mesh. The trawling at the two stations inside the Kuroshio in the 18°N section off the east Luzon coasts have shown microplastics larger than 0.35 mm only in the station nearest to the coast, with the abundances as low as in the 130°E section, suggesting that the convergence of the water mass near the western boundary does not generate significantly high abundance of microplastics (Fig. 2). The largest abundance in the 130°E section is found in the southernmost station, off the New Guinea coasts and east of the Halmahera Island, suggesting the coastal influence. The microplastics abundance of our measurements in the 130°E section is similar to the measurements of 0.02–0.1 particles m^{-3} using a Manta net on the same cruise (Liu et al., 2021). Given that only a few fragments of microplastics larger than the 0.35 mm were collected in a large volume of water, the differences of the two trawling methods are considered as due to the sparse distribution of the microplastics and are deemed as equivalent to each other.

Off the southeastern China coasts, the microplastics abundances are as low as in the western Pacific, probably because of the intrusion of the Kuroshio waters into the Taiwan Strait during the summer of 2017 (Fig. 1). The abundance of microplastics is an order of magnitude higher off the Zhejiang coasts of China than in the western Pacific, suggesting the influence from nearby river run-offs.

The SADCP data have shown clearly the westward NEC in the central 130°E section and the eastward NECC in the southern section, which are consistent with the trajectories of the surface drifters released in the 130°E section during the cruise (Fig. 3). The null counts of the microplastic fragments larger than the 0.35 mm in the NEC mainstream suggest that the leakage of the Great Pacific Garbage Patch has not been transported into the western Pacific by the NEC so far. In addition, the convergence of the currents near the western boundary has not resulted in an accumulation of microplastics, which is perhaps not directly intuitive. In contrast, the microplastics abundances in the NECC are higher than in the NEC, due to the influence from the coasts and from the Indonesian seas (Fig. 2).

3.2. Microplastic abundances in the Indonesian seas

The microplastic abundances in the Indonesian seas are one or two orders of magnitude higher than in the western Pacific (Fig. 2). The average abundance in the Makassar Strait is ~0.01 particle m^{-3}, while the abundance in the northeastern Indonesian seas is ~0.1 particle m^{-3}, which are one and two orders of magnitudes higher than the average abundance <0.001 particle m^{-3} in the western Pacific along 130°E. The significant increase of the abundances in the Makassar Strait from that in the NEC suggests the influence of the surrounding lands, possibly through river run-offs that carry microplastics into the ocean (Table 1). The largest abundances are found in the northeastern Indonesian sea, especially in the northern Maluku Sea, where multiple major currents meet to generate the beginning of the NECC. It is worth mentioning that the 350 μm filtering at 2°N 130°E generates microplastics abundances comparable with the 300 μm filtering in the Maluku Sea.

Observations have shown that neither the MC nor the NGCC carries waters of high enough microplastics abundances into the area (Fig. 2). The high abundance in the northeastern Indonesian seas is difficult to

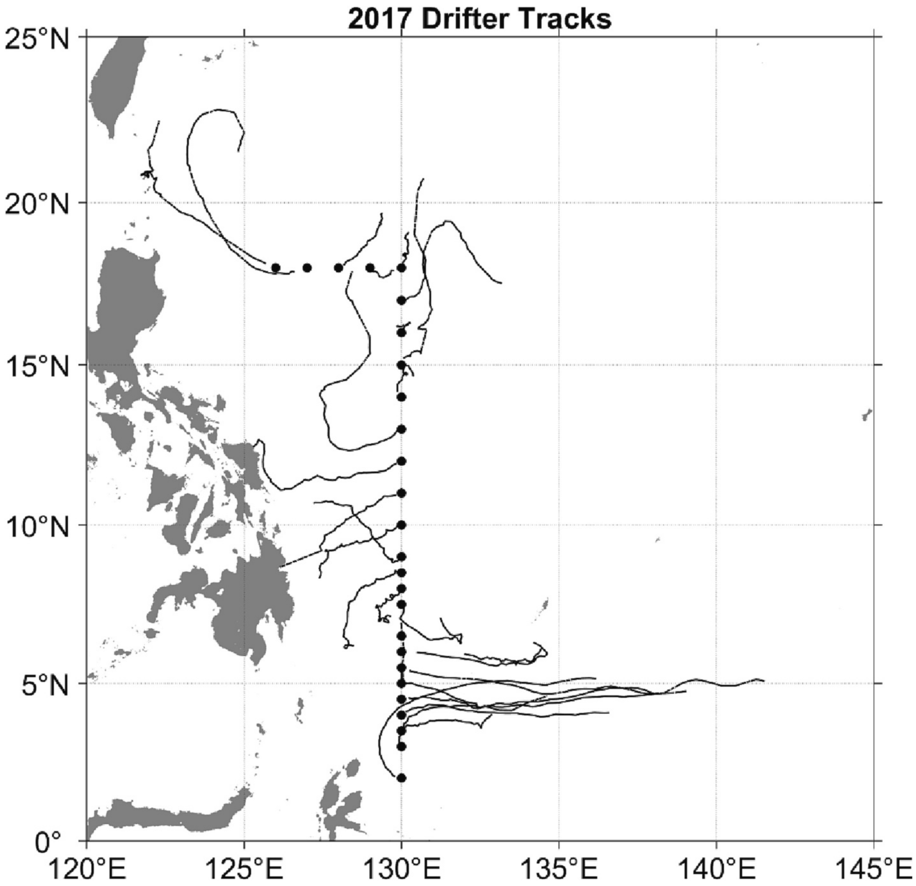

Fig. 3. Trajectories of satellite-tracked surface drifters during October through November 2017. Dots are the starting positions of the drifters.

understand, in spite of the fact that the 350 μm filtering may result in slightly lower microplastics abundances in the NGCC. Traditionally, the transport through the Maluku Strait is thought to flow to the south into the Indonesian seas (Sprintall et al., 2009; Gordon et al., 2019), which implies that the microplastics abundances in the northern Maluku Sea should be lower than that inside the Indonesian seas.

Recent studies based on in situ long-term mooring measurements have shown a northward mean upper-layer transport through the Maluku Channel (Yuan et al., 2018; Yin et al., 2023). The concurrent SADCP measurements with the microplastics trawling indeed show that the surface currents in the Maluku Channel, especially in the eastern channel, flow northward into the Pacific Ocean. The MC retroflects in the eastern Sulawesi Sea and merges with the currents from the Sulawesi Sea, the Maluku Channel, and the NGCC to form the beginning of the NECC. The highest abundance of the microplastics in the northern Maluku Sea is likely due to the convergence of these multiple currents, especially those coming from the eastern Indonesian seas, since the microplastics abundances in the MC are not high enough. Therefore, the microplastics abundances in the northeastern Maluku Sea, as high as 2 orders of magnitude higher than those in the western Pacific, are suggested to be accumulated inside the eastern Indonesian sea and carried to the northern Maluku Sea by the northward surface transports through the Lifamatola Passage and the Maluku Channel (van Aken et al., 2009; Yuan et al., 2018; Yin et al., 2023).

3.3. *FT-IR and Raman spectra analysis*

The western Pacific water samples were filtered with a paper filter of 50 μm. The samples on the paper filters and the fragments larger than 0.35 mm were sent to the Sun Yet-Sen University laboratory for the FT-IR analysis. The FT-IR analysis report suggests that the microplastics in the western Pacific are composed of nylon 6/10 (15%), polyester (13%), polyvinyl alcohol (10%), polystyrene (8%), polyethylene (8%), polycaprolactone triol (4%), polypropylene (4%), etc. These microplastics are mostly between 200 and 350 μm sizes. The fragments larger than 350 μm are too few to form statistical meaningful composition of the microplastics in the western Pacific Ocean.

Randomly chosen microplastic fragments collected in the Indonesian seas have been analyzed with the Raman spectra, an example of which is shown in Fig. 4. To identify polymers using micro-Raman spectra, we used the most used bands in the vibrational spectrum as in previous studies (Andreassen, 1999; Crawford and Quinn, 2017; Käppler et al., 2015; Kotha and Shirbhate, 2015; Löder and Gerdts, 2015). The μRaman analysis indicated fiber and fragment-film microplastics mainly composed of polyethylene, followed by polyethylene terephthalate, and others (polypropylene, polyvinyl chloride and nylon 6/10) (Table 2). Fiber microplastics are dominated by polyethylene and polyethylene terephthalate. A small portion of the fiber polymers is identified as nylon 6/10.

The fragments of the 200–300 μm sizes in the Indonesian seas were not stored nor analyzed, unfortunately. Nevertheless, the comparison suggests that the fragments in the western Pacific are smaller, perhaps due to long distance travel and aging, and are composed of mainly of nylon and polyester, instead of dominated by polyethylene fragments as in the Indonesian seas.

3.4. *Comparison with existing studies*

Our analyses have basically produced similar microplastics ingredients to the existing studies in the western Pacific, with the size and type varying from sample to sample inevitably. The average abundances of this study are within the magnitudes reported in the published literature, showing a wide range of microplastic abundances in the open ocean due partly to the use of different mesh sizes and partly to highly spatially heterogeneous distributions of the microplastics (Table 3).

Microplastic abundances ranges from 0 to 0.034 (mean: 0.008) particles m^{-3} or 0 to 9657 (mean 1250) particles km^{-2} in the Northwestern Pacific Ocean, whilst from 0 to 0.17 (mean: 0.044) particles m^{-3} or 0 to 17,311 (mean 5488) particles km^{-2} in the Indonesian seas, which spans over four orders of magnitude across the tropical western Pacific Ocean (Table 1). The average abundances (Table 3) reported in this study were relatively of the same magnitudes as reported in the North Pacific subtropical gyre (Goldstein et al., 2012), in the north western Pacific (Pan et al., 2019b), in the western North Pacific, the Bering Sea, and the Chukchi Sea (Mu et al., 2019), and in the middle western Pacific (Wang et al., 2020). The variability of microplastics in this study was lower than that reported in other studies in the Pacific Ocean (Desforges et al., 2014; Eriksen et al., 2013, 2014; Isobe et al., 2017; Li et al., 2020; Moore et al., 2001; Pan et al., 2019a; Yamashita and Tanimura, 2007). The wide ranges of microplastic abundances indicate that microplastic abundances in the open ocean are highly spatially heterogeneous on a broad scale (Goldstein et al., 2013; Schmidt et al., 2018), which may be attributed to hydrodynamic effects, wind-and-wave-driven turbulence, ocean currents, or land-based inputs (Collignon et al., 2012; Schmidt et al., 2018; Suaria and Aliani, 2014).

4. Conclusions

In this study, water samples collected from two cruises in the surface waters of the western Pacific and inside the Indonesian seas are filtered, and the fragments are analyzed to estimate the abundance of microplastics near the western boundary of the Pacific Ocean. The fragments in the water samples have been identified as microplastics using the FT-IR and Raman spectrum analyses. Based on the fragment counts, the abundances of microplastics larger than 0.35 mm are calculated and are found to be very low (<0.018 particles m^{-3}) in the surface waters of the NEC and the Kuroshio. The low abundances in the NEC (Fig. 2) suggest that the leakage of the Great Pacific Garbage Belt has not been transported to the western Pacific so far. Recent studies suggest that pelagic microplastics made from polyethylene lighter than seawater are not buoyant eternally but might settle down into deep oceanic layers after drifting a long distance due to biofouling and/or aggregation (e.g., Long et al., 2015; Kaiser et al., 2017; Michels et al., 2018), which is consistent with the finding of this study. The low abundances in the Kuroshio suggest that the convergence of ocean currents near the western boundary does not produce significantly accumulated abundances of the microplastics in the western boundary currents. In addition, the low abundances also suggest that the high abundance microplastics due to the coastal influences around the Indonesian and Philippine islands were not carried downstream by the Kuroshio, but were trapped inside the Indonesian seas or carried westward into the Indian Ocean by the ITF.

The microplastics abundances in the far western Pacific and the Indonesian seas have been measured and estimated simultaneously for the first time in history by this study. The abundances of the microplastics in the Indonesian seas are one or two orders of magnitudes higher than those in the Northwestern Pacific Ocean. The largest abundance has been found in the northeastern Maluku Sea, where a branch of the ITF carries Indonesian sea waters with accumulated microplastics into the converging area of multiple currents. Large variations of microplastics abundances across short distances suggest the necessity of better spatial and temporal coverage of microplastics measurements in estimating global budgets of microplastics distributions and transportation. The measurements underline the importance of ocean circulation in transporting and re-distributing microplastics in the ocean, the study of which has been deemed inadequate so far.

Due to limited observations, it is not clear at present how the high abundances of microplastics in the northern Maluku Sea vary with the currents at time scales from intraseasonal to interannual. The detailed pathways of the microplastics movement are important for understanding the microplastics abundances and the associated variations, but are beyond the scope of this study. In the future, analyses of Lagrangian trajectories of surface drifters based on numerical simulations will be

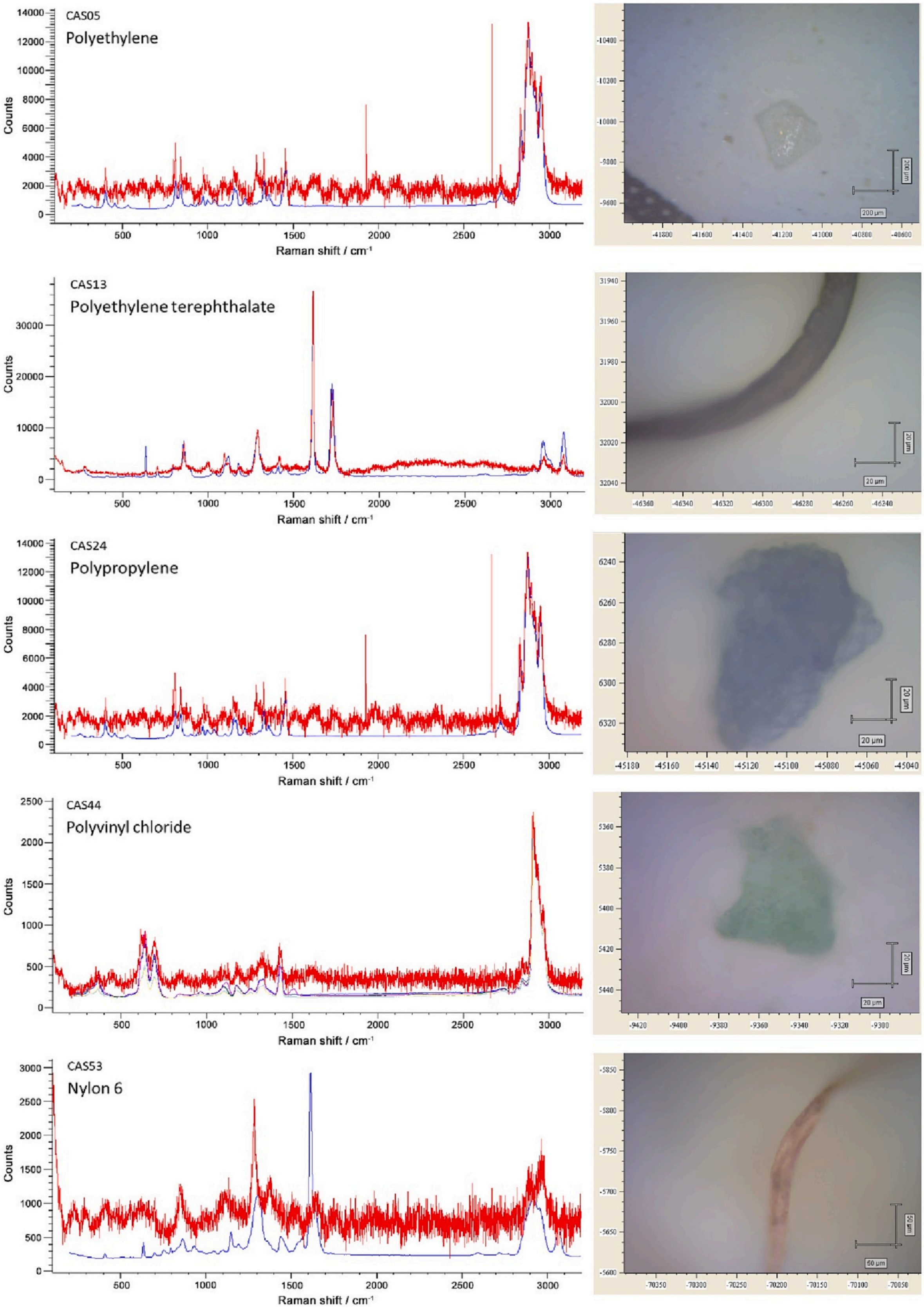

Fig. 4. Raman spectra of microplastic fragments and their photos on the right from the Indonesian seas. Red curves stand for the sample spectra. Blue curves are the library data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Microplastic abundance reported in the literature for several locations in the Pacific Ocean region.

No	Region	Mesh size/collection method	Particles m^{-3}	Particles km^{-2}	References
1	North Pacific central gyre	330 μm	–	31,982–969,777	(Moore et al., 2001)
2	North Western Pacific- Kuroshio Current area	330 μm	–	170,000–470,000	(Yamashita and Tanimura, 2007)
3	North Pacific subtropical gyre	–	0.12	–	(Goldstein et al., 2012)
4	South Pacific subtropical gyre	330 μm	–	0–400,000	(Eriksen et al., 2013)
5	Pacific Ocean	330 μm	–	120,000	(Eriksen et al., 2014)
6	North Eastern Pacific Ocean	Saltwater intake in the vessel 62.5 μm	279 ± 178	8000–9200	(Desforges et al., 2014)
7	North Pacific - around Japan	350 μm	–	1,700,000	(Isobe et al., 2017)
8	North Western Pacific	330 μm	–	640–42,000 (mean: 10,000)	(Pan et al., 2019a)
9	Northwest Pacific, the Bering Sea, and the Chukchi Sea	330 μm	0.018–0.31	–	(Mu et al., 2019)
10	North Western Pacific	330 μm	–	620,000	(Pan et al., 2019b)
11	Mid-west Pacific	333 μm	0.012–0.2	6028–95,335	(Wang et al., 2020)
12	Western Pacific	In situ filtration, 60 μm	0.2–2	–	(Li et al., 2020)
13	Western Pacific	330 μm	0.02–0.1	–	(Liu et al., 2021)
14	North Western Pacific	350 μm	0–0.034 (mean: 0.008)	0–9657 (mean 1250)	This study
15	The Indonesian seas	300 μm	0–0.17 (mean: 0.044)	0–17,311 (mean 5488)	This study

conducted to identify the origin of the microplastics and to assess the potential pathways of their movement, as conducted by some of the existing studies in the open ocean (e.g., Maximenko et al., 2012; Iskandar et al., 2022).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to the data in the manuscript file.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seares.2023.102406.

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