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Selective transport of microplastics and mesoplastics by drifting in coastal waters

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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

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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