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Selective transport of microplastics and mesoplastics by drifting in coastal waters

Atsuhiko Isobe [a,*], Kenta Kubo [b], Yuka Tamura [c], Shin'ichio Kako [d], Etsuko Nakashima [e], Naoki Fujii [f]

[a] Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-Koen, Kasuga 816-8580, Japan
[b] Graduate School of Science and Engineering, Ehime University, 2-5 Bunkyo-cho, Matsuyama 790-8577, Japan
[c] Faculty of Science, Ehime University, 2-5 Bunkyo-cho, Matsuyama 790-8577, Japan
[d] Graduate School of Science and Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan
[e] Tosa Food Business Creator Project Team, Kochi University, B-200, Monobe, Nankoku 783-8502, Japan
[f] Institute of Lowland and Marine Research, Saga University, Honjo 1, Saga 840-8502, Japan

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ABSTRACT

The quantity and size distributions of small plastic fragments in the Seto Inland Sea, Japan were investigated using field surveys and a numerical particle-tracking model. The model was used to interpret the distributions of small plastic fragments and the possible transport processes in coastal waters. Of note, the size and quantity of mesoplastics (approximately >5 mm) gradually increased close to the coast irrespective of the existence of river mouths, which probably act as a major source of anthropogenic marine debris. Additionally, microplastics were more dominant as we moved further offshore. The numerical model reproduced the near-shore trapping of mesoplastics, suggesting that mesoplastics are selectively conveyed onshore by a combination of Stokes drift and terminal velocity, dependent on fragment sizes. It is suggested that mesoplastics washed ashore on beaches degrade into microplastics, and that the microplastics, which are free from near-shore trapping, are thereafter spread offshore in coastal waters.

1. Introduction

Plastic marine debris drifting in the ocean gradually degrades into small fragments. These fragments are categorized by their sizes, into nanoplastics (less than a few micrometers), microplastics (approximately <5 mm), and mesoplastics (Andrady, 2011; Cole et al., 2011). The present study deals with microplastics and mesoplastics, whose sizes have a range from 0.3 mm to a couple of centimeters (this lower limit was dependent on the mesh size of the neuston net used in the study). To date, biological and chemical studies have elucidated that these small plastic fragments have been widely spread in the oceans (even inside the bodies of live marine organisms; Browne et al., 2008; Boerger et al., 2010; Murray and Cowie, 2011). These plastic fragments are potentially a threat to marine lives because they can be a transport vector of toxic metals (Aston et al., 2010; Holmes et al., 2012; Nakashima et al., 2012) and persistent organic pollutants (Mato et al., 2001; Endo et al., 2005; Rochman et al., 2013).

To understand the fate of plastic debris in nature including the biosphere, we need to know how ocean currents and/or waves carry small plastic fragments. Up to now, several numerical studies have investigated behavior of marine debris drifting in the large-scale ocean circulation (Kubota, 1994; Yoon et al., 2010; Kako et al., 2011; Maximenko et al., 2012; Kako et al., 2014). However, the oceanic transport processes of plastic fragments smaller than mesoplastics are poorly understood, except to map their quantity in open oceans (e.g., Day and Shaw, 1987; Law et al., 2010; Cózar et al., 2014). The present study therefore attempts to elucidate the transport processes of meso- and microplastics, based on a combination of field surveys with a numerical particle-tracking model. First, the field surveys were conducted to map the quantity and size distributions of microplastics and mesoplastics in coastal waters where plastic marine debris is loaded directly from the land. Thereafter, a simple numerical model was established to reasonably explain the quantity and size distributions that result from the transport processes of small plastic fragments in the real world.

Before considering the transport processes of small plastic fragments, we start with the question of how mesoplastics in the ocean degrade into microplastics (except "primary" ones such as scrubbers; Cole et al., 2011). According to Gregory and Andrady (2003), Corcoran et al. (2009), and Andrady (2011), the degradation of plastic marine debris occurs more on beaches than in seawater, as exposure to ultraviolet radiation and mechanical erosion are

* Corresponding author. Tel.: +81 92 583 7726; fax: +81 92 573 1996.
E-mail address: aisobe@riam.kyushu-u.ac.jp (A. Isobe).

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minimal in the latter. In particular, the degradation is slower in seawater because the plastic is kept at a lower temperature because of no heat buildup in water, and because fouling covers the plastic shielding it from solar ultraviolet. However, from a physical oceanographic viewpoint, this may appear paradoxical in considering how infrequently mesoplastics are washed ashore on beaches. In general, plastic debris floating in the oceans consists mostly of polymers lighter than seawater (polyethylene and polypropylene; Andrady, 2011; Nakashima et al., 2011). Hence, they are likely to be trapped around oceanic fronts and streaks ubiquitously formed in coastal waters, because floating objects and bubbles are immediately accumulated toward these features by convergent surface currents. Nonetheless, large marine debris floating partly above the sea surface may become free of convergence, because they are readily pushed by winds (i.e., leeway drift; Richardson, 1997). However, it is impossible for leeway drift to exert drag directly on mesoplastics, which are drifting completely beneath the sea surface. Additionally, a nonnegligible fraction of mesoplastics in coastal waters must leak into the open oceans as a result of ocean currents. Therefore, the probability of mesoplastics being washed ashore onto beaches may be lower than projected.

How do mesoplastics degrade into microplastics? As well as waiting for mesoplastics to wash ashore by chance, it is natural to seek an oceanic transport process favoring the degradation of mesoplastics. We thus examined two hypotheses. Firstly, we hypothesize that mesoplastics have mostly degraded into microplastics before leaving river mouths, which are a major source of plastic debris into oceans. It is suggested that mesoplastics are repeatedly washed ashore onto riverbanks during their journey downstream, and thus degraded. The other hypothesis is that mesoplastics in the ocean are "selectively" conveyed onshore, and that microplastics return to the offshore after their degradation on beaches. Although the latter hypothesis may sound optimistic for the readers, it is this process on which we will focus in the present study.

2. Methods

2.1. Field surveys

To investigate the quantity and size distributions of small plastic fragments, field surveys were conducted at 15 stations from 2010 to 2012 (Fig. 1 and Table 1). We chose coastal stations at the Hiji River mouth, in the Iyo Sea, the Uwa Sea, and the Hyuga Sea, which are all located in the western part of the Seto Inland Sea, Japan. To investigate how sizes of plastic fragments vary spatially, sampling was conducted only in the coastal waters. Plastic marine debris mostly originates from the land except those used for offshore fisheries, and thereafter may start to degrade to small fragments gradually while drifting in the ocean. The sampling stations close to the Hiji River mouth (h_1, h_2, and h_3 in Fig. 1) were selected as sites where small plastic fragments could be collected, as they were loaded into the ocean. If the size composition at the river mouth is nearly the same as in the surrounding areas (e.g., Stas. i_1, i_2, and i_3 within the same Iyo Sea), it can be suggested that degradation mostly occurs before plastic fragments leave the river mouths (i.e., the first hypothesis). The stations in the Uwa Sea (u_1 to u_8) were selected for investigating the spatial variation where there were no big rivers. The station in the Hyuga Sea (*hy*) was closest to the open ocean (Kuroshio Current) among all our stations. Sampling was conducted during the period May through September (see year/month/date in Table 1) to avoid the period with the intense northwesterly East Asian winter monsoon, which might drastically change the ocean circulation (hence, the quantity-size distribution of plastic debris) over the study area, and wind mixing might change the vertical distribution of small plastic fragments (Kukulka et al., 2012).

A neuston net (5552; RIGO Co., Ltd., Tokyo, Japan; Fig. 2a), originally designed for sampling of zooplankton, fish larvae, and fish eggs near the sea surface, was used for sampling mesoplastics and microplastics (Hidalgo-Ruz et al., 2012). The net mouth was 75 cm × 75 cm, with a length of 300 cm, and mesh size of 0.35 mm. As mentioned earlier, the lower limit of the microplastics sampled in the present study depends on this mesh size. A flow meter (5571A; RIGO Co., Ltd.) was equipped at the mouth of the net to measure the water volume passing through during sampling.

The neuston net was towed by the training vessel *Yuge-maru* (240 t) belonging to the Yuge National College of Marine Technology at Sta. *hy*. All other sampling was conducted using the research vessel *Isana* (14 t) belonging to Ehime University. To collect small plastic fragments efficiently, we first sought oceanic fronts along which the accumulation of drifting objects and bubbles was observed by eye. Thereafter, the neuston net was towed at a typical speed of 2–3 knots continuously for 10–15 min around the fronts (Fig. 2b). The quantity of small plastic fragments may be dependent on distance from oceanic fronts and/or strength of convergence. Thus, we should compare the size composition of fragments among stations, rather than the quantity of fragments. Over the course of the surveys, the temperature and salinity of seawater were measured every second using a conductivity and temperature sensor (Compact-CT, JFE Advantech Co., Ltd., Hyogo, Japan) on the water continuously pumped up onto the deck. Salinity data were useful for examining the extent that freshwater (hence, plastic fragments) from rivers had mixed into the seawater at each station.

2.2. Measurements of microplastics and mesoplastics

Microplastics and mesoplastics (photo in Fig. 2c) collected on board were brought back to our laboratory to count the number of pieces (defined as "quantity" in the present study), and to measure their sizes. All samples were first observed on a monitor display (Fig. 2d) via a USB camera (HDCE-20C; AS ONE Corporation, Osaka, Japan) attached to a stereoscopic microscope (SZX7; Olympus Corporation, Tokyo, Japan). Small plastic fragments were thereafter identified visually by their colors and shapes (Hidalgo-Ruz et al., 2012). We then counted the quantities in every size range with an increment of 0.1 mm for microplastics (<4 mm in this case), 1 mm for mesoplastics between 4 mm and 10 mm, and 10 mm for mesoplastics larger than 10 mm. Sizes were defined by the longest length of each irregular-shaped fragment measured using an image processing software (ImageJ downloaded from http://imagej.nih.gov) on the monitor display. The quantities within each size range were divided by the water volumes measured by the flow meter at each sampling station to convert them to the number of pieces per unit seawater volume (hereinafter, "drift density" in the unit of pieces/m^3). Polymer types of the samples collected at Stas. i_1 and i_2 were identified using a Fourier transform infrared spectrophotometer (FT-IR alpha; Bruker Optics K.K., Tokyo, Japan).

3. Results

Using all sampling data except those from Sta. u_2 to Sta. u_8, drift densities of microplastics and mesoplastics are shown for all size ranges (Fig. 3). One of the remarkable features regardless of stations is that the drift density has the mode at sizes smaller than 1 mm, which is a similar size to zooplankton. Hence, fish are likely

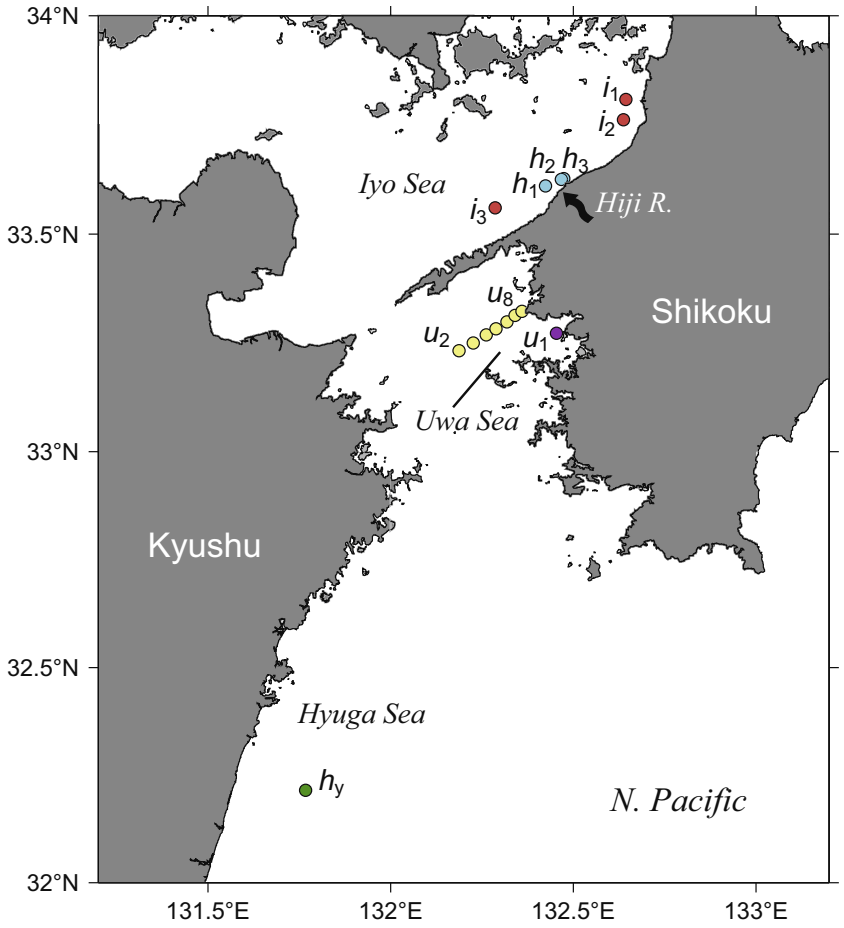

Fig. 1. Observation stations in the western part of Seto Inland Sea, Japan.

Table 1
Salinity and distance from the nearest coast of the sampling stations.

Sea	Year/month/date	Stas.	Salinity	Distance (km)
Iyo Sea	2010/06/11	i_1	32.0	4.5
	2010/09/01	i_2	31.4	5.0
	2011/07/14	i_3	31.8	9.5
Hiji R. mouth	2011/07/14	h_1	26.1	1.2
	2011/08/09	h_2	31.2	4.2
	2011/09/13	h_3	30.2	1.6
Hyuga Sea	2011/06/01	hy	32.1	21.6
Uwa Sea	2011/08/09	u_1	31.7	2.2
	2012/05/17	u_2, u_3, u_4, u_5	33.4, 32.5, 32.4, 32.6	19.7, 15.6, 11.6, 8.8
		u_6, u_7, u_8	32.4, 32.5, 32.6	5.5, 2.9, 1.1

to ingest microplastics, and thus microplastics will be easily integrated into the marine food chain. However, a question naturally arising is why the drift density of microplastics rapidly decreases as their sizes approach the lower sampling limit (i.e., 0.3 mm in the present case). One possible answer is that microplastics smaller than a few hundred micrometers may exhibit resistance to degradation. If this is the case, nanoplastics (although it is beyond the scope of the present study) drifting in the ocean are mostly particles in the form that they were originally manufactured. An alternative answer is that microplastics frequently slip through the neuston net as their sizes are close the mesh size. In the present study, the fragment size is defined as the longest length of each fragment, thus fragments with irregular shapes may slip through the net, despite their longest part being greater than the mesh size. Nonetheless, we have no way of knowing why smaller microplastics are low in density, and thus this paper will not delve into the mechanisms of why the drift density of microplastics decreases rapidly beyond the mode less than 1 mm.

In response to the observed size compositions in Fig. 3(a) and (b), we have to reject the first hypothesis that microplastics are formed mainly along rivers. We noted that large quantity of mesoplastics was collected at the Hiji River mouth (Fig. 3b), but were rarely collected in the Iyo Sea (Fig. 3a). The relatively less saline water observed at the Hiji River mouth (see Table 1 for salinity at all stations) shows that the small plastic fragments collected at Stas. h_1, h_2, and h_3 certainly contained those loaded directly from the river mouth, along with freshwater input. Meanwhile, mesoplastics were absent at Stas. i_1, i_2, and i_3, which were located

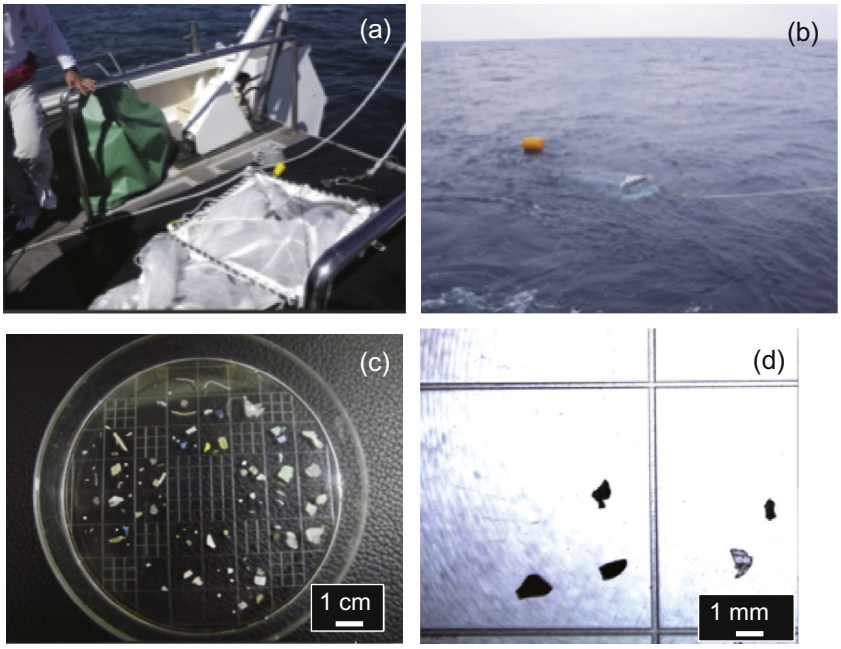

Fig. 2. Photographs of the sampling and measurement procedure for small plastic fragments. (a) The neuston net on deck, (b) towing of the neuston net from the R/V *Isana*, (c) collected small plastic fragments, and (d) microplastics observed on a monitor display via a stereoscopic microscope.

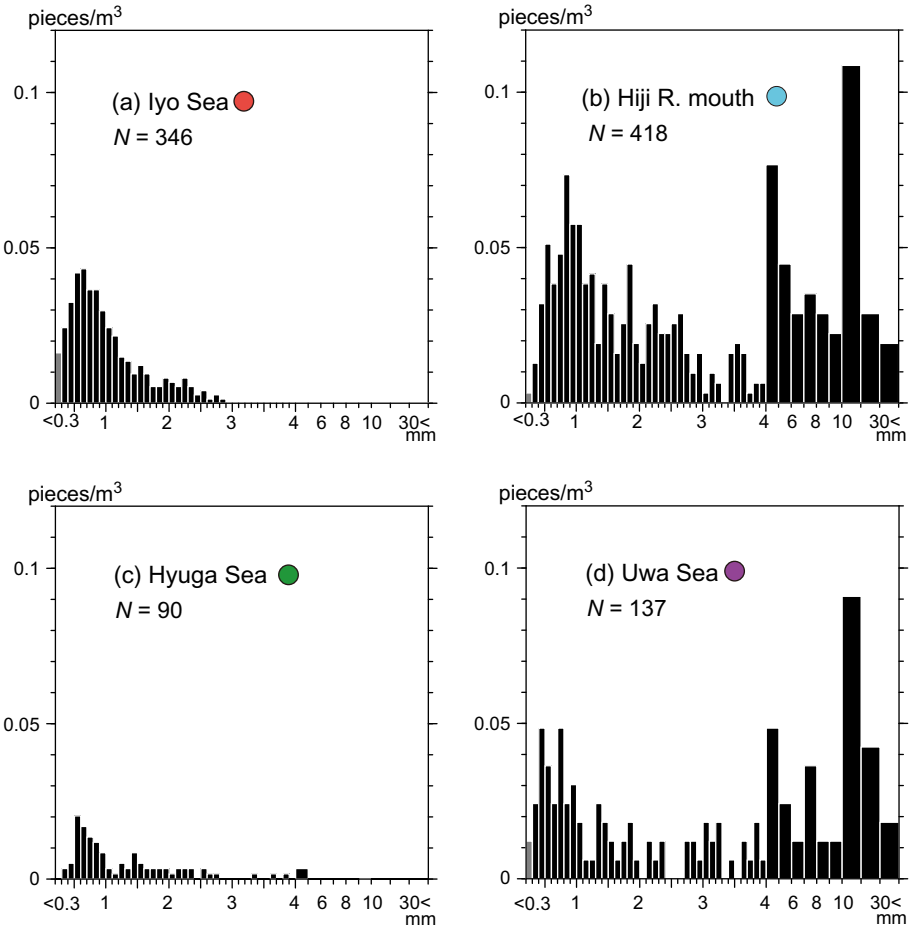

Fig. 3. Drift density and size distribution of small plastic fragments in the (a) Iyo Sea, (b) Hiji River mouth, (c) Hyuga Sea, and (d) Uwa Sea. In each panel, different color circles denote the stations with the same colors in Fig. 1. Note that size intervals of the bars are altered by sizes as described in the text. The bar smaller than 0.3 mm is shown in gray, representing that the quantity was ambiguous because of the mesh size of the neuston net (0.35 mm). *N* denotes the total number of pieces in each panel.

around 10 km from the river mouth (Fig. 1). Thus, it is suggested that the degradation from mesoplastics to microplastics occurred within this short distance in the coastal area.

The most notable finding is that the drift density of small plastic fragments depended not only on the distance of the stations from the river mouth, but also on distance from the nearest coast from each station. The plastic fragments collected in the Uwa Sea (Sta. u_1; Fig. 3d), which lacks large rivers (see salinity in Table 1), certainly contained a large proportion of mesoplastics, which is similar to the Hiji River mouth (Fig. 3b). This station in the Uwa Sea differed from the stations in the Iyo Sea (Fig. 3a) and Hyuga Sea (Fig. 3c), not in salinity, but in the distance from the nearest coast (Table 1). Hence, a field survey was added in 2012 to investigate the dependency of the size composition of small plastic fragments on the distance from the coast (Stas. u_2 to u_8 in Fig. 1). The drift density is plotted as a function of both size and distance from the nearest coast, using all samples except those at the Hiji River mouth (Fig. 4). The drift density indicates that small plastic fragments larger than a few mm rapidly disappeared as we went offshore. Meanwhile, microplastics, especially those smaller than 1 mm were spread widely in an offshore direction. The absence of mesoplastics offshore suggests that the degradation occurred close to the coast (probably on beaches as suggested by Andrady (2011)). The implication is that the near-shore trapping of mesoplastics occurred because of "selective transport" in coastal waters, with mesoplastics chosen for moving onshore, and microplastics degraded on beaches and then spread widely offshore.

4. Discussion

4.1. Concept and model set-up for the transport of small plastic fragments

In the present study, we attempt to explain the selective onshore transport of small plastic fragments drifting in coastal waters by a combination of buoyancy force, friction, and Stokes drift (Fig. 5 for a schematic view). Around 80% of the small plastic fragments collected in the present survey were composed of

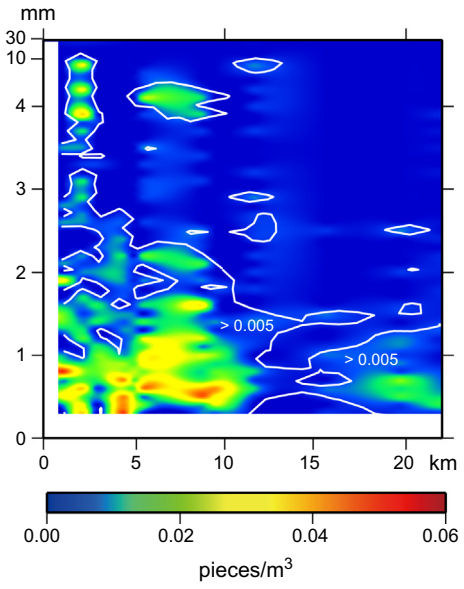

Fig. 4. Drift density (colors) of small plastic fragments as a function of their size (ordinate) and distance from the nearest coast (abscissa). All collected samples, except those found at the Hiji River mouth, are depicted. The scale of drift density is at the bottom of the figure. The white curves show the contour line of 0.005 pieces/m^3.

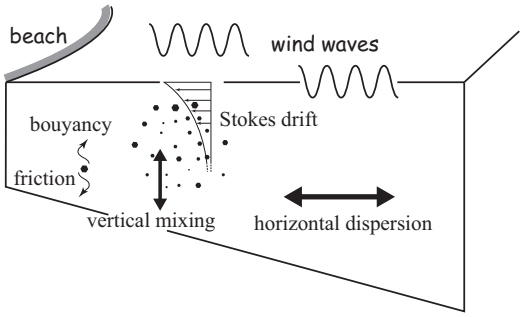

Fig. 5. Schematic view of the selective onshore transport of mesoplastics. See Section 4.1 for details.

polyethylene or polypropylene, of which densities are both lighter than seawater (Table 2). Mixed intensely in the turbid uppermost layer, small plastic fragments are therefore forced to move upward because of the buoyancy force. However, upward motion in seawater always exerts friction on the surface of the plastic fragments. In general, the larger the particles are, the faster the upward terminal velocity. Thus, mesoplastics are drifting in the uppermost layer, which is shallower than the layers in which microplastics drift. Meanwhile, wind waves in shallow coastal waters cause an onshore mass transport velocity (Stokes drift) because of nonlinearity. The Stokes drift in the upper layer is always faster than in deeper layers, and thus relatively large mesoplastics are likely to be carried onshore faster than microplastics.

We formalized the above speculation by modeling the selective onshore transport of mesoplastics. A particle-tracking model was established on a vertical two-dimensional plane with the x-axis directed offshore, and with the z-axis directed upward. Under the assumption of homogeneity in the alongshore direction, we only dealt with motion in the x–z plane. Horizontal and vertical positions, $\mathbf{x} = (x, z)$, of small plastic fragments at time $t + \Delta t$ were solved numerically using those at t as follows:

$$\mathbf{x}(t + \Delta t) = \mathbf{x}(t) + \mathbf{u}\Delta t \tag{1}$$

where Δt denotes the time increment of the iteration, and $\mathbf{u}$ the horizontal (u) and vertical (w) velocities carrying small plastic fragments.

The horizontal velocity (u) was calculated from a combination of Stokes drift in the finite ocean depth (h) and a random walk as follows:

$$u = -\frac{a^2\sigma k \cos h\{2k(h+z)\}}{2(\sin h\ kh)^2} + \frac{R\sqrt{2K_h\Delta t}}{\Delta t} \tag{2}$$

where a denotes the wave amplitude, σ the wave frequency, k the wave number, R the random number ranging from −1 to 1, and K_h the horizontal diffusivity, respectively. The first term on the right-hand side of Eq. (2) represents the onshore (hence, negative) Stokes drift, and the second term the horizontal dispersion by various ocean currents such as rip currents, tidal currents, density-driven currents, and wind-driven currents, which all typically

Table 2
Density and polymers of collected samples.

Polymer types	Stations (year/month/date)		Density (g/cm^3)
	i_1 (2010/06/11)	i_2 (2010/09/01)	
Polypropylene	19%	25%	0.85–0.9[a]
Polyethylene	68%	53%	0.91–0.97[a]
Others	13%	22%	–

[a] Andrady (2003).

occur in shallow coastal waters. The values chosen for the parameters are listed in Table 3. The parameters related to wind waves (a, σ, and k) were determined from annually averaged values observed at the western part of the Seto Inland Sea in 2010 (Kanda Station, downloaded from http://www.mlit.go.jp/kowan/nowphas/index_eng.html). The ocean depth was calculated from an approximate average of the depths at the field surveys stations, except at Sta. hy. The value of K_h was determined through trial and error so as that the offshore extent of the modeled fragment distribution reproduced the observed one in Fig. 4. Hence, our concern was not the extent to which modeled fragments spread offshore, but the differences in dispersion among fragment sizes.

Modeled small fragments were assumed to be spherical for simplicity. Thereby, we were able to formalize the vertical velocity (w) by a combination of the terminal velocities (Japan Society of Civil Engineers, 1999) and a random walk as follows:

$$w = \frac{d^2(\rho-\rho')g}{18\eta} + \frac{R\sqrt{2K_z\Delta t}}{\Delta t}, \quad R_e < 1, \tag{3}$$

$$w = 0.223d\left\{\frac{(\rho-\rho')^2 g^2}{\rho\eta}\right\}^{1/3} + \frac{R\sqrt{2K_z\Delta t}}{\Delta t}, \quad 1 \leqslant R_e \leqslant 100, \tag{4}$$

$$w = 1.82\left\{\frac{(\rho-\rho')gd}{\rho}\right\}^{1/2} + \frac{R\sqrt{2K_z\Delta t}}{\Delta t}, \quad 100 < R_e, \tag{5}$$

where the terminal velocities (first terms on the right-hand side) were classified into three groups by the Reynolds number ($R_e = \rho w d/\eta$), ρ denotes the seawater density, d the particle size, η the viscosity of seawater, ρ' the density of particles, g the gravitational acceleration, and K_z the vertical diffusivity, respectively. The parameter values in Eqs. (3)–(5) are listed in Table 3. The density of polyethylene was used for the value of ρ' because of the predominance of this polymer type among the collected samples (Table 2). The eddy diffusivity, K_z, was determined somewhat arbitrarily, but is justified by recent measurements using microstructure profilers in coastal waters (e.g., Tsutsumi and Matsuno, 2012). The vertical velocity (w) before onetime step ($t - \Delta t$) is substituted to the Reynolds number in the computation for each particle.

The computational procedure was as follows. First, we released 10,000 particles at $x = 0$ (coast) and $z = 0$ (sea surface), and $t = 0$. The size composition of these modeled particles was adjusted to be equal to the observed value (Fig. 4). Thereafter, the locations of the particles were repeatedly computed using Eqs. (1)–(5) by iteration. After some time, an equilibrium state was reached, and it is on this state that we will focus. In the present application, the iteration was continued for 5 days.

Table 3
Parameters used in the numerical model.

Variables	Physical quantities	Equations	Values
Δt	Time increment	(1), (3)–(5)	10 s
a	Wave amplitude	(2)	0.5 m
σ	Wave frequency	(2)	2.2 s^{-1}
k	Wave number	(2)	0.45 m^{-1}
h	Ocean depth	(2)	20 m
K_h	Horizontal diffusivity	(2)	4000 $m^2 s^{-1}$
ρ	Seawater density	(3)–(5)	1025 kg m^{-3}
ρ'	Particle density	(3)–(5)	950 kg m^{-3}
η	Viscosity of seawater	(3)–(5)	1.025×10^{-3} kg m^{-1} s^{-1}
g	Gravitational acceleration	(3)–(5)	9.8 m s^{-2}
K_z	Vertical diffusivity	(3)–(5)	0.01 m^2 s^{-1}

4.2. Selective transport of small plastic fragments

Two snapshots of modeled particles clearly demonstrate how the particles spread in the model domain from the beginning of the computation (Fig. 6). One hour after from their release, the particles had spread rapidly offshore up to 10 km from the coast ($x = 0$ km), owing to the random walk given to each particle. Meanwhile, the Stokes drift returns these particles toward the coast, shown as a vertical profile in the upper panel. Thus, the drift density of the modeled particles became high near the coast even 24 h after their release. It is also remarkable that particles larger than 1 mm was absent in the layers deeper than 1 m. Size dependency was only incorporated in Eqs. (3)–(5), so that the variation in particle sizes at different depths result from these terminal velocities. Both the horizontal and vertical extent of particle spreading did not differ much with time after 24 h (not shown). Hence, it is considered that an equilibrium state was mostly accomplished after 24 h.

The modeled drift density, which was dependent on both size and distance, gives us confidence in concluding the selective transport process of microplastics and mesoplastics. The dependency of particle sizes on the modeled drift density never appeared, if the terminal velocities were independent of particle sizes. However, this is not the case. Figure ure7 is the same as Fig. 4, but for the modeled particles drifting above 0.75 m, that is, the height of the neuston net used for the sampling. The similarity is quite apparent when comparing Figs. 4 and 7, where particles larger than a few millimeters were trapped near the coast, and where the offshore extension of particles was greater as particle size became smaller. Therefore, it is considered that the selective onshore transport of

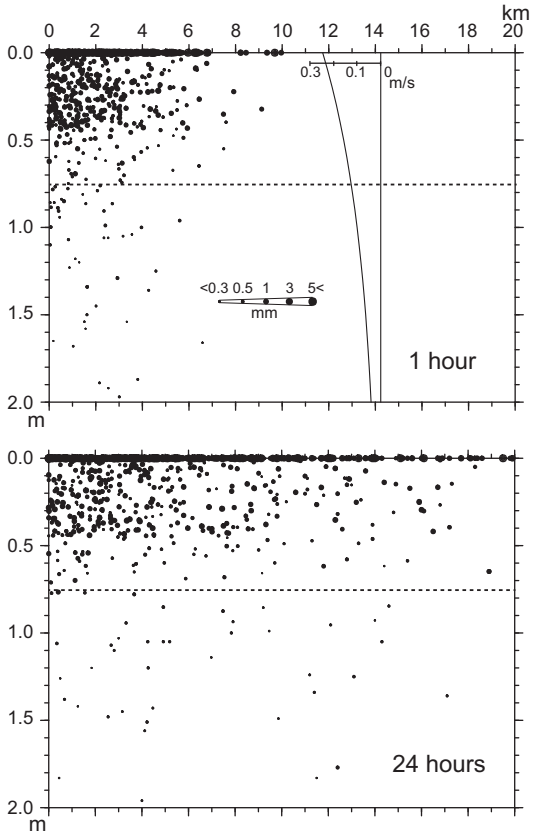

Fig. 6. Modeled particle positions after 1 h (upper panel) and 24 h (lower panel), in the upper 2-m layer of the model domain. The diameters of the particles denote the modeled sizes as shown in the upper panel. The broken line indicates the depth of 0.75 m above which particles were chosen to depict the modeled drift-density map in Fig. 7. Also shown in the upper panel is the current profile of the Stokes drift given to the model.

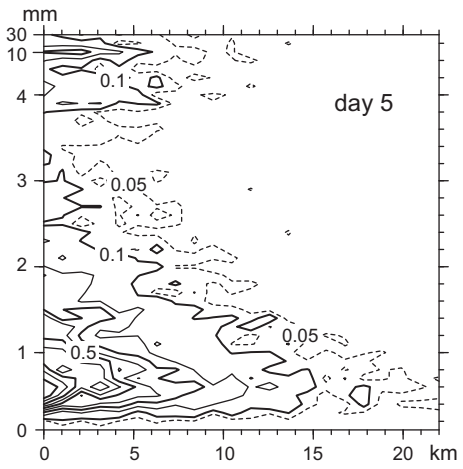

Fig. 7. Same as Fig. 4, but for the modeled result on day 5. Values are normalized by the maximal value in this figure. Contour interval is 0.1. The contour of 0.05 is added (broken curves).

mesoplastics occurs, as a result of a combination of the Stokes drift in coastal waters and terminal velocities dependent on particle size. It is also suggested that microplastics are formed by degradation on beaches, and thereafter return to the offshore.

5. Conclusion

In the present study, we found that the transport process in coastal waters favors the degradation of mesoplastics. The field surveys, in conjunction with the numerical model, demonstrated the near-shore trapping of mesoplastics by a combination of the Stokes drift and terminal velocities dependent on particle sizes. The mesoplastics drifting close to the coast are likely to be washed ashore on beaches, and easily return to the ocean by tides and waves. This selective onshore transport of mesoplastics works persistently until they degrade on beaches into microplastics. Once mesoplastics degrade into fragments smaller than a few millimeters (see Fig. 3a and c for the size composition far from the coasts), these microplastics are free of the near-shore trapping, and thus able to spread offshore.

Last, we have to emphasize that our simplified model is still sketchy in uncovering the fate of small plastic fragments in the ocean. One of the limitations is that the total quantity of small plastic fragments is assumed to be constant within the model domain. Plastic marine debris is commonly added from the land and never disappears in nature. Hence, the quantity of small-degraded plastic fragments drifting in the ocean is ever increasing. Nonetheless, it is a difficult task to truly quantify the plastic-debris cycle, that is, the loading rate into the oceans, the degrading rate into microplastics, and the increasing addition of small plastic fragments. Furthermore, buoyant plastic fragments drifting within the thin uppermost layer (see Fig. 6) make the problem a highly complex one. In addition to the Stokes drift incorporated in the present numerical model, small plastic fragments in the real world are also carried by Langmuir circulation, Ekman drift, mass transport associated with breaking waves, and ambient ocean currents such as tidal currents. Therefore, the fate of plastic debris will remain ambiguous unless more research is conducted to uncover oceanic pathways within the turbid surface "skin" layer, although it has received little attention to date.

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