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# The vertical distribution of buoyant plastics at sea

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## Abstract

5 Millimeter-sized plastics are numerically abundant and widespread across the world's ocean surface. These buoyant macroscopic particles can be mixed within the upper water column due to turbulent transport. Models indicate that the largest decrease in their concentration occurs within the first few meters of water, where subsurface observations are very scarce. By using a new type of multi-level trawl at 12 sites within the North Atlantic accumulation zone, we measured concentrations and physical properties of plastics from the air–seawater interface to a depth of 5 m, at 0.5 m intervals. Our results show that plastic concentrations drop exponentially with water depth, but decay rates decrease with increasing Beaufort scale. Furthermore, smaller pieces presented lower rise velocities and were more susceptible to vertical transport. This resulted in higher depth decays of plastic mass concentration ( $\text{mg m}^{-3}$ ) than numerical concentration (pieces  $\text{m}^{-3}$ ). Further multi-level sampling of plastics will improve our ability to predict at-sea plastic load, size distribution, drifting pattern, and impact on marine species and habitats.

## 1 Introduction

20 Plastics pose physical and chemical threats to the oceans' ecosystem. Their widespread occurrence at the sea surface may be shifting the distribution and abundance of marine populations due to (1) enhanced ocean drift opportunities and (2) damaging effects on biota and habitats. Plastics harbour organisms – such as fouling microorganisms, invertebrates, and fish – that can widely disperse on this new type of habitat, potentially entering non-native waters (Winston et al., 1997; Barnes, 2002; Thiel and Gutow, 2005; Zettler et al., 2013; Reisser et al., 2014a). Plastic objects can also entangle or be ingested/inhaled by marine animals, leading to impacts such as starvation, death, and hepatic stress (Derraik, 2002; Browne et al., 2008; Gregory, 2009; Rochman et al., 2013; Watts et al., 2014).

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Most of what is known about at-sea plastic characteristics and concentrations comes from surface net sampling, where the top few centimetres of the water column is filtered to collect plastics larger than 0.2–0.4 mm (Hidalgo-Ruz et al., 2012). Each square kilometre of the world's sea surface contains thousands of plastic pieces known as “microplastics” when smaller than 5 mm in length (Carpenter and Smith, 1972; C3zar et al., 2014). Plastic contamination is widespread across oceans, with higher contamination levels at convergence zones such as those within subtropical gyres (Carpenter and Smith, 1972; Maximenko et al., 2012; Lebreton et al., 2012; van Sebille et al., 2012; C3zar et al., 2014). Plastic pieces are mostly fragments of packaging and fishing gear made of polyethylene and polypropylene (Mor3t-Ferguson et al., 2010; Reisser et al., 2013). These two resins are less dense than seawater and account for approximately 62 % of the plastic volume produced each year (Andrady, 2011).

Turbulence in the upper-ocean layer can vertically mix buoyant plastic particles. It is predicted that the largest decrease in their concentration occurs over the first meters of the water column, where only a few low-resolution measurements exist (Lattin et al., 2004; Doyle et al., 2011; Kukulka et al., 2012; Isobe et al., 2014). As studying ocean turbulent transport is heavily dependent on observations (Ballent et al., 2013; D'Asaro, 2014), high-resolution multi-level plastic sampling is urgently needed. A better understanding of the vertical transport of buoyant plastics is fundamental for improving estimates of concentration, size distribution, and dispersal of plastics at the world's ocean (Kukulka et al., 2012; Reisser et al., 2013; Law et al., 2014; Isobe et al., 2014).

In this context, the present study aimed at obtaining depth profiles of plastic pollution at the top layer of the oceans (0–5 m). We performed multi-level sampling with a new type of equipment to (1) quantify the exponential decays of plastic mass and numerical concentration with depth, and (2) demonstrate how these vary with sea state. We also provide the first experimental measurements of the rise velocity of plastic pieces, evaluating its relation to the type and size of pieces.

## 2 Materials and methods

### 2.1 At-sea sampling

We conducted 12 multi-level net tows that sampled the upper 5 m of the North Atlantic accumulation zone (Law et al., 2010; Maximenko et al., 2012; Lebreton et al., 2012) during day hours, from 19 to 22 May 2014, aboard the sailing vessel Sea Dragon (Fig. 1). We used a new type of equipment composed of eleven frames with 0.5 m height × 0.3 m width fitted with 2.1 m-long 150 μm mesh polyester nets. These nets were stacked onto each other by an external frame that was dragged in the water from eight towing points, ensuring its stability and perpendicular position in relation to the sea surface, with the top net above mean water line. Tow durations ranged from 55 to 60 min and were all undertaken while the vessel was travelling at a speed of 1–1.9 knots. The captain, who has 20 years sailing experience, estimated wind speeds and sea state while the net system was towed: beaufort scale 1 ( $N = 3$  tows), 3 ( $N = 4$  tows), and 4 ( $N = 5$  tows). After each tow, we transferred the collected contents to a 150 μm sieve and stored them in aluminium bags that were kept frozen for transportation.

### 2.2 Estimating depth profiles of plastic contamination

We calculated plastic numerical and mass concentrations by dividing the number of plastic pieces and total plastic mass by the volume of filtered seawater of each net sample (pieces  $m^{-3}$  and  $mg m^{-3}$ ). Filtered volume was estimated using frame dimensions and readings from a mechanical flowmeter (32 cm per rotation).

Samples were washed into a clear plastic container filled with filtered seawater, and floating macroscopic plastics were organised into gridded petri dishes for counting and characterisation. The searches for plastic pieces were of at least one hour per sample, with the aid of thumb forceps, dissecting needles, magnifying glasses, and LED torches. The latter was particularly important for detecting thin transparent plastic frag-

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terial used to produce plastic items (Fotopoulou and Karapanagioti, 2012). We also identified the resin composition of 60 pieces using Raman spectroscopy (WITec alpha 300RA+), and measured the rise velocity of 0–3 plastics from each sample collected.

Our method of rise velocity measurement is an adaptation of an experiment to examine the fall velocity of various types of sediment particles in different fluids (Allen, 1985). Firstly, we made two marks 12.5 cm from the ends of a 1 m long clear plastic tube (diameter = 40 mm). Secondly, we filled the tube with filtered seawater, capped both its ends with rubber stops, and locked it in place with a clamp. One of the tube ends was then opened, a plastic piece placed inside, the tube closed again (with no trapped air), and quickly turned upside down and locked in place with a clamp, using a spirit level to adjust its vertical position. Finally, we recorded the time taken for the plastic piece to rise from one mark to the other (distance = 75 cm) using a stopwatch. This was measured 4 times per plastic piece, and the average was used as the estimation of its rise velocity ( $w_b$ ). Rise velocities of different plastic types were separately plotted against plastic lengths ( $l$ ), and linear regressions of the form  $w_b = al + b$  were applied to assess the effect of plastics' characteristics on its rise velocity. We also plotted the rise velocities of plastic pieces collected at different depths to visualise depth patterns.

Finally, we calculated the fractions of plastics of different size classes (0.5–1, 1.5–2, 2.5–3, 3.5–4, 4.5–5, > 5.5 mm) that were located at the sea surface (depth < 0.5 m) and in deeper layers (depth > 0.5 m) during sampling at Beaufort scales 1, 3, and 4. We calculated these fractions using all plastics collected, as well as separated by plastic type.

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surface layer. The major difference between this model and our observations occurred at the calmest sea state condition (Beaufort scale 1): while the model predicted that all plastics would be at the surface, we still observed some particles underwater (> 0.5m deep). This could have been a consequence of the presence of other types of vertical flow at our sampled sites (e. g. downwelling) or the occurrence of plastics rising from deeper waters due to previous wind-driven mixing events. This difference may be better explained in the future, by increasing sampling effort at calm conditions and collecting as much oceanographic data as possible during plastic research expeditions.

Our results indicate that plastic numerical concentration decays at a lower rate than plastic mass concentration, as lighter plastics are more susceptible to vertical transport. The uncertainties related to how plastic numerical concentration translates into plastic mass concentration have already led to differences between plastic load estimates arising from different studies. Cózar et al. (2014) used a correlation based on simultaneous surface tow measurements of total mass and abundance of plastic to convert depth-integrated numerical concentrations into mass concentrations. These authors estimated that the total plastic load in the world's sea surface layer is between 7000 and 35 000 tons. On the other hand, Law et al. (2014) multiplied depth-integrated numerical concentrations by the average plastic particle mass ( $1.36 \times 10^{-5}$  kg), and estimated that the microplastic load at the North Pacific accumulation zone alone is of at least 21 290 tons. Such differences evidence the importance of better predicting the vertical transport of ocean plastics to develop standard plastic load estimation methods. More sampling is required to better quantify both profiles of plastic mass and numerical concentration over a broader range of sea states, and then translate these observations into prediction models.

As shown here, in a previous turbulence assay (Ballent et al., 2013), and in a modelling study (Isobe et al., 2014), vertical mixing affects the size distribution of plastics floating at the surface. We observed this effect even at low winds (1 knot), when proportions of plastics mixed into deeper waters were still increasing towards smaller particle sizes. This observation has implications for studies assessing size distribution of

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plastics using surface sampling devices. Cózar et al. (2014) quantified the size distribution of plastics from worldwide sampling locations and concluded that there are major losses of small plastics from the sea surface. Here we show that at least a fraction of this “missing” plastic could be just under their sampled surface layer (0–0.5 m).

For instance, 20 % of 0.5–1 mm, 13 % of 1.5–2 mm, and 8 % of 2.5–3 mm long plastics were between 0.5 and 5 m deep during our Beaufort scale 1 net tows. More at-sea and experimental work is required to quantify this effect and estimate depth-integrated size distribution of buoyant plastics drifting at sea.

The vertical mixing of buoyant plastics also affects the horizontal drifting patterns and ecological impacts of plastic pollution. For instance, larger pieces of plastic coming from land-based sources may stay trapped near the shore until further fragmentation, due to a combination of their high buoyancy and the effect of Stokes drift produced by waves parallel to coastlines (Isobe et al., 2014). Furthermore, the vertical distribution of quantities and sizes of plastics will affect how plastic contamination affects marine organisms inhabiting different depths. For instance, animals such as sea birds, turtles, and mammals (Derraik, 2002; Tourinho et al., 2010), which breath air and generally feed at the sea surface, present high plastic ingestion and entanglement rates.

Our findings show that vertical mixing affects the number, mass, and size distribution of buoyant plastics captured by surface nets, a standard equipment for at-sea plastic pollution sampling (Hidalgo-Ruz et al., 2012). Subsurface samples are still scarce and the processes influencing distribution of plastics throughout the ocean’s water column are poorly understood. Further multi-level plastic sampling across a broader range of sea states is necessary for better quantifying the vertical mixing process. This will improve predictions of buoyant plastic concentration levels (Kukulka et al., 2012), size distributions (Cózar et al., 2014), drifting patterns (Isobe et al., 2014), and interactions with neustonic and pelagic species of the world’s oceans.

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- Fotopoulou, K. N. and Karapanagioti, H. K.: Surface properties of beached plastic pellets, *Mar. Environ. Res.*, 81, 70–77, 2012.
- Gregory, M. R.: Environmental implications of plastic debris in marine settings – entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions, *Phil. Trans. R. Soc. B.*, 364, 2013–2025, 2009.
- Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., and Thiel, M.: Microplastics in the marine environment: a review of the methods used for identification and quantification, *Environ. Sci. Technol.*, 46, 3060–3075, 2012.
- Isobe, A., Kubo, K., Tamura, Y., Nakashima, E., and Fujii, N.: Selective transport of microplastics and mesoplastics by drifting in coastal waters, *Mar. Pollut. Bull.*, 89, 324–330, 2014.
- Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D., and Law, K.: The effect of wind mixing on the vertical distribution of buoyant plastic debris, *Geophys. Res. Lett.*, 39, 1–6, 2012.
- Lattin, G. L., Moore, C. J., Zellers, A. F., Moore, S. L., and Weisberg, S. B.: A comparison of neustonic plastic and zooplankton at different depths near the southern California shore, *Mar. Pollut. Bull.*, 49, 291–294, 2004.
- Law, K. L., Morét-Ferguson, S., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., and Reddy, C. M.: Plastic accumulation in the North Atlantic subtropical gyre, *Science*, 329, 1185–1188, 2010.
- Law, K. L., Moret-Ferguson, S., Goodwin, D. S., Zettler, E. R., DeForce, E., Kukulka, T., and Proskurowski, G.: Distribution of surface plastic debris in the eastern Pacific Ocean from an 11-year dataset, *Environ. Sci. Technol.*, 48, 4732–4738, 2014.
- Lebreton, L.-M., Greer, S., and Borrero, J.: Numerical modelling of floating debris in the world's oceans, *Mar. Pollut. Bull.*, 64, 653–661, 2012.
- Maximenko, N., Hafner, J., and Niiler, P.: Pathways of marine debris derived from trajectories of Lagrangian drifters, *Mar. Pollut. Bull.*, 65, 51–62, 2012.
- Morét-Ferguson, S., Law, K. L., Proskurowski, G., Murphy, E. K., Peacock, E. E., and Reddy, C. M.: The size, mass, and composition of plastic debris in the western North Atlantic Ocean, *Mar. Pollut. Bull.*, 60, 1873–1878, 2010.
- Reisser, J., Shaw, J., Wilcox, C., Hardesty, B. D., Proietti, M., Thums, M., and Pattiaratchi, C.: Marine plastic pollution in waters around Australia: characteristics, concentrations, and pathways, *PLoS ONE*, 8, e80466, doi:0.1371/journal.pone.0080466, 2013.

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- 5 Reisser, J., Slat, B., Noble, K., du Plessis, K., Epp, M., Proietti, M., de Sonnevile, J., Becker, T., and Pattiaratchi, C.: Data from “Float or dive? Vertical ditribution of buoyant plastics at sea”, Figshare, 2014b.
- Rochman, C. M., Hoh, E., Kurobe, T., and Teh, S.: Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress, *Nature*, 3, 3263, doi:10.1038/srep03263, 2013.
- 10 Thiel, M. and Gutow, L.: The ecology of rafting in the marine environment. II. The rafting organisms and community, *Oceanogr. Mar. Biol.*, 43, 279–418, 2005.
- Tourinho, P. S., Ivar do Sul, J. A., and Fillmann, G.: Is marine debris ingestion still a problem for the coastal marine biota of southern Brazil?, *Mar. Pollut. Bull.*, 60, 396–401, 2010.
- van Sebille, E., England, M. H., and Froyland, G.: Origin, dynamics and evolution of ocean garbage patches from observed surface drifters, *Environ. Res. Lett.*, 7, 044040, doi:10.1088/1748-9326/7/4/044040, 2012.
- 15 Watts, A. J., Lewis, C., Goodhead, R. M., Beckett, S. J., Moger, J., Tyler, C. R., and Galloway, T. S.: Uptake and retention of microplastics by the shore crab *Carcinus maenas*, *Environ. Sci. Technol.*, 48, 8823–8830, 2014.
- 20 Winston, J. E., Gregory, M. R., and Stevens, L. M.: Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biogeographical, environmental, and conservation issues, in: *Marine Debris*, Springer, 81–97, 1997.
- Zettler, E. R., Mincer, T. J., and Amaral-Zettler, L. A.: Life in the “Plastisphere”: microbial communities on plastic marine debris, *Environ. Sci. Technol.*, 47, 7137–7146, 2013.

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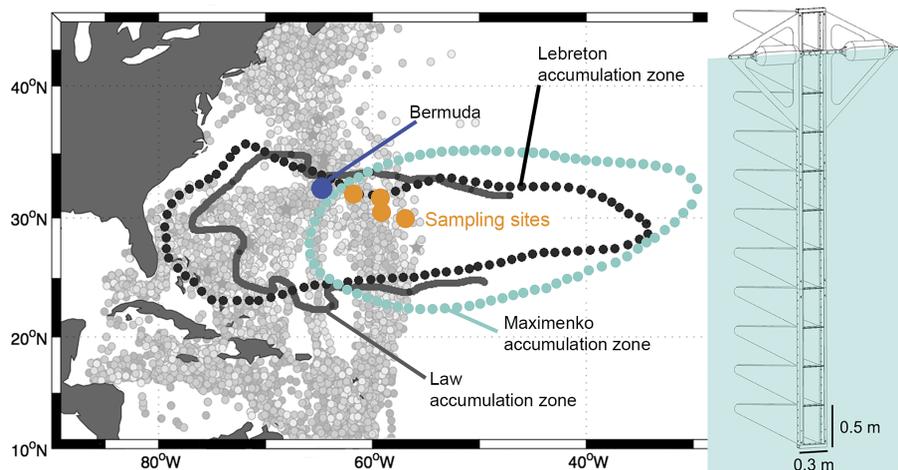
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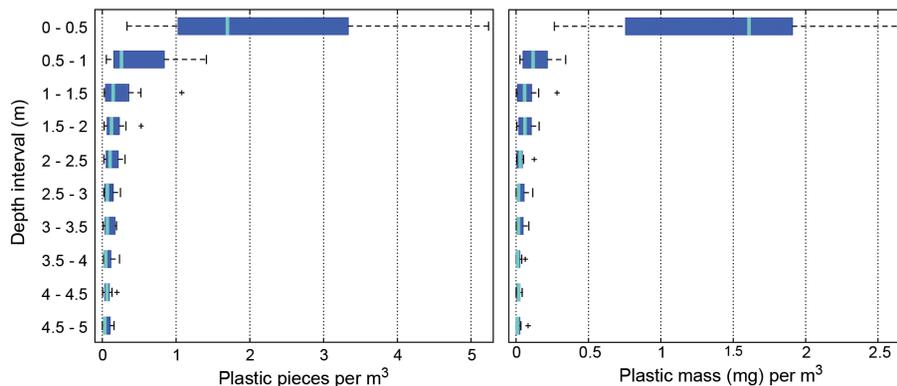
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**Figure 1.** North Atlantic map indicating locations sampled during this study (orange dots) using the multi-level net displayed in the right panel. The map also shows the expedition departure and arrival location (Bermuda), plastic accumulation zones as predicted by ocean modelling (Lebreton et al., 2012; Maximenko et al., 2012), and a surface net tow dataset (Law et al., 2010).

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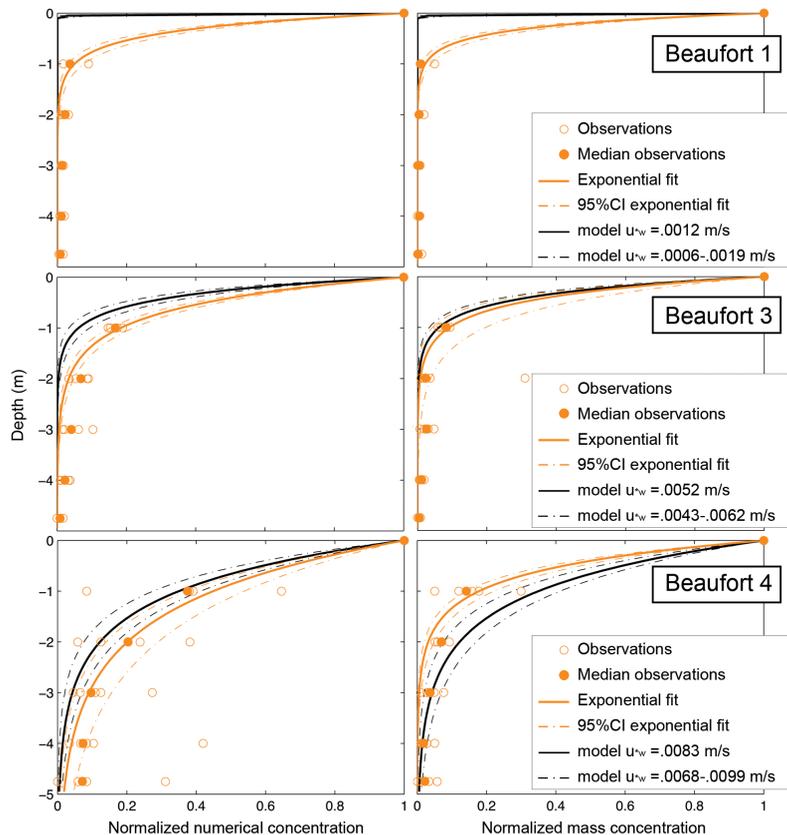


**Figure 2.** Boxplots of plastic numerical (left) and mass (right) concentrations at different depth intervals ( $N = 12$  multi-level net tows). The central line is the median value, edges of the box are the 25th and 75th percentiles, whiskers extend to extreme data points not considered outliers, and outliers are plotted individually as crosses.

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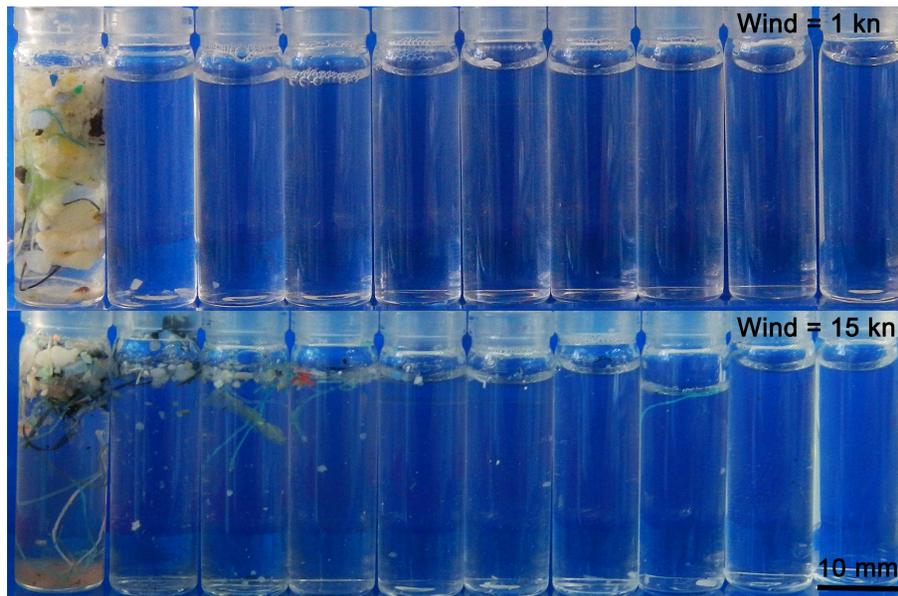


**Figure 3.** Depth profiles of normalized plastic numerical and mass concentrations under different Beaufort scales: 1 ( $N = 3$  net tows; 3283 plastic pieces), 3 ( $N = 4$  net tows; 4049 plastic pieces), and 4 ( $N = 5$  net tows; 5419 plastic pieces). Black lines show model predictions (Kukulka et al., 2012) using median plastic rise velocity ( $0.0053 \text{ m s}^{-1}$ ), and the typical range of frictional velocity of water ( $u_{*w}$ ) at each of the sea states sampled.

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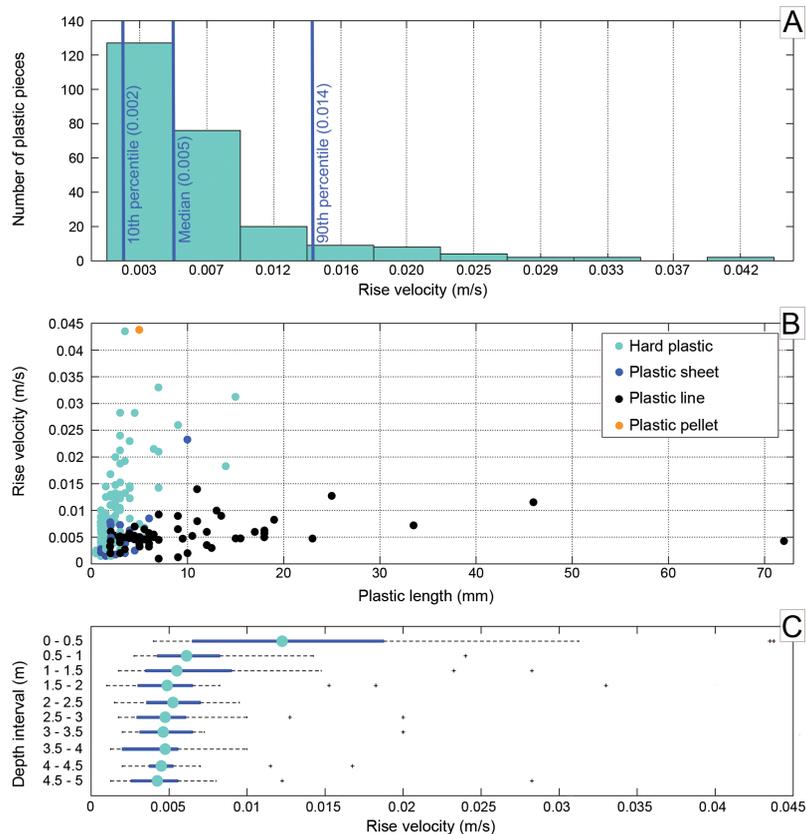


**Figure 4.** Glass jars with filtered water and plastic samples collected under wind speeds of 1 knot (top image) and 15 knots (bottom image). From left to right: 0–0.5, 0.5–1, 1–1.5, 1.5–2, 2–2.5, 2.5–3, 3–3.5, 3.5–4, 4–4.5, and 4.5–5 m depth intervals.

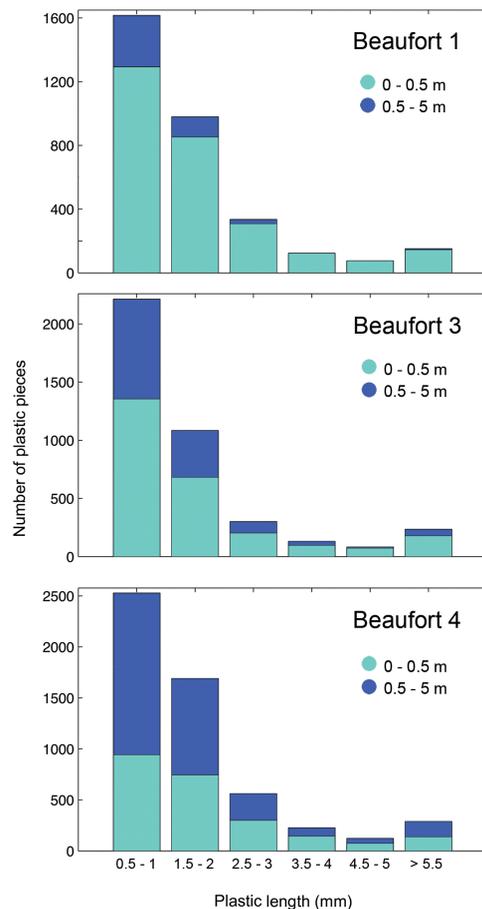
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**Figure 5.** Histogram of rise velocity of plastics (a), plots of plastic sizes  $\times$  rise velocities of different types of plastic (b), and boxplot of rise velocity at different depth intervals (c). In (c), the central dot is the median value, edges of the box are the 25th and 75th percentiles, whiskers extend to extreme data points not considered outliers, and outliers are plotted individually as crosses.



**Figure 6.** Size histograms of plastics collected at depths 0–0.5 and 0.5–5 m during Beaufort scale 1 (top panel), 3 (middle panel), and 4 (bottom panel).

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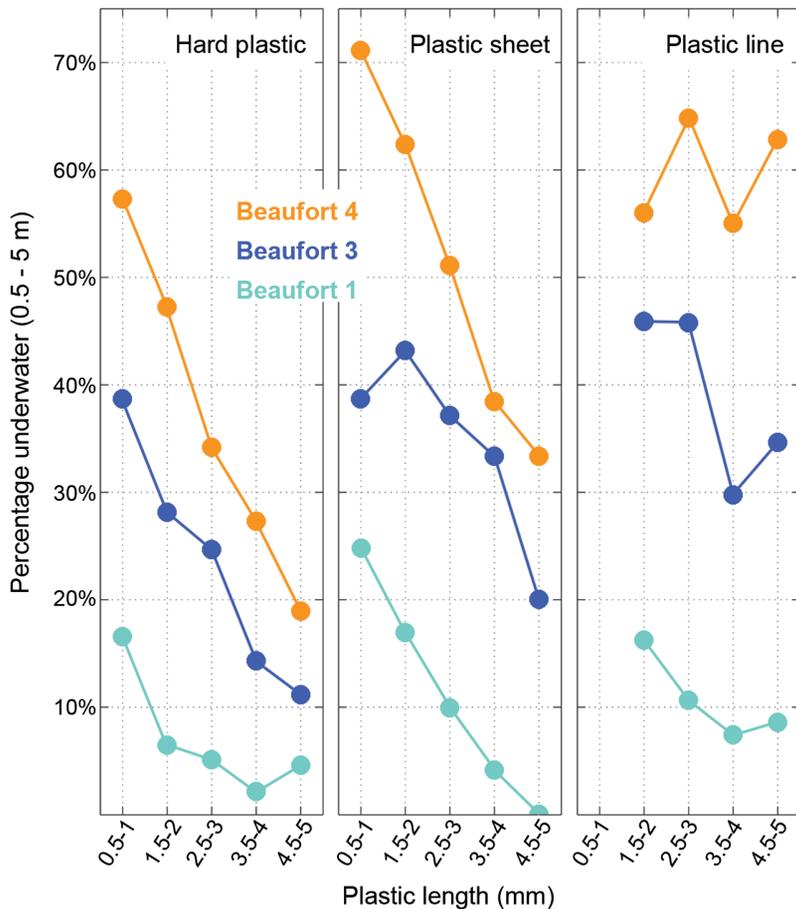
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**Figure 7.** Percentage of plastic pieces of different types and size classes located at depths greater than 0.5 m during sampling at Beaufort scale 1, 3, and 4.

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