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Microplastics in the Southern Ocean

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ABSTRACT

A field survey to collect microplastics with sizes <5 mm was conducted in the Southern Ocean in 2016. We performed five net-tows and collected 44 pieces of plastic. Total particle counts of the entire water column, which is free of vertical mixing, were computed using the surface concentration (particle count per unit seawater volume) of microplastics, wind speed, and significant wave height during the observation period. Total particle counts at two stations near Antarctica were estimated to be in the order of 100,000 pieces km^{-2}.

Mismanaged plastic waste can escape into the natural environment, particularly in regions with high population density (Jambeck et al., 2015). Numerous plastic fragments are typically found in the oceans of the Northern Hemisphere in areas where plastic debris has degraded on beaches (Andrady, 2011). A number of recent studies have reported the collection of tiny plastic fragments with diameters of <5 mm (referred to as microplastics) in open oceans, including the Arctic polar waters (Thompson et al., 2004; Goldstein et al., 2012; Cózar et al., 2014; Eriksen et al., 2014; Reisser et al., 2015; Lusher et al., 2015), marginal seas (de Lucia et al., 2014; Isobe et al., 2015), and coastal waters (Isobe et al., 2014). Table 1 summarizes the concentrations (particle count per unit seawater volume) of pelagic microplastics reported in the Northern Hemisphere. Importantly, microplastics can act as a transport vector of chemical pollutants into the marine ecosystem, owing to the absorption of pollutants onto their surfaces (Mato et al., 2001; Teuten et al., 2009), and their subsequent ingestion by organisms as small as zooplankton (Desforges et al., 2015). If the discharge of pelagic microplastics into the oceans continues, such pollution will be unavoidable in the future.

Based on the synthesis of the results of several Southern Hemisphere surveys, it has been suggested that pelagic microplastics are less widespread in the Southern oceanic regions, compared with the oceans of the Northern Hemisphere (see Fig. S5 in Cózar et al. (2014)). This may indicate that microplastics have not yet spread across the oceans of the Southern Hemisphere. However, there have been few comprehensive surveys of the distribution of microplastics in the Southern Hemisphere (Fig. S1 in Cózar et al. (2014)), and previous findings are inconclusive. In particular, it is currently unclear whether pelagic microplastics can be detected in the Southern Ocean (also known as the Antarctic Ocean); a marine area with the lowest population in the world, where minimal mismanagement of plastic is likely to occur. Observations of a significant concentration of microplastics in the Southern Ocean would suggest that pelagic microplastics have already spread across the world's oceans. Global plastic production has increased by >500 times over the last 60 years (Thompson et al., 2009). However, microplastic surveys in the Southern Ocean have not been reported in peer-reviewed publications, except for a small number of surveys conducted in the Drake Passage close to South America (unpublished, but data were used in Cózar et al. (2014) and Eriksen et al. (2014)).

In the present study, we conducted microplastic surveys in the Southern Ocean from January 30 to February 4, 2016, at five stations along a route from Fremantle to Hobart, Australia, using a T/V *Umitaka-maru* belonging to Tokyo University of Marine Science and Technology (Fig. 1). Wind speed and significant wave height were measured on the vessel, and hourly averaged data were recorded during the surveys (Fig. 2). These data were used to deduce the vertical distribution of microplastics for comparison with data collected in other oceans under different wind and wave conditions. A Neuston net (5552; RIGO Co., Ltd., Tokyo, Japan) was used for sampling the small plastic fragments. The mouth, length, and mesh size of the net were 75 × 75 cm, 3 m, and 0.35 mm, respectively. The T/V *Umitaka-maru* towed the Neuston net around each station continuously for 20–40 min at a constant speed of 2–3 knots. To avoid collecting plastic fragments originating from the ship, the net was positioned at a distance of approximately

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Table 1
Observed surface microplastic concentration reported by previous studies. Apart from Goldstein et al. (2012), who synthesized the previous surveys, the studies below computed the concentrations using particle counts and seawater volume measured by a flow meter.

Oceans	Concentration (pieces m^{-3})
East Asian seas (Isobe et al., 2015)	3.70
N. Atlantic (accumulation area) (Reisser et al., 2015)	1.70
Seto Inland Sea (Isobe et al., 2014)	0.39
Arctic polar waters (Lusher et al., 2015)	0.34
Mediterranean Sea (de Lucia et al., 2014)	0.15
N. Pacific (Goldstein et al., 2012)	0.12

2 m during the towing, and thereafter was rinsed on the deck by pouring seawater from the outside of the net. A flow meter (5571A; RIGO Co., Ltd.) was installed at the net mouth. Once the surveys were completed, the flow-meter readings and net mouth dimensions (75 × 75 cm) were used to estimate the volume of water filtered during each tow.

The seawater samples, including the suspended matter, were sent to Kyushu University for the extraction of plastic fragments. The small plastic fragments were first observed using a monitor display via a USB camera (HDCE-20C; AS ONE Corporation, Osaka, Japan) attached to a stereoscopic microscope (SZX7; Olympus Corporation, Tokyo, Japan) and identified visually by their colour and shape. Polymer types were identified using a Fourier transform infrared spectrophotometer (FT-IR alpha; Bruker Optics K.K., Tokyo, Japan) when the fragments were too small for visual differentiation between microplastics and biological matter. Expanded-polystyrene particles (three particles were detected), fibers (a single piece), and biological elements were all removed before any further analyses. Primary microplastics such as pellets were not detected in the present surveys.

The numbers of plastic fragments in each size range were counted with an increment of 0.1 mm for microplastics <5 mm and 1 mm for mesoplastics >5 mm. The sizes were defined by the longest length of each irregularly shaped fragment visible on the monitor display, measured using image-processing software (ImageJ; downloaded from http://imagej.nih.gov). The numbers within each size range were thereafter divided by the water volumes measured by the flow meter at each

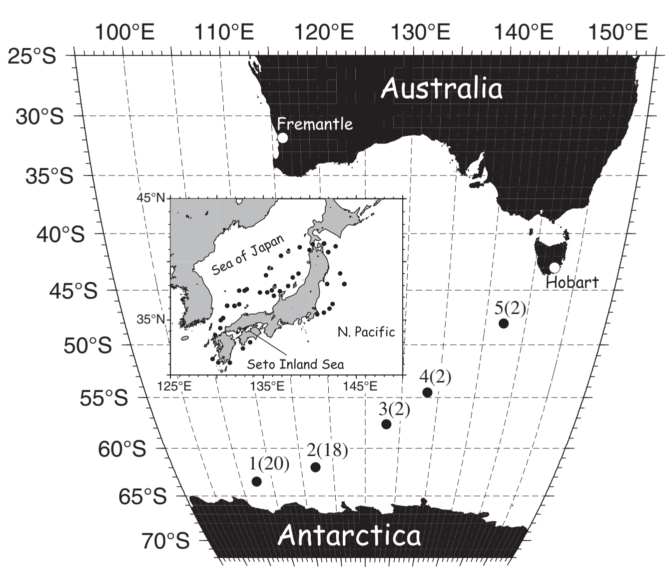

Fig. 1. Survey stations. The digits in parentheses denote the particle count (number of pieces) of microplastics collected at each station. The survey stations around Japan are shown in the inset map.

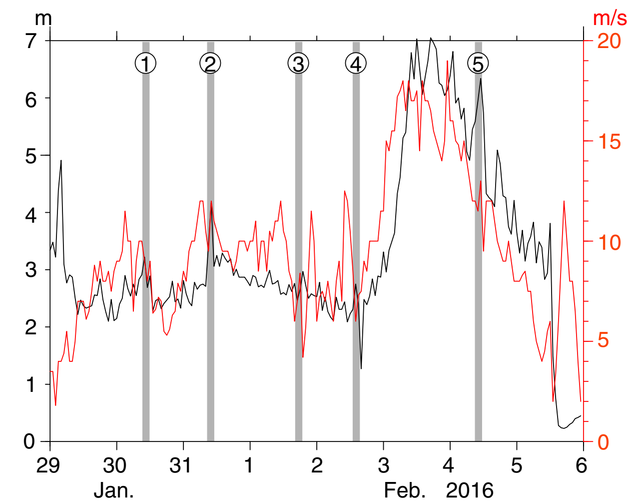

Fig. 2. Temporal variation of significant wave height and wind speed measured during the survey period. The black (red) curve indicates the wave height (wind speed) for which the ordinate is shown on the left (right) side of the figure. The gray bars show the observation periods at the five stations in Fig. 1.

sampling station to convert them to a measure of concentration in units of the number of pieces m^{-3}.

Direct comparison of microplastic concentrations observed in different ocean areas under different wave and wind conditions can be difficult because light-weight microplastics are vulnerable to vertical mixing caused by oceanic turbulence, and because the vertical distribution (and the surface concentration observed using a Neuston net) is affected by these oceanic conditions (Kukulka et al., 2012; Reisser et al., 2015; Isobe et al., 2015). The surface concentrations of microplastics obtained in different oceans can be converted to the total particle count (particle count per unit area) by vertically integrating the concentration at depths using the wind speed and significant wave heights measured during each microplastic survey (hereinafter, wind/wave correction). The total particle count, which is regarded as the quantity of pelagic microplastics in the entire water column, is independent of vertical mixing. Thus, it is a useful measure for the comparison of microplastic quantities in different oceans.

Let us consider microplastics with size δ. Assuming an equilibrium state between plastic rise (terminal) velocity (w) and vertical diffusion with the diffusivity (A_0), we anticipate that their concentration (N_δ) will decrease exponentially into deeper layers (Kukulka et al., 2012; Reisser et al., 2015) as follows:

$$N_\delta = N_{\delta 0} e^{\frac{w}{A_0} z}, \tag{1}$$

where $N_{\delta 0}$ denotes the concentration of microplastics collected using a Neuston net, w is set to 0.0053 mm s^{-1} obtained experimentally (Reisser et al., 2015), and z is the vertical axis in the upward direction from the sea surface. Parameter A_0, with respect to the oceanic turbulence in the upper layer is computed as:

$$A_0 = 1.5 u_* k H_S, \tag{2}$$

where u_* represents the frictional velocity of water ($=0.0012\,U$), k is the von Karman coefficient (0.4), Hs is the significant wave height, and U is the wind speed. The applicability of the above formulation was examined by Reisser et al. (2015) in the North Atlantic gyre using multi-level net towing. In the present study, wind speed and wave height were averaged over 24 h before each survey. Vertically integrating Eq. (1) from the sea surface ($z = 0$) to the infinitely deep layer ($z \to -\infty$) yields the total particle count of microplastics per unit area, M_δ (pieces per unit area), as follows:

$$M_\delta = N_{\delta 0} A_0 / w. \quad (3)$$

Integrating Eq. (3) over microplastic sizes smaller than 5 mm gives the total particle count of microplastics.

Overall, 44 pieces of microplastic, excluding fibers and expanded polystyrene, were collected over the course of the surveys (see photos [a–c] in Fig. 3 as examples). Of the 44 fragments, one fragment (photo [c] in Fig. 3) was 5.5 mm in length, slightly larger than the <5 mm definition of microplastics (Andrady, 2011; Cole et al., 2011). However, this fragment was considered as a microplastic fragment for convenience in the present study. In this short report, we focus specifically on the concentrations of pelagic microplastics in the Southern Ocean. The analysis of other types of data from these 44 samples, including biofouling (Morét-Ferguson et al., 2010) and carbonyl index (Andrady et al., 1993; Satoto et al., 1997) will be examined in the next phase of our research.

The microplastics were predominantly found at Stas. 1 and 2, south of 60°S (nearest Antarctica), while only two pieces of microplastic were detected at each of Stas. 3, 4, and 5 (Fig. 1). The results indicated that the abundance of plastic fragments was negligibly small in the latter three stations, because the fragment count was so low that may have been due to contamination by the ship, in spite of the effort to avoid collecting ship-derived plastics. Of the 44 fragments, 29 were made of polyethylene, polypropylene, and polyethylene combined with unidentified polymers. These microplastics can be carried long distances because they are less dense than seawater (~1025 kg m^{-3}). However, 14 of the remaining 15 microplastics were made of polystyrene, and 1 was made of polyvinyl chloride, which are all denser than seawater. These dense microplastics are unlikely to have drifted independently in the upper ocean. We speculate that they were likely to have been detected in the surface water because they were entangled with drifting pelagic objects such as zooplankton and krill, which were collected concurrently with the microplastics.

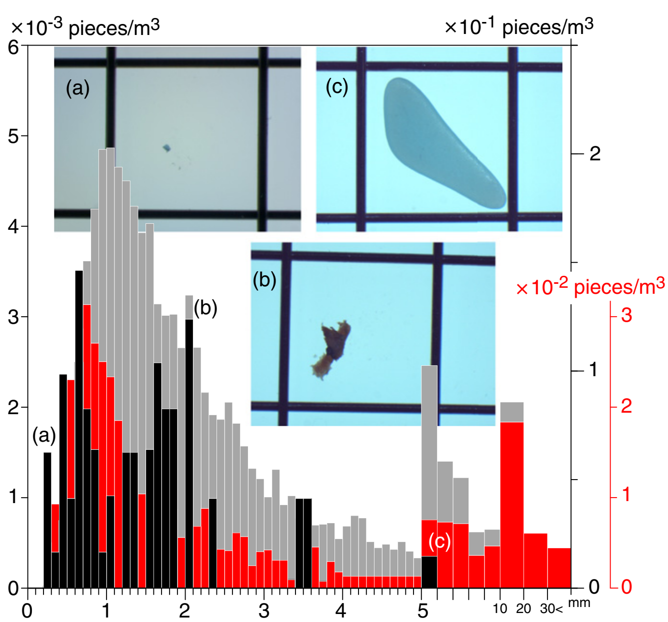

Fig. 3. Size distribution of plastic fragments in the Southern Ocean (black bars; present study), Seto Inland Sea (red; Isobe et al., 2014), and East Asian seas around Japan (gray; Isobe et al., 2015). The location of the Seto Inland Sea and stations around Japan are shown in Fig. 1. The bar height at each size range indicates the concentration averaged over all survey stations. Note that the intervals of size ranges are 0.1 mm for microplastics <5 mm, 1 mm for mesoplastics <10 mm, and 10 mm for mesoplastics > 10 mm. The left ordinate is used for microplastics in the Southern Ocean, while the black (red) ordinate on the right side is used for those in the East Asian seas (Seto Inland Sea). The photographs (a), (b), and (c) are of microplastics collected in the Southern Ocean in the size ranges corresponding to the columns with the same letter at the top. The photographs include a 5-mm grid, with grid lines of 0.3 mm.

Table 2
Results of microplastic surveys at each station.

Sta.	Date	Particle count (pieces)	Seawater volume (m^3)	Concentration (pieces m^{-3})
1	Jan 30, 2016	20	202	9.9×10^{-2}
2	Jan 31, 2016	18	392	4.6×10^{-2}
3	Feb 1, 2016	2	566	3.5×10^{-3}
4	Feb. 2, 2016	2	502	4.0×10^{-3}
5	Feb. 4, 2016	2	417	4.8×10^{-3}
Average				3.1×10^{-2}

As with microplastics collected in mid-latitudes (Cózar et al., 2014; Isobe et al., 2014; Isobe et al., 2015), high concentrations of microplastics were found only in the smaller size range (Fig. 3). This result is likely to have been due to single pieces of plastic debris gradually degrading into multiple tiny pieces as they move within the environment. Nevertheless, it is of particular interest that mesoplastics (diameter: >5 mm) were rarely observed in the present surveys. The absence of relatively "fresh" (i.e., less degraded) mesoplastics implies that the areas around the Southern Ocean are unlikely to be significant sources of pelagic plastic debris, and that any tiny fragments must have been transported considerable distances.

Integrating the concentration data shown in Fig. 3 with sizes data from fragments <5 mm yields the averaged concentration of microplastics at each station (Table 2). Except for Sta. 1, the concentrations of pelagic microplastics in the Southern Ocean were found to be 1–2 orders of magnitude smaller than those reported in the North Pacific, Arctic polar waters, Mediterranean Sea, and the Seto Inland Sea of Japan (Table 1). Furthermore, the concentrations we observed were 2–3 orders of magnitude smaller than areas of other oceans with high concentrations of pelagic microplastics, including the East Asian seas and the accumulation (frontal) area of the North Atlantic (Table 1). However, the microplastic concentration observed at Sta. 1 was comparable with those observed in the oceans of the Northern Hemisphere.

As mentioned above, the total particle count, as a measure of the quantity of pelagic microplastics in the entire water column, is useful for the comparison of microplastic abundance in different oceans. The current microplastic surveys in the Southern Ocean were conducted under stormy conditions with wind speeds and significant wave heights of 10 m s^{-1} and 3.3 m, respectively, averaged over the survey period (Fig. 2). However, in previous studies in both the East Asian seas (Isobe et al., 2015) and the Seto Inland Sea (Isobe et al., 2014), the microplastics were collected under relatively calm conditions, with wind speeds of <5 m s^{-1} and significant wave heights of <1 m. The surface concentrations in these areas may have been lower if the surveys had been conducted under the same severe conditions as the present surveys. Thus, there is clearly room to conclude that the abundance of pelagic microplastics in the Southern Ocean is lower than in many other areas. We computed the total particle counts at Stas. 1 and 2, where relatively large amounts of microplastic were collected (Table

Table 3
Comparison of the total particle counts estimated in different oceans. The total particle count in each ocean was computed in Isobe et al. (2015) by averaging the total particle counts for data from various oceans reported by Eriksen et al. (2014).

Oceans	Total particle count (pieces km^{-2})
East Asian seas[a]	1,720,000
N. Pacific[b]	105,100
World's oceans[b]	63,320
Seto Inland Sea[c]	76,000
Sta. 1	286,000
Sta. 2	136,000

[a] Isobe et al. (2015).
[b] Eriksen et al. (2014).
[c] Isobe et al. (2014).

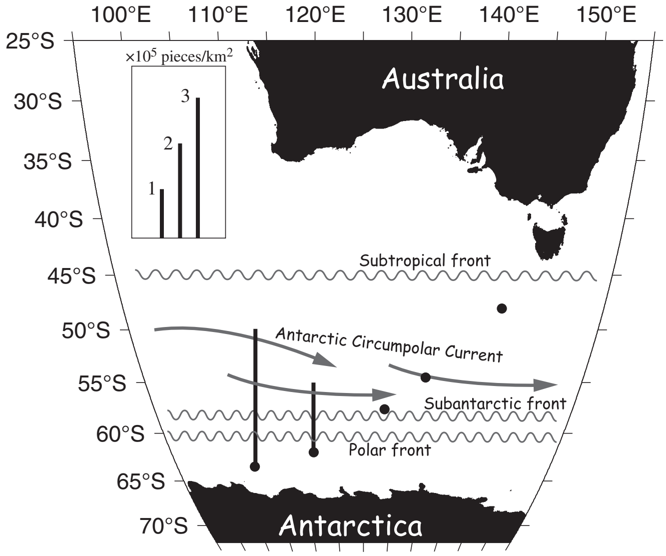

Fig. 4. Observed total particle counts and schematic view of oceanic conditions in the Southern Ocean. The bars at Stas. 1 and 2 indicate the total particle counts listed in Table 3; see the reference scale shown in the upper left corner. The particle counts at Stas. 3, 4, and 5 were not shown because the numbers of collected microplastics were negligibly small. We referred to Fig. 6.7 in Tomczac and Godfrey (1994) for the positions of three oceanic fronts in the schematic view. The arrows represent the Antarctic Circumpolar Current, placed approximately on the curves along which the wind-stress curl vanishes (i.e., maximal wind stress) in Fig. 6.5b of Tomczac and Godfrey (1994).

2). The approximate estimation of the total particle count around the East Asian seas is still one order of magnitude greater than at these stations in the Southern Ocean (Table 3). However, it should be noted that the total particle counts at Stas. 1 and 2 were comparable with the average counts observed in the other oceans.

Importantly, the microplastics concentrations observed close to Antarctica (Stas. 1 and 2) were more abundant than those observed at the offshore stations (Stas. 3, 4, and 5), although they were likely to have originated from northern inhabited areas, as suggested by the size distribution (Fig. 3). Stas. 1 and 2 were located south of the oceanic fronts (convergence zone) around Antarctica (see Fig. 4 for schematic view), and were located around the southern boundary of the Antarctic Circumpolar Current (ACC; see Fig. 7 in Orsi et al., 1995). Unlike seawater subducted into the abyssal ocean by deep convection around Antarctica, buoyant microplastics have typically been found to remain in the upper ocean; see Fig. 2 of Reisser et al. (2015) for the dense concentration of microplastics in the uppermost layer. This implies that the microplastics are likely to be trapped around Antarctica once they are transported beyond the ACC and oceanic fronts. However, more comprehensive microplastic surveys in the Southern Ocean are required to confirm this speculation.

Significant concentration of microplastics in the Southern Ocean would suggest that marine plastic pollution has spread across the world's oceans. The current surveys revealed a relatively dense concentration of microplastics in the Southern Ocean, comparable with concentrations observed in the Northern Hemisphere oceans (two of five stations in the present case). The present findings raise concern about the widespread nature of marine plastic pollution, indicating that plastic-free ocean environments are increasing rare.

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