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East Asian seas: A hot spot of pelagic microplastics

Atsuhiko Isobe [a,*], Keiichi Uchida [b], Tadashi Tokai [b], Shinsuke Iwasaki [a]

[a] Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka 81-8580, Japan
[b] Department of Ocean Sciences, Tokyo University of Marine Science and Technology, 4-5-7 Konan, Minato-ku, Tokyo 108-8477, Japan

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ABSTRACT

To investigate concentrations of pelagic micro- (<5 mm in size) and mesoplastics (>5 mm) in the East Asian seas around Japan, field surveys using two vessels were conducted concurrently in summer 2014. The total particle count (pieces km^{-2}) was computed based on observed concentrations (pieces m^{-3}) of small plastic fragments (both micro- and mesoplastics) collected using neuston nets. The total particle count of microplastics within the study area was 1,720,000 pieces km^{-2}, 16 times greater than in the North Pacific and 27 times greater than in the world oceans. The proportion of mesoplastics increased upstream of the northeastward ocean currents, such that the small plastic fragments collected in the present surveys were considered to have originated in the Yellow Sea and East China Sea southwest of the study area.

1. Introduction

According to a recent estimate by Jambeck et al. (2015), the volume of plastic waste input from the East Asian continent into the surrounding ocean is the largest in the world. Marine plastic debris can be found widely on the beaches of East Asian countries (e.g., Kusui and Noda, 2003; Kako et al., 2010; Nakashima et al., 2011; Zhou et al., 2011; Hong et al., 2014; Kuo and Huang, 2014). In the environment, plastic debris gradually degrades into mesoplastics (>5 mm) and thereafter into microplastics (<5 mm) because of exposure to ultraviolet radiation and mechanical erosion on beaches (Andrady, 2011). Hence, dense concentrations of pelagic microplastics are liable to be observed in the East Asian seas in comparison with other oceans. However, except for a few previous studies conducted within limited spatial scope (Isobe et al., 2014; Zhao et al., 2014), there are no estimates regarding the concentrations of microplastics over wide areas of the East Asian seas. In the present study, the concentrations of microplastics in the seas around Japan were surveyed concurrently using two training vessels during summer 2014. The primary objective of the present study was a comparison of the concentrations of microplastics in the East Asian seas around Japan with those observed in the world oceans (Cózar et al., 2014; Eriksen et al., 2014). A question of particular interest is whether the East Asian seas are regarded as a “hot spot” of microplastics.

The secondary subject of interest concerns the source(s) of meso- (>5 mm) and microplastics (<5 mm) found within the study area. Hereinafter, the term “small plastic fragments” is used to represent both meso- and microplastics. The transport process of small plastic fragments is a challenging topic in physical oceanography, because pelagic plastic fragments are mostly made of polystyrene and polyethylene: 98.5% in Reisser et al. (2013) and 78% in Isobe et al. (2014). The plastic fragments are less dense than seawater and they move within the upper 1-m “skin” layer of the water (Reisser et al., 2015) where highly turbulent motion (Kukulka et al., 2012) and Stokes drift (Isobe et al., 2014) make their behavior complex. Nonetheless, the ratio of the quantity of mesoplastics within the small plastic fragments is likely to increase nearer to the contamination source, because macroplastic debris gradually degrades into smaller fragments as it moves within the oceans. Thus, it is anticipated that the size distribution of the plastic fragments and their spatial distribution could be used as strong indicators of their sources.

2. Methods

2.1. Study area

Japan is generally surrounded by northeastward or eastward ocean currents. On the surface current map (Fig. 1), the eastward or northeastward Kuroshio Current, with a speed of around 1 m s^{-1} (~2 knots), can be seen south of Japan. It is well known that the Kuroshio Current separates from Japan at 35°N and then flows eastward as the Kuroshio Extension (e.g., Stommel and Yoshida, 1972). In the Sea of Japan, the northeastward Tsushima Current is connected continuously to the northeastward ocean currents over the East China Sea shelf (Isobe, 2008). The Tsushima Current separates into at least two branches in the Sea of Japan: one is the offshore branch ($O(10)$ cm s^{-1}) that flows eastward in the central portion of

* Corresponding author.
E-mail addresses: aisobe@riam.kyushu-u.ac.jp (A. Isobe), kuchida@kaiyodai.ac.jp (K. Uchida), tokai@kaiyodai.ac.jp (T. Tokai), iwasaki@riam.kyushu-u.ac.jp (S. Iwasaki).

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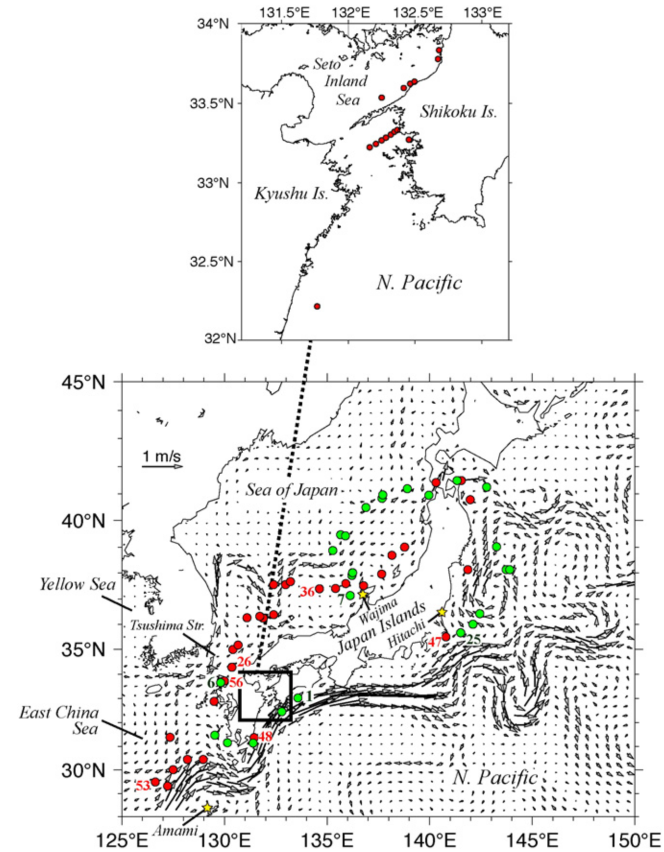

Fig. 1. Study area of the present surveys (lower panel) and the Seto Inland Sea in Isobe et al. (2014) (upper panel; 15 stations shown by the red spots). In the lower panel, the samplings at stations shown by green (red) spots were conducted by the *T/V* Umitaka-Maru (Shinyo-Maru). The station numbers are shown at selected stations. The yellow stars indicate locations of the three NOWPHAS wave observatories. The vectors represent surface ocean currents reproduced in the Data Assimilation Research of the East Asian Marine System (DREAMS; Hirose et al., 2013). The velocities were averaged over the period July through August 2014 (survey period in Table 1).

the sea, while the other is the nearshore branch ($O(10)$ cm s^{-1}) that flows northeastward paralleling Japan (Kawabe, 1982).

2.2. Field surveys

The dual surveys were conducted concurrently during the period of July 17 through September 2, 2014, using two training vessels: the *T/V* Umitaka-Maru (1886 tons) and *T/V* Shinyo-Maru (649 tons), both belonging to the Tokyo University of Marine Science and Technology. To collect the small plastic fragments, 56 stations were placed around Japan, except for an area to south of the country (lower panel of Fig. 1). The surveys were conducted in a clockwise direction from Sta. 1 to Sta. 25 by the Umitaka-Maru and from Sta. 26 to Sta. 56 by the Shinyo-Maru (see Table 1 for detailed schedule). The sampling of the small plastic fragments was conducted three times daily (0600, 1300, and 1800 LST), although some samplings were skipped or delayed because of uncontrollable circumstances such as stormy weather.

Table 1
Stations and survey periods in 2014.

Vessels	Stations	Date
Umitaka-Maru	Sta. 1–Sta. 25	July 17–August 8
Shinyo-Maru	Sta. 26–Sta. 47	July 20–August 4
Shinyo-Maru	Sta. 48–Sta. 56	August 21–September 2

A neuston net (5552; RIGO Co., Ltd., Tokyo, Japan), originally designed for sampling zooplankton, fish larvae, and fish eggs near the sea surface, 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 lower limit of the microplastics discussed in the present study was dependent on this mesh size. The training vessels towed the neuston nets around each station continuously for 20 min at a constant speed of 2–3 knots. A flow meter (5571A; RIGO Co., Ltd.) was installed at the net mouths to measure the water volume passing through during the sampling; otherwise, the estimates of the concentration of small plastic fragments would become inaccurate because the speed of the ocean current within the study area frequently exceeded $O(1)$ knot. Once the surveys were completed, the flowmeter readings and net mouth dimensions (75×75 cm) were used to estimate the volume of water filtered during each tow.

In addition to comparisons with previous surveys in other oceans (e.g., Cózar et al., 2014; Eriksen et al., 2014), the results of the present surveys were compared with the findings of work conducted in the Japanese coastal area by Isobe et al. (2014). Their field surveys were conducted at 15 stations in the western Seto Inland Sea during the summers from 2010 to 2012 (upper panel of Fig. 1).

2.3. Measurements of small plastic fragments

The small plastic fragments collected were brought back to the laboratory to distinguish them from other suspended matter. All samples were first observed on 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 color and shape (Hidalgo-Ruz et al., 2012). Polymer types of material were identified using a Fourier transform infrared spectrophotometer (FT-IR alpha; Bruker Optics K.K., Tokyo, Japan) when fragments were too small for visual differentiation between microplastics and biological matter. Lines (probably fishing lines), expanded-polystyrene particles, and biological elements were removed before any further analyses. Primary microplastics such as pellets (Cole et al., 2011) were included in the subsequent analyses despite their small numbers.

The numbers of remaining pieces (hereinafter "quantity") in each size range were counted with an increment of 0.1 mm for microplastics, 1 mm for mesoplastics between 5 and 10 mm, and 10 mm for mesoplastics >10 mm. The sizes were defined by the longest length of each irregularly shaped fragment visible on the monitor display, as measured using image-processing software (ImageJ downloaded from http://imagej.nih.gov). The quantities within each size range were thereafter divided by the water volumes measured by the flow meter at each sampling station to convert them to quantities per unit seawater volume (hereinafter "concentration" with units of pieces m^{-3}). The concentration of microplastics (mesoplastics) was computed by integrating the concentrations of the fragments with sizes from 0.3 to 5 mm (from 5 to 40 mm).

The data sets produced in this study are available at figshare (Isobe et al., 2015).

2.4. Data analyses

To compare the estimated concentrations of microplastics obtained in this study with previous studies that deduced quantities per unit area (e.g., Eriksen et al., 2014; referred to as "count density" or "total particle count" in their paper), the concentration (pieces m^{-3}) of microplastics was integrated vertically (pieces km^{-2}). The quantities of small plastic fragments decrease exponentially into deeper layers (Kukulka et al., 2012; Reisser et al., 2015), and thus, the vertical distribution of the concentration (N) of microplastics can be expressed as follows:

$$N = N_0 e^{\frac{w}{A_0} z}, \quad (1)$$

where N_0 denotes the concentration of microplastics collected using the neuston net, w is the plastic rise velocity (5.3 mm s^{-1}) obtained experimentally by Reisser et al. (2015), and z is the vertical axis looking upward from the sea surface. The parameter A_0 is computed as:

$$A_0 = 1.5 u_* k H_S, \quad (2)$$

where u_* represents the frictional velocity of water (=0.0012 W_{10}), k is the von Karman coefficient (0.4), H_s is the significant wave height, and W_{10} is the 10-m wind speed (Kukulka et al., 2012). Vertically integrating Eq. (1) from the sea surface ($z = 0$) to the infinitely deep layer ($z \to -\infty$) yields the number of microplastics per unit area M (pieces km^{-2}) as:

$$M = N_0 A_0 / w, \quad (3)$$

which can be used for comparison with previous studies. We hereinafter refer to M as the "total particle count" in line with Eriksen et al. (2014). To determine W_{10} (4.5 m s^{-1}), the 10-m wind speeds measured by the Advanced Scatterometer (Kako et al., 2011) during the survey period were averaged spatially over the study area (lower panel of Fig. 1). In addition, to determine H_s (0.75 m), average significant wave heights during the survey period from three observatories: Wajima for waves in the Sea of Japan, Amami for the East China Sea, and Hitachi for areas east of Japan (Fig. 1), were obtained from the NOWPHAS website (http://nowphas.mlit.go.jp/index_eng.html). In the case of the Seto Inland Sea, we used 0.34 m and 4.3 m s^{-1} for H_s and W_{10}, respectively, based on in situ data averaged over the survey period (2010–2012 summers) at the nearest observatories.

To compare the estimates obtained during the present study with those of Cózar et al. (2014) in units of g km^{-2}, the concentration n (pieces m^{-3}) of each size (δ) was converted to weight per unit area M_w (g km^{-2}), i.e., the "concentration" in Cózar et al. (2014) and "weight density" in Eriksen et al. (2014), which was computed as follows:

$$M_w = \left\{ \rho \sum_{\delta < 5\,\mathrm{mm}} \left(\alpha \delta^3 n \right) \right\} A_0 / w, \quad (4)$$

where ρ denotes the density of polyethylene (950 kg m^{-3}) and α is the "shape factor", where 0.1 corresponds to a flat-shaped volume (Cózar et al., 2014). Note that N_0 in Eq. (3) is equal to $\sum_{\delta < 5\,\mathrm{mm}} (n)$, and that the volume of a flat-shaped piece of microplastic with size δ (thickness of $\alpha\delta$) is computed as $\alpha\delta^3$ in Eq. (4).

3. Results

Generally, large marine plastic debris gradually degrades into smaller pieces. It is therefore reasonable that the concentrations of small plastic fragments increase as their sizes decrease (Fig. 2). However, the concentrations of microplastics decrease rapidly at sizes <1 mm. The mesoplastics collected in the surveys were one order of quantity smaller than microplastics (Table 2). Nonetheless, as with microplastics, the concentrations of mesoplastics also increase monotonically as their sizes decrease; note that the increment of the size range is altered twice at 5 and 10 mm.

The statistics obtained in the present survey are listed in Table 2. The averaged concentration of pelagic microplastics around Japan is 3.7 pieces m^{-3}, which is about 10 times greater in the Seto Inland Sea (0.4 pieces m^{-3}; integrated value over the microplastics range in Fig. 3 of Isobe et al. (2014)). The standard deviations indicate that the concentrations of small plastic fragments vary considerably by station. The standard deviations of both micro- and mesoplastics are about three times their averages, although the concentrations that exceeded three times the standard deviation from the average were removed. The only outlier eliminated by this 3σ limit was Sta. 6, where a conspicuous quantity of microplastics (491 pieces m^{-3}) was entangled with floating seaweed that entered the neuston net.

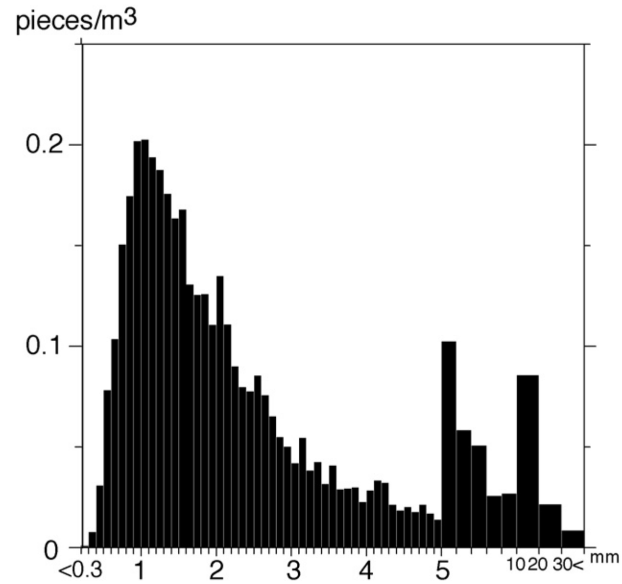

Fig. 2. Size distribution of small plastic fragments. The bars indicate the concentration in each size range on the abscissa. Note that the intervals of size ranges are 0.1 mm for microplastics, 1 mm for mesoplastics <10 mm, and 10 mm for mesoplastics >10 mm.

The concentration maps (Fig. 3a and b) also demonstrate the high variability of the small plastic fragments. The concentrations of microplastics become higher both to the north of the Sea of Japan and to the south of Japan. However, negligibly small concentrations are observed, even at those stations neighboring those with high values. In addition, of particular interest is that the concentrations reduce drastically in the southwestern part of the Sea of Japan, that is, the upstream of the Tsushima Currents (Fig. 1). The accumulation of microplastics in the downstream areas might result from unintended station placement near oceanic fronts where microplastics accumulate. However, this paper does not address the mechanism behind the accumulation of microplastics in the downstream regions of the Tsushima Currents. The distribution pattern of concentrations of mesoplastics is similar to the microplastics, although their concentrations are much smaller, irrespective of the station.

4. Discussion

4.1. Are the East Asian seas recognized as a hot spot of microplastics?

Substituting the averaged concentrations of microplastics (Table 2) into N_0 in Eq. (3) yields the total particle count in the East Asian seas

Table 2
Statistics of small plastic fragments collected in the present surveys. The units (except for the number of collected pieces) are pieces m^{-3}. Note that the maximal concentrations of both microplastics and mesoplastics were not used in computing the averages, standard deviations, and medians, because they were outliers of the 3σ cut (see text for details).

Statistics	Microplastics	Mesoplastics
Number of collected pieces	12,120	782
Averaged concentration	3.74	0.38
Standard deviation	10.40	1.06
Median	0.740	0.074
Maximal concentration	491.0	70.0
Minimal concentration	0.03	0.00

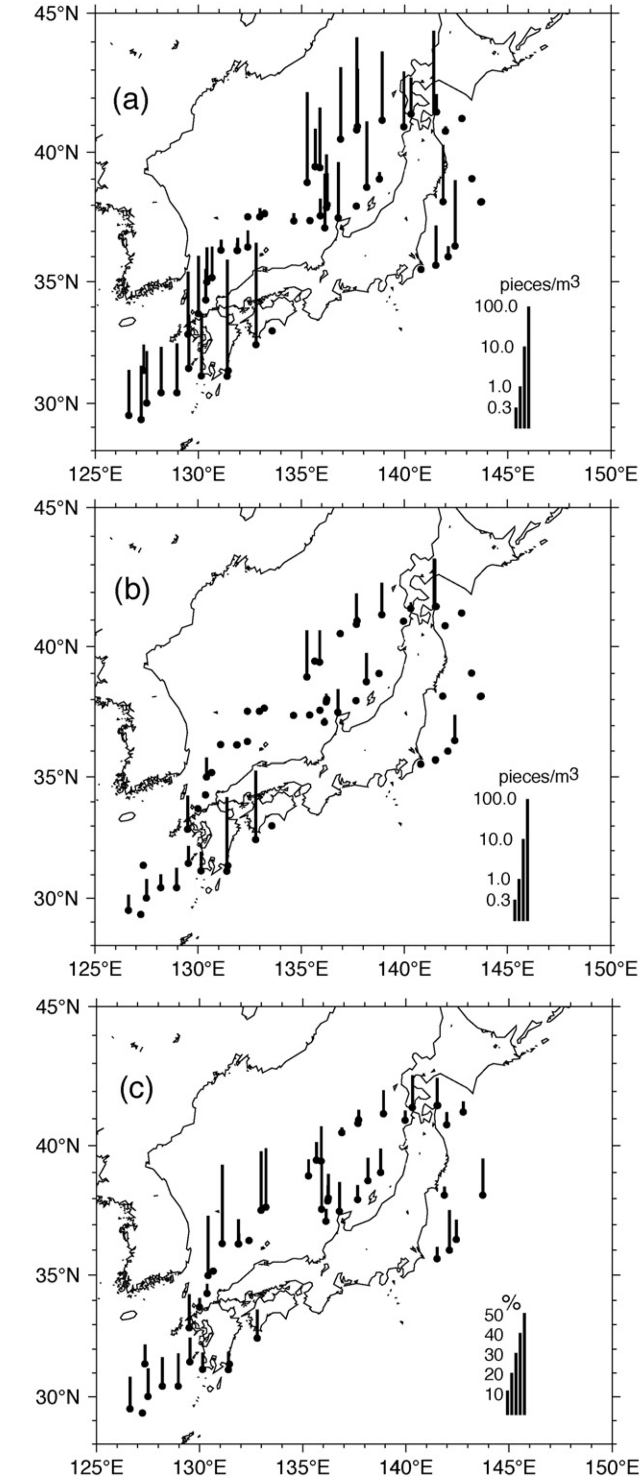

Fig. 3. Maps of concentrations of (a) microplastics, (b) mesoplastics, and (c) mesoplastics ratio. The stations with quantities of <10 pieces were removed in (c).

around Japan. The total particle count of microplastics in the North Pacific was computed from Table S4 in Eriksen et al. (2014) by summing the measured means of particles <4.75 mm, the upper limit of the definition of microplastics. In addition, the total particle count over the world oceans was computed by averaging the measured means of particles <4.75 mm in all oceans listed in Eriksen et al. (2014).

The East Asian seas around Japan are certainly regarded as hot spots of pelagic microplastics (Fig. 4). Of note, the total particle count in the East Asian seas is 1,720,000 pieces km^{-2}, i.e., 16 times greater than in

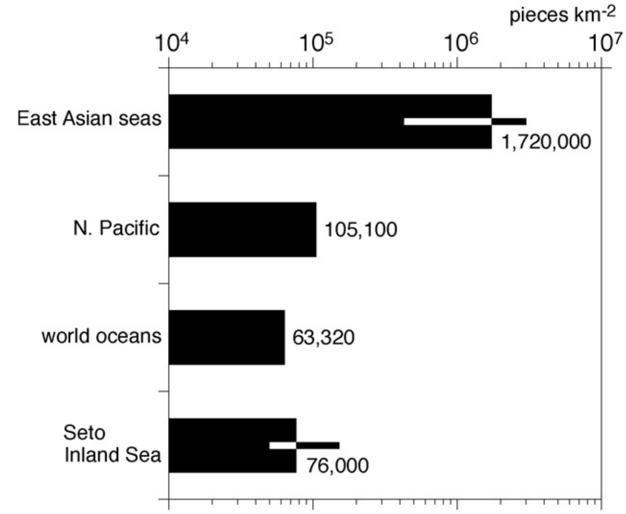

Fig. 4. Comparison of total particle counts computed in four areas. The total particle counts are shown by digits as well as bar heights. Superimposed on the bars of the East Asian seas and the Seto Inland Sea is the margin of error evaluated by a *t*-test with a 95% confidence interval.

the North Pacific and 27 times greater than in the world oceans. Using Eq. (4), it is possible to convert the total particle count (M in Eq. (3)) to the weight per unit area (M_w in Eq. (4)) as 2422 g km^{-2}. This surface density is about seven times greater than the North Pacific value of Eriksen et al. (2014; 337 g km^{-2} in their Table S4). Furthermore, the surface density is one order of magnitude greater than that found by Cózar et al. (2014) in non-accumulation zones in the North Pacific. Their surface density, even in accumulation (oceanic frontal) zones, was 500 g km^{-2} or less, which is significantly smaller than the present estimate. In this application, an approximate estimate of the total particle count of microplastics is provided. In particular, homogeneous values might be inadequate for the significant wave height and wind speed in Eq. (2). Nonetheless, the conspicuous count found in the present study is unlikely to diminish drastically, even if locally varying wave heights and wind speeds at each station were used for the computation, because the present surveys were conducted under relatively calm conditions throughout the entire period.

It is also interesting that the total particle count in the Seto Inland Sea (Isobe et al., 2014) accounts for <5% of the present estimate (Fig. 4). The Seto Inland Sea remains relatively uncontaminated by microplastics, even though it is surrounded by the East Asian seas that have high concentrations of microplastics, and the water exchange between it and the outer ocean is completed within a relatively short period (15 months; Takeoka, 1984). First, the Seto Inland Sea is unlikely to be a primary source of microplastics in the East Asian seas because of its significantly small count in comparison with the surrounding seas. Second, coastal waters such as the Seto Inland Sea might act as a sink of microplastics via shore deposition by onshore waves, nanofragmentation on beaches under the action of sunlight, and active biofouling and/or ingestion in the high-productivity zone. However, in-depth examinations are needed to confirm the above suppositions, especially regarding the transport processes of small plastics fragments.

4.2. Sources of plastic debris suggested by the size distribution

Different from the macroplastics littered on beaches, it is mostly impossible to identify the sources of small plastic fragments by reading legible textual information frequently found on the surface of marine debris. Instead, the size distribution of small plastic fragments is indicative of both their sources and possible transportation pathways within the oceans (e.g., Isobe et al., 2014). This is because the concentration of relatively "fresh" mesoplastics must increase in areas closer to their sources. Fig. 3c presents a map of the mesoplastics ratio: $N_m/(N_m + N_0) \times 100\%$, where N_m (N_0) denotes the concentration of mesoplastics (microplastics) collected by the neuston nets. Stations with quantities of small plastic fragments of <10 were eliminated in the construction of the map because their fluctuating ratios were unreliable.

The map of the ratio of mesoplastics suggests that the small plastic fragments were carried by the northeastward ocean currents. The long bars north of the Sea of Japan indicate the accumulation of small plastic fragments in the downstream of the Tsushima Current (Fig. 3a and b). However, these northern long bars mostly disappear in the map of the ratio of mesoplastics (Fig. 3c), in which the positions of the long bars move to the south of the Sea of Japan and East China Sea, i.e., the upstream regions of the Tsushima Current (Fig. 1). It is therefore considered that the mesoplastics degraded gradually as they were carried by the northeastward ocean currents. However, it must be noted that the current speed in the Sea of Japan is typically of the order of 10 cm s^{-1} (Hase et al., 1999) and thus, the time taken for small plastic fragments to move across the entire Sea of Japan (~1000 km) is estimated to be about 2–3 months. Apparently, the degradation of mesoplastics to microplastics is unlikely to proceed within such a short period; a field experiment has shown that the time required for degrading plastics exposed in air is about half a year (Andrady, 2011). The shift in the size distribution to smaller fragments north of the Sea of Japan (Fig. 3c) indicates the plastic fragments were not carried by ocean currents directly to the northeast, but rather they moved slowly downstream as they were repeatedly washed ashore on beaches and returned to the ocean. Northeastward currents prevail over the Yellow and East China seas, as well as in the areas around Japan (Isobe, 2008). Therefore, the small plastic fragments collected in this survey are considered to originate in these upstream areas.

Finally, it should be noted that the concentration of microplastics <1 mm decreases rapidly in Fig. 2, although the concentration increases in a quadratic sense, even within the smaller range. The rapid decrease of the concentrations of these tiny microplastics was observed irrespective of the station (not shown). Such microplastics might frequently have slipped through the neuston net because their sizes are close to the mesh size (0.35 mm). However, Cózar et al. (2014) found that a similar rapid decrease in small-sized fragments never occurred for non-plastic particles (see their Fig. S12). In addition, the rapid decrease in small-sized fragments was not observed by Reisser et al. (2015) using a 5-m-deep multi-level net (see their Fig. 6). The suggestion drawn from these recent studies is that the removal of tiny microplastics from the upper oceans is a consequence of the deep intrusion of the microplastics that are prevented from ascending because of friction due to their large surface area to volume ratio (Isobe et al., 2014). Nevertheless, further examinations are required urgently to uncover the fate of such tiny microplastics, because biofouling (Zettler et al., 2013; Long et al., 2015) and ingestion by zooplankton (Cole et al., 2015; Desforges et al., 2015) potentially have non-negligible roles in the removal of microplastics from the upper oceans.

5. Conclusions

Based on field surveys using two vessels in the East Asian seas around Japan, it was established that the total particle count of pelagic microplastics is one order of magnitude higher than observed in other world oceans. Nevertheless, this study area was limited to within a part of the East Asian seas, and therefore the origins, pathways, fate, and environmental impacts of the microplastics, which are not confined to territorial waters, should be investigated further in a cooperative research project involving participants from across East Asia. In fact, recent studies on the biological impacts of microplastics (e.g., Yamashita et al., 2011; Rochman et al., 2013; Wright et al., 2013) have offered a pessimistic outlook for the earth, in which the amount of microplastics in the oceans will continue to increase because they never disappear in nature. What transpires in the East Asian seas will eventually materialize in the rest of the world oceans, and thus studies on marine plastic pollution in these areas are of paramount importance.

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