Ref: "The vertical distribution of buoyant plastics at sea" by J. Reisser et al.

15 February 2015

Dear Dr. Gerhard Herndl,

Sincerest thanks for the opportunity to revise our manuscript for Biogeosciences. We have modified the manuscript in response to the reviewer comments. Below we respond to each of the points raised by reviewers #1 and #2.

Sincerely, Julia Reisser

and on behalf of the co-authors

Replies to Referee #1 (Anika Ballent) Comments

Comment 1: *Overall / General Comments: This paper is scientifically significant (rated: excellent) due to the novelty of using a multi-level trawl to quantitatively address the lack of understanding about the vertical distribution of microplastics within the surface layer of the world's oceans. The authors' thorough investigation of the effect of sea-state on surface plastic estimations has important implications for improving estimations and models of total surface plastic loads in the oceans.*

The scientific quality (rated: good) could be improved by addressing a couple instances of overgeneralization within the text and clarifying statements which are ambiguous as to where the information was take from (see below). In text citations could be used more specifically. For example, there are several cases where a citation is listed at the end of the sentence, although it only refers to a part of the previous statement. These instances could be improved by instead writting "Author et al., year suggested/reported/etc. that …". Otherwise, the experiments and calculations are clearly traceable allowing for reproduction of the work presented here in future studies.

The paper's presentation quality is excellent. Overall, the paper is clearly written and flows well. It is well structured and demonstrates appropriate use of the English language. Tables and figures are supportive in presenting the results. In my opinion, pronouns "It, them, they, etc" were used too often, especially within the methods section, however this simply an aspect of writing style. Although the pronouns are used correctly, this style may increase the chance for readers to misunderstand the methods. The abstract is concise and complete and the title *is representative of the paper, but it could be clarified with a subtitle, for example, "The vertical distribution of buoyant plastics at sea: a case study in the North Atlantic Ocean."*

Reply 1: Thank you for reviewing our manuscript. We have made most of the suggested changes (see our following replies to your comments), which made our text clearer and more specific in relation to references. We have also added a subtitle to our study. It is now entitled "The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic Gyre"

Comment 2: *Specific Issues/Concerns: In the introduction, on page 16209, line 9, "mostly fragments of packaging and fishing line" is only supported by Reisser et al., 2013 for the waters surrounding Australia. I would suggest finding additional support for this statement, e.g. Hidalgo-Ruz et al., 2012, or clarify the statement by making it less generalized.*

Reply 2: Changed accordingly. We have added 2 extra references (reviews) in there (Hidalgo-Ruz et al. 2012 and Barnes et al. 2009) to better support this statement.

Comment 3: *The methods and assumptions are valid and clearly outlined, but in several cases it was necessary to read the figure captions to fully comprehend some points. I would suggest to include the information that is in the figure captions within the text as well so as to minimize confusion when reading. For example, it is not clear whether or not each of the four sampling stations were sampled at each of the 3 sea-states until one reads Figure 3. Also, in the methods section, it is not clear whether the Kukulka model is specifically for the prediction of numerical or mass concentration.*

Reply 3: Changed accordingly. We made a few minor revisions along the methods section to make it clearer.

We conducted net tows at 12 locations, but some sampling sites were quite close to each other and thus appeared as a unique orange dot in Figure 1, which is why it seems we have only four stations. We have added this information to the caption of Figure 1.

Furthermore, we state in the methods section the number of net tows conducted under each Beaufort sea state: ' (…) Beaufort scale 1 (N = 3 tows), 3 (N = 4 tows), and 4 (N = 5 tows)'.

Similarly to previous studies (e.g. Eriksen et al. 2014, Law et al. 2014, Cozar et al. 2014), we used the Kukulka et al. 2012 model to predict both numerical and mass plastic concentration depth profiles. Our study found that these depth profiles are different, and additional vertical sampling of ocean plastics will allow us to better predict the vertical distribution of both mass and numerical concentrations.

Comment 4: *In the discussion section, I suggest to discuss the implications of not including any thin filaments from samples in analysis. Additionally, on page 16215, lines 11-20, other studies concerning estimation of total surface plastic amounts are mentioned. I would suggest also mentioning of the most recent publication by Eriksen et al. 2014 (Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea) which aims to extrapolate and estimate total global plastic amounts. On page 16215, line 25, the citation of Ballent et al, 2013 is inaccurate; it was not specifically a turbulence assay but rather and examination of the effects of subsurface velocity and shear stress on subsurface transport of plastics using a model. I would change "As shown here, in a previous turbulence assay (Ballent et al. 2013)…surface." to "As shown here and in two modelling studies, vertical mixing affects the subsurface transport of plastics and the size distribution of plastics floating at the surface." On page 16216, the statement in lines 15-17 is underdeveloped and does not satisfactorily support the previous statement. How do/may the study results affect this observation? In general, the discussion could go into more depth regarding potential effects of the results on estimates of plastics concentration, total amounts, models, subsurface transport, and effects on biota.*

Reply 4: We don't believe that excluding a few thin fibers had a major effect on the results of this study, which is focused on macroscopic buoyant plastic debris. As we (1) did not use microscope to inspect samples, and (2) used filtered seawater to separate floating plastics from 'sinking' plastics (e.g. textile fibers), it was quite rare to detect thin fibers such as those from air dust and clothing. We are now emphasizing that thin fibers were rarely detected in this study: "*Two* thin filaments resembling textile fibres were discarded due to potential air contamination *as noted in* (Foekema et al., 2013)." We added this sentence mostly to emphasize to our readers that those interested in studying microscopic plastic debris should follow a different approach to ours. For instance, they would need special clean air conditions (as described in Foekema et al. 2013) to achieve this.

When we submitted this manuscript to Biogeosciences, Eriksen et al. 2014 paper was not published yet. We have added this reference to our Introduction and Discussion sections.

As suggested, we have re-phrased the sentence where Ballent et al. 2013 is mentioned.

We have added a few sentences to the penultimate paragraph of the discussion section to clarify how the vertical distribution of plastic debris affects their effect on different pelagic species.

We hope our modifications improved our discussion on the significance of our results for estimates of plastics concentration, total amounts, models, subsurface transport, and effects on biota.

Comment 5: *Technical Corrections: (mostly suggestions) Page 16208 Line 5: change "subsurface" to "in situ"*

Reply 5: Changed accordingly

Comment 6: *Line 6: "12 sites" is misleading. Change to 4 sites or 12 samples?*

Reply 6: As explained in Reply 3, sampling was conducted at 12 different sites. None of the samples were collected at the same location, although some were collected proximally to others (e.g. those conducted in the same day). In any case, they are considered 12 different sites.

Comment 7: *Line 7: Sentence beginning with "By using…" sounds like the physical properties were measured using the trawl. I suggest rewording this sentence.*

Reply 7: Changed accordingly.

Comment 8: *Line 9: Change "but" to "and"*

Reply 8: Changed accordingly

Comment 9: *Line 21: Change "on" to "via"*

Reply 9: Changed accordingly

Comment 10: *Page 16209 Line 3: I don't think the word "Each" can be used as it is too much of an extrapolation and is thus unscientific.*

Reply 10: Changed accordingly

Comment 11: *Line 5: Carpenter and Smith, 1972 mentions plastics being smaller than .5 cm but doesn't seem to define microplastics as such. I would remove this citation and find a review-type study to support the statement, e.g. Hidalgo-Ruz et al., 2012 (see Review of Methods section) and Arthur et al., 2009 (Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. Sept 9-11,* *2008. Arthur, C., Baker, J., Bamford, H., Eds.; NOAA Technical Memorandum NOS-OR&R-30, 2009).*

Reply 11: Changed accordingly: we have deleted Carpenter and Smith 1972 citation and added Hidalgo et al. 2012 and Arthur et al. 2009 instead.

Comment 12: *Line 10: Again, to extrapolate results from the North Pacific to the entire world's oceans is not valid in my opinion. I would suggest to instead change "mostly" in Line 9 to "commonly". Moret-Ferguson et al. only studied the North Atlantic. Either make the sentence more specific (i.e. Plastic in the North Atlantic are mostly...) or add more references to include studies done in the other gyres).*

Reply 12: Changed accordingly. We have made this sentence more specific and added a few more references/reviews.

Comment 13: *Line 13: "It is predicted.." It is not clear whose prediction this is. Is this the guiding hypothesis of this study?*

Reply 13: This is the Kukulka et al. 2012 model prediction. We have re-phased this sentence to make it clearer: "A model developed by Kukulka et al. 2012 predicted that …". This is indeed our guiding assumption and the reason to develop a shallow multi-level sampling device capable of obtaining high-resolution data from the sea surface to 5m deep.

Comment 14: *Line 15: "…,where only a few low-resolution measurements exist (Lattin et al…)" I would suggest moving this to the beginning on the sentence; e.g. "As suggested by a few low-resolution measurements (Lattin…), it is predicted in this study that…"*

Reply 14: The prediction is derived from the Kukulka et al. 2012 model, which was supported by very few direct observations prior to this study. This is the justification of our study, and we hope that our re-phrased sentence clarifies this.

Comment 15: *Line 20: change "at" to "in"*

Reply 15: Changed accordingly.

Comment 16: *Line 23: change "at" to "in"*

Reply 16: Changed accordingly.

Comment 17: *Line 24: change "decays" to "decay rates"*

Reply 17: Changed accordingly.

Comment 18: *Page 16210 Line 3: Insert "from 4 sampling locations" after "12 multi-level net tows"*

Reply 18: As explained above, none of the net tows were conducted in the same site, so we actually have 12 sampling sites. Figure 1 caused this confusion, since due to scale it was not possible to plot the individual sites. We hope that the improved figure legend clarifies this. Readers interested in the exact coordinates (latitude, longitude) of each of our net tows can refer to the datasets published in Figshare.

Comment 19: *Line 6: Change "type of equipment" to "collection device"*

Reply 19: Changed accordingly.

Comment 20: *Line 8: Change "onto each other by an" to "vertically and secured within an"*

Reply 20: Changed accordingly.

Comment 21: *Line 10: Insert "completely" between "net above"*

Reply 21: Changed accordingly.

Comment 22: *Line 13: Change "while the net system was towed" to "of each sampling period"*

Reply 22: Changed accordingly.

Comment 23: *Line 15: Change "for" to "during"*

Reply 23: Changed accordingly.

Comment 24: *Page 16211 Line 2: Two other recent studies could be cited: Mathalon and Hill, 2014, Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia and Dekiff et al., 2014, Occurrence and spatial distribution of microplastics in sediments from Norderney.*

Reply 24: We would rather refer only the Foekema et al. 2013 study, where they clearly state the issue of studying plastic fibers in laboratories that do not have clean/filtered air. For instance, their abstract says: "small fibers were initially detected in most of the samples, but their abundance sharply decreased when working under special clean air conditions. Therefore, these fibers were considered to be artifacts related to air born contamination and were excluded from the analyses." This is exactly the point we are trying to make.

Comment 25: *Line 9: Change "at:" to "at depths of" and remove "deep" from end of sentence.*

Reply 25: Changed accordingly.

Comment 26: *Line 17: Include units after wb = 0.0053 (m s-1)*

Reply 26: Changed accordingly.

Comment 27: *Line 21: Missing reference for Pugh (1987)*

Reply 27: Changed accordingly.

Comment 28: *Page 16213. Line 2: Insert "Depth" before "Profiles"*

Reply 28: Changed accordingly.

Comment 29: *Line 16: Explain that the three numerical ranges refer to the ranges of frictional velocity typical for each sea-state. This is explained in one of the figure captions but would be helpful to have in text too.*

Reply 29: These numerical ranges refer to the depth decay rates (λ) as estimated by the Kukulka et al. 2012 model. We have made a few modifications to this second paragraph of the results section to make it clearer.

Furthermore, we have added the numerical ranges of frictional velocity of water considered in this study in the 5th paragraph of the methods section, so now these values can be found not only in the figure legend but also in the manuscript.

Comment 30: *Line 20: Change "plastics" to "plastic pieces"*

Reply 30: Changed accordingly.

Comment 31: *Page 16214, Line 6: Change "deeper" to "greater"*

Reply 31: Changed accordingly.

Comment 32: *Line 8: Word "proportion" is ambiguous. Is it referring to the fractional amount or the length of plastic pieces? Also, change "underwater" to "submerged below 0.5 m"?*

Reply 32: It is referring to the percentage of plastics displayed in Figure 7. We have made a few modifications to this sentence to make it clearer.

We also changed "underwater" to "submerged bellow 0.5m".

Comment 33: *Line 21: "is due to the fact" is too absolute in my opinion. Would change to "can be explained by our observation"*

Reply 33: Changed accordingly.

Comment 34: *Page 16215, Line 1: Insert "as determined in our study" after "surface layer"*

Reply 34: Changed accordingly.

Comment 35: *Line 3: Change "underwater (>0.5 m deep)" to "submerged > 0.5 m below the water surface"*

Reply 35: Changed accordingly.

Comment 36: *Line 10: "lighter" is ambiguous, change to "less dense" or "smaller"*

Reply 36: Changed accordingly.

Comment 37: *Line 23: Change "then" to "better"*

Reply 37: Changed accordingly.

Comment 38: *Line 27-29: Reword this sentence: "We observed...sizes" to "We observed the proportions of plastics mixed into deeper waters to increase towards smaller size even under low wind speed (1 knot) conditions."*

Reply 38: Changed accordingly.

Comment 39: *Page 16216, Line 7: Insert "further" before "quantify"*

Reply 39: Changed accordingly.

Comment 40: *Line 29: Capitalize Eric*

Reply 40: This was changed when the Biogeosciences staff formatted our .doc manuscript into their .pdf. We will make sure this is correct in the peer-reviewed publication.

Comment 41: *Page 16217, Line 3: Change "receives" to "received"?*

Reply 41: Changed accordingly.

Comment 42: *Page 16219, Line 5: cannot find the data set using Information given for figshare (Reisser et al., 2014b). Data sets from Reisser et al, 2014a (Millimeter sized marine plastics: a new pelagic habitat for microorganisms and invertebrates) were found but not data sets from this paper.*

Reply 42: The dataset of this paper is now available at:

http://figshare.com/articles/Data_from_The_vertical_distribution_of_buoyant_plastics_at_sea_an_observational_study_in_the_North_Atlantic_subtropical_gyre_/1308506

Comment 43: *Page 16220, Figure 1 caption should include a note about the trawl depiction. Add "and solid grey line" to (grey dots)*

Reply 43: We have added "solid grey line" to this figure legend. The first sentence of the legend says "using the multi-level net device displayed in the right panel".

Comment 44: *Page 16223 Include corresponding Beaufort values with 1 knot and 15 knot wind speeds in captions*

Reply 44: Changed accordingly.

Comment 45: *Page 16224 Change "x" to "versus". Change "boxplot of rise velocity at different depth intervals" to "boxplot of rise velocity for plastics collected at different depth intervals"*

Reply 45: Changed accordingly.

Replies to Referee #2 Comments

Comment 1: *General: This paper represents a thoroughly desigened study, which combines field data with results from laboratory experiments in a very elegant manner. The informations presented are based on a new type of sampling device, a sound sampling strategy and this study also presents new information about rise velocity of plastic pieces. The text is very clear and reads fluently. The material and method section illustrates all required informations (sampling and experimental design, sampling gear, analyses, definition of used modells and their parameters) very clearly and in a comprehensive manner.*

Specific comments I have three minor comments/proposals:

1) You may consider to show/to add a graph of the relationships presented in Figure 3 (normalized plastic numerical and mass concentrations under different Beaufort scales) as predicted (model of Kukulka et al., 2012) versus observed values, in order to demonstrate the fit/differences between the two approaches.

Reply 1: We are already showing the normalized plastic numerical and mass concentrations under different Beaufort scales as predicted by Kukulka et al. 2012 (black lines), and observed values (orange dots and lines).

We have re-phrased some parts of the results session to make such comparison clearer (following suggestions of reviewer #1).

Comment 2: *Page 16215, Line 20 - 25 "Such differences evidence the importance of better predicting the vertical transport of ocean plastics to develop standard plastic load estimation methods". I agree, however you would also need detailed information about sea state zones (i.e. size and effects of convergence zones) to increase the accuracy of predictions.*

Reply 2: Changed accordingly. We have added an extra sentence to this paragraph acknowledging that improved predictive models may need to be three-dimensional and account not only for wind mixing effects, but also ocean plastic properties (e.g. particle size) and other types of vertical transport processes.

Comment 3: *Figure 5 B, C: I would suggest to use m s-1 not m/s.*

Reply 3: Changed accordingly.

The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic Gyre

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Abstract

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 *in situ* observations are very scarce. In order to investigate the depth profile and physical properties of buoyant plastic debris, we used a new type of multi-level trawl at 12 sites within the North Atlantic subtropical gyre to sample 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, and 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 (milligrams m^{-3}) than numerical concentration (pieces 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.

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1 Introduction

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 via 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., 2014). 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).

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). These sea surface samples have shown that the world's sea surface contains many millimetre-sized plastic pieces known as 'microplastics' when smaller than 5 mm in length (Arthur et al., 2009;Hidalgo-Ruz et al., 2012). This type of plastic pollution 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;Cózar et al., 2014;Eriksen et al., 2014). Plastic debris collected by surface nets are mostly fragments of packaging and fishing gear made of polyethylene and polypropylene (Barnes et al., 2009;Morét-Ferguson et al., 2010;Hidalgo-Ruz et al., 2012;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. A model developed by Kukulka et al. 2012 predicted that the largest decrease in plastic 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., 2012;D'Asaro, 2014), high-resolution multi-level plastic sampling is urgently needed to test this prediction. A better understanding of the vertical transport of buoyant plastics is fundamental for improving estimates of concentration, size distribution, and dispersal of

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plastics in 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 in 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 decay rates 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 meters 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 (Figure 1). We used a new collection device capable of sampling surface waters from the air-seawater interface to a depth of 5 m, at 0.5 m intervals. This equipment is composed of eleven frames with 0.5 m height x 0.3 m width fitted with 2.1 m-long 150 µm mesh polyester nets. These nets were stacked vertically and secured within 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 completely above mean water line (see Figure 1). Tow durations ranged from 55 to 60 minutes 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 of each sampling period: Beaufort scale 1 (N = 3 net tows), 3 (N = 4 net tows), and 4 (N = 5 net tows) (Reisser et al., 2015). After each tow, we transferred the collected contents to a 150 µm sieve and stored them in aluminium bags that were kept frozen during 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}

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and milligrams 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 fragments, which had low detection probability when not reflecting light. Two thin filaments resembling textile fibres were discarded due to potential air contamination as noted in (Foekema et al., 2013). Once all plastics were counted and characterised, they were washed with deionised water, transferred to aluminium dishes, dried at 60° C, and weighed.

To quantify the variation of plastic concentration with depth and assess the effect of changing sea state on these vertical profiles, we first divided plastic concentration of samples by their correspondent surface concentration value. We then took the average of these normalised concentrations between adjacent nets to estimate normalised plastic concentration values at depths of: 0 m (top 2 nets), 1 m (3rd and 4th nets), 2 m (5th and 6th nets), 3 m (7th and 8th nets), 4 m (9th and 10th), and 4.75 m (11th net). Finally, numerical and mass concentration values from tows collected under same Beaufort scale were grouped and fitted to exponential decay models of the form $N = e^{-\lambda z}$, where N = normalised plastic concentration, z = depth, and λ = decay rate.

We also predicted normalised plastic concentration depth profiles using the model described in Kukulka et al. (2012): $N = e^{z w_b A_0^{-1}}$, where z = depth, w_b = plastic rise velocity, and $A_0 = 1.5 u_{*w} k H_s$ with u_{*w} = frictional velocity of water, k = 0.4 (von Karman constant), and H_s = significant wave height. We considered w_b = 0.0053 m s^{-1} (plastics' median rise velocity, as estimated in this study), H_s = 0.1 m, 0.6 m, or 1m (typical wave heights experienced at Beaufort scales 1, 3, and 4, respectively), and used the wind ranges of Beaufort 1, 3, and 4 (1-3 knots, 7-10 knots, and 11-16 knots, respectively) to estimate their respective u_{*w} values through the approximation proposed by (Pugh, 1987): u_{*w} = 0.00012W_{10}, where W_{10} = ten-metre wind speed in m/s. Thus, the considered numerical ranges of frictional velocity of water (u_{*w}) were: 0.0006-0.0019 m s^{-1} for Beaufort scale 1, 0.0043 – 0.0062 m s^{-1} for Beaufort scale 3, and 0.0068-0.0099 m s^{-1} for Beaufort scale 4.

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2.3 Characterising plastic length, type, resin, and rise velocity

We measured the length of all plastic pieces using a transparent ruler (0.5 mm resolution), and classified them into the following types: hard plastic - fragments of rigid plastic; sheet - fragments of thin plastic, with some degree of flexibility; line - fragments of fishing lines or nets; foam - expanded polystyrene fragments; and pellet - raw material 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 mm, 1.5-2 mm, 2.5-3 mm, 3.5-4 mm, 4.5-5 mm, > 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.

3 Results

3.1 Depth profiles of mass and numerical concentrations

Plastic numerical and mass concentrations both decreased abruptly from their peak values at the sea surface, where median values were equal to 1.69 pieces m^{-3} and 1.60 mg m^{-3} (Figure 2). Concentration differences between surface and deeper layers were higher in terms of mass than number of particles. For instance, median mass and numerical concentrations at 0.5-1 m were respectively 13.3 and 6.5 times lower than their median plastic peaks at 0-0.5 m.

Exponential models fitted well with both numerical and mass concentrations (R^2 = 0.99–0.84), with depth decay rates (λ) consistently higher for mass than numerical concentration. Furthermore, both numerical and mass concentration decay rates were inversely proportional to Beaufort state (Figure 3). Depth decay rate of numerical concentration went from 3.0 at Beaufort 1 (95% confidence interval - 95%CI = 2.56-3.45), to 1.7 at Beaufort 3 (95%CI = 1.51-1.88), and 0.8 at Beaufort 4 (95%CI = 0.62-0.98). Decay rate of mass concentration went from 3.8 at Beaufort 1 (95%CI = 3.23-4.33), to 2.4 at Beaufort 3 (95%CI = 1.63-3.14), and 1.7 at Beaufort 4 (95%CI = 1.50-1.94).

These exponential fits had relatively similar depth decay rates to those predicted by Kukulka's model for Beaufort 3 (λ = 2.36–3.37) and 4 (λ = 0.88–1.28). However, for Beaufort 1 the statistical fit showed much smaller λ (2.56-4.33) than those predicted by Kukulka's model (λ = 141.73–47.2492).

3.2 Lengths, types, resins and rise velocities of plastics

We counted and classified 12,751 macroscopic plastic pieces with lengths varying from 0.5 to 207 mm (median = 1.5 mm; Figure 4). They were mostly fragments of polyethylene (84.7%), followed by polypropylene (15.3%) items. Hard plastics (46.6%) and sheets (45.4%) were predominant, with lower presence of plastic lines (7.9%), pellets (0.05%) and foams (0.008%).

Plastic rise velocity ranged from 0.001 to 0.0438 m/s (Figure 5a). It was directly proportional to plastic length, with the slope of this linear relationship differing among types of plastic (Figure 5b). While both hard plastics and sheets had a slope equal to 0.002 (95% CI = 0.0017-0.0026 and 0.0012-0.0023, respectively), plastic lines had a flatter slope of 0.00007 (95% CI = 0.00002-0.00013), since their rise velocity increased only slightly towards longer pieces.

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Rise velocities differed among sampled depths, with particles at the surface (0-0.5 m) having a wider range of values and a higher median value than pieces at greater depths (Figure 5c).

The vertical mixing process was size-selective, and affected the size distribution of plastics located at the sea surface (Figure 6), with the proportion of plastics at depths over 0.5 m generally increasing towards smaller plastic lengths (Figure 7). For hard plastics and sheets, this trend was observed at all Beaufort scales sampled. Plastic lines however, only displayed this trend at Beaufort 1, with different size classes showing similar and relatively high underwater proportions at Beaufort 3 and 4.

Datasets produced and analysed in this study are available at Figshare (Reisser et al., 2015).

4 Discussion

This study describes high-resolution depth profiles of plastic concentrations, which were shown to decrease exponentially with depth, with decay rates decreasing towards stronger winds. It also provides the first measurements of the rise velocity of ocean plastics, which varies with particle size and type. Furthermore, it shows that depth profiles of plastic mass are associated with higher decay rates than depth profiles of plastic numbers. This can be explained by our observation of smaller/lighter plastic pieces generally associated with lower rising velocities, being therefore more susceptible to vertical transport.

Predictions of plastic vertical mixing are commonly used to correct numerical concentrations obtained by surface net sampling (Kukulka et al., 2012;Reisser et al., 2013;Cózar et al., 2014;Law et al., 2014). As determined in our study, the model described in Kukulka et al. (2012) performed relatively well in estimating the total number of plastic pieces at the wind-mixed 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 submerged at depths greater than 0.5 m below the water surface. 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.

Our results indicate that plastic numerical concentration decays at a lower rate than plastic mass concentration, as smaller plastics are more susceptible to vertical transport. The uncertainties related to how plastic numerical concentration translates into plastic mass

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concentration have already led to differences between plastic load estimates arising from different studies. For instance, 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 7,000 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 x 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 translate these observations into prediction models. Such models may need to be three-dimensional, and account not only for wind mixing effects, but also ocean plastic properties (e.g. particle size) and other types of vertical transport processes (e.g. Langmuir circulation).

As shown here, and in two modelling studies (Ballent et al., 2012;Isobe et al., 2014), vertical mixing affects the size distribution of plastics floating at the surface. We observed that the proportion of plastics mixed into deeper waters increases towards smaller sizes even under low wind speed (1 knot) conditions (see Figure 7). This observation has implications for studies assessing size distribution of plastics using surface sampling devices. Cózar et al. (2014) and Eriksen et al. (2014) quantified the size distribution of ocean 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 the 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 further quantify this effect and estimate depth-integrated size distribution of buoyant plastics drifting at sea.

Predicting the vertical mixing of buoyant plastics is also important as it 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 plastics will influence the likelihood of animals inhabiting different depths to

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encounter, and potentially interact, with plastic. For instance, sea birds, turtles, and mammals, which breathe air and use the sea surface for daily activities, present high rates of plastic ingestion and entanglement (Derraik, 2002;Tourinho et al., 2010). These high interaction rates could be partly explained by the relatively high concentrations of plastic debris at the sea surface, as shown in this study.

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 sampling across a broader range of sea states is necessary for better quantifying the vertical mixing of buoyant plastics. This will improve predictions of ocean plastic concentration levels (Kukulka et al., 2012), size distributions (Cózar et al., 2014;Eriksen 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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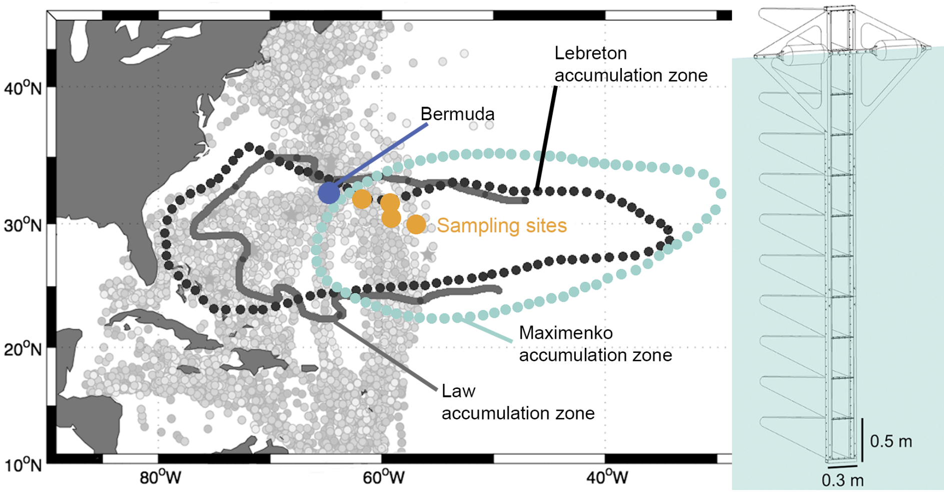

Figure 1. North Atlantic map indicating locations sampled during this study (orange dots) using the multi-level net displayed in the right panel. The four orange dots include all 12 multi-level net tows conducted in the study, which could not be shown separately due to scale. The map also shows the expedition departure and arrival location (Bermuda), as well as plastic accumulation zones predicted by ocean modelling (dotted lines) (Lebreton et al., 2012;Maximenko et al., 2012), and a surface net tow dataset (solid gray line; grey dots show locations of net tows) (Law et al., 2010).

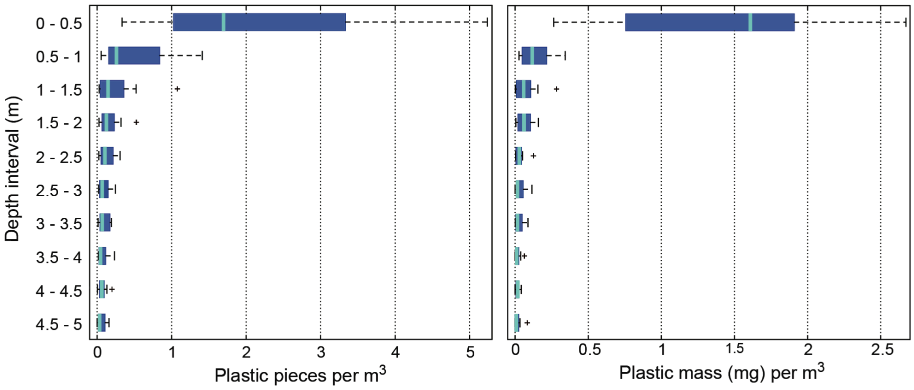

Figure 2. Boxplots of plastic numerical (left) and mass (right) concentrations at different depth intervals (N = 12 multi-level net tows). The central line is the median value, edges of the box are the 25th and 75th percentiles, whiskers extend to extreme data points not considered outliers, and outliers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

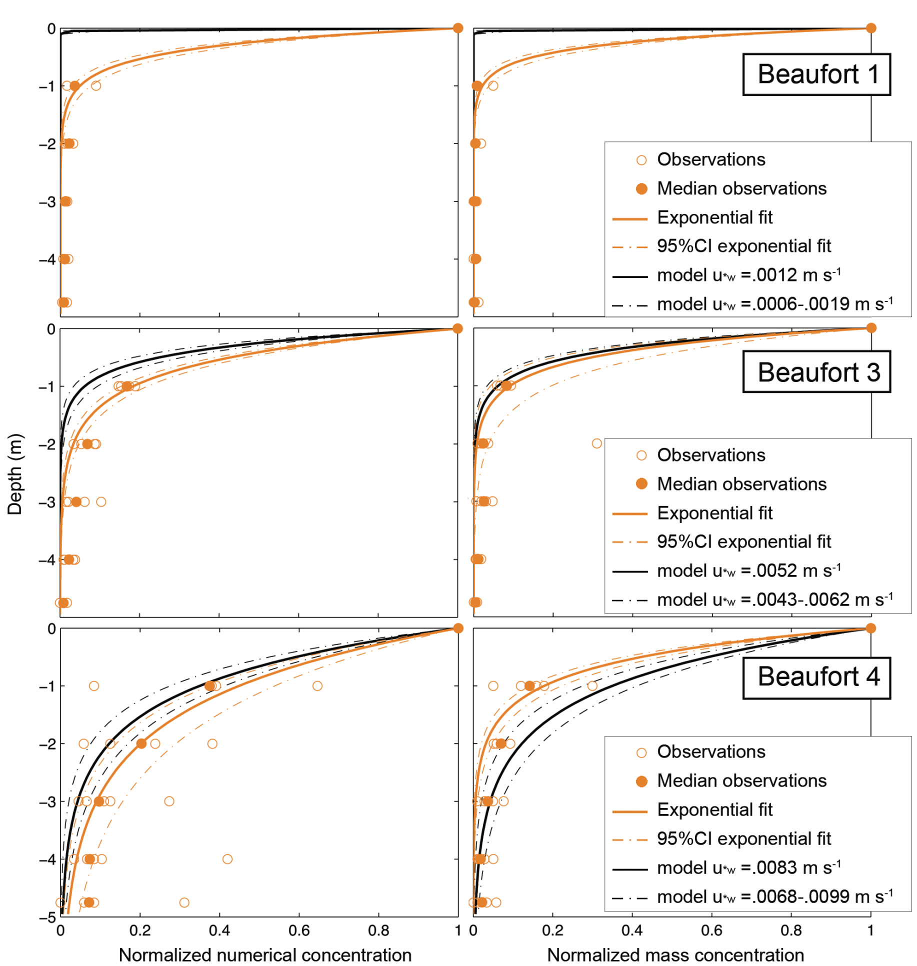

Figure 3. Depth profiles of normalized plastic numerical and mass concentrations under different Beaufort scales: 1 (N = 3 net tows; 3283 plastic pieces), 3 (N = 4 net tows; 4049 plastic pieces), and 4 (N = 5 net tows; 5419 plastic pieces). Black lines show model predictions (Kukulka et al., 2012) using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

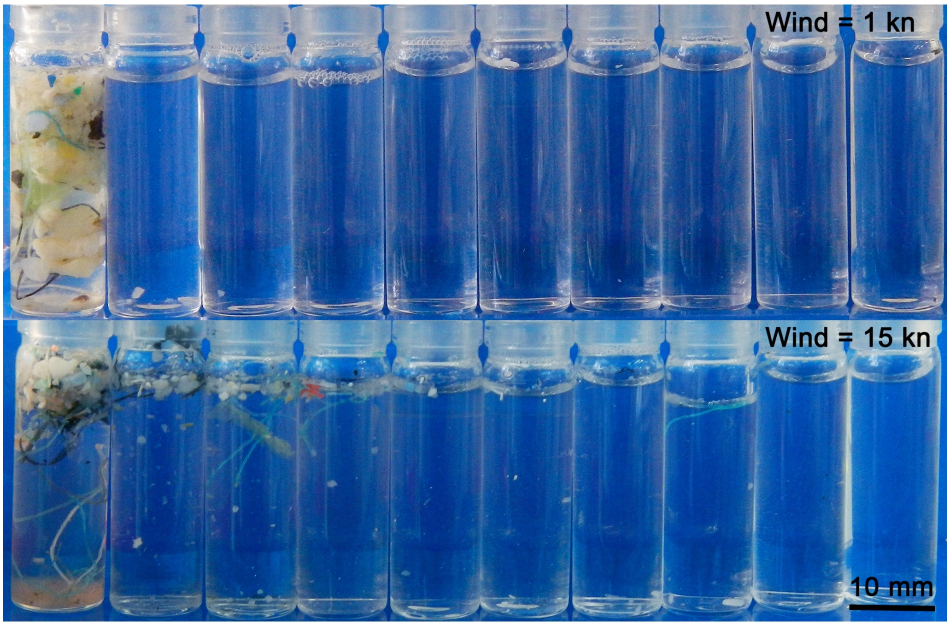

Figure 4. Glass jars with filtered water and plastic samples collected under wind speeds of 1 knot (Beaufort scale 1, top image) and 15 knots (Beaufort scale 4, bottom image). From left to right: 0 – 0.5 m, 0.5 – 1 m, 1 – 1.5 m, 1.5 – 2 m, 2 – 2.5 m, 2.5 – 3 m, 3 – 3.5 m, 3.5 – 4 m, 4 – 4.5 m, and 4.5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

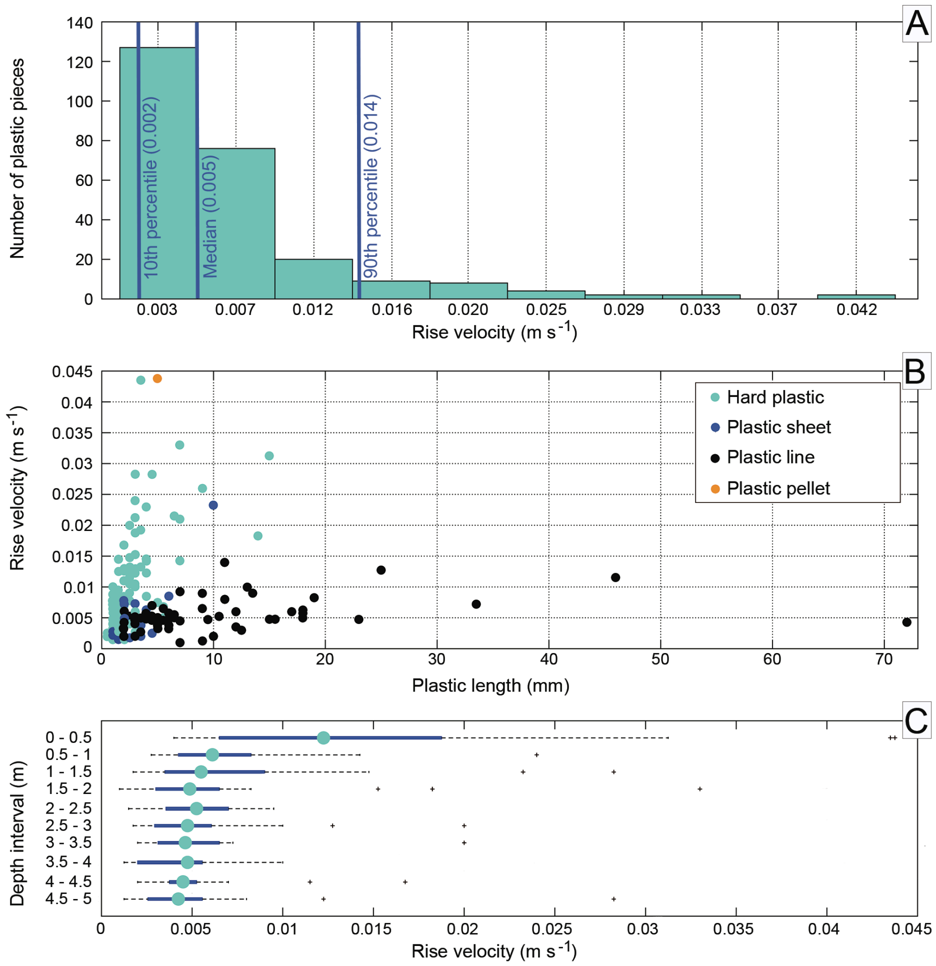

Figure 5. Histogram of rise velocity of plastics (A), plots of plastic sizes versus rise velocities of different types of plastic (B), and boxplot of rise velocity for plastics collected at different depth intervals (C). In C, the central dot is the median value, edges of the box are the 25th and 75th percentiles, whiskers extend to extreme data points not considered outliers, and outliers are plotted individually as crosses.

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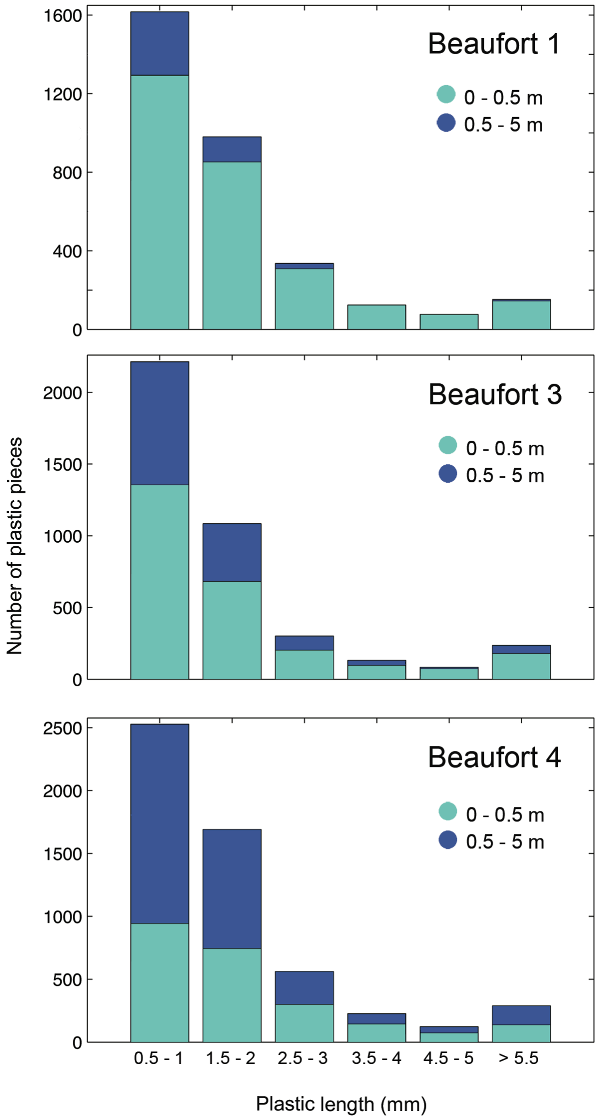

Figure 6. Size histograms of plastics collected at depths 0-0.5 m and 0.5-5 m during Beaufort scale 1 (top panel), 3 (middle panel), and 4 (bottom panel).

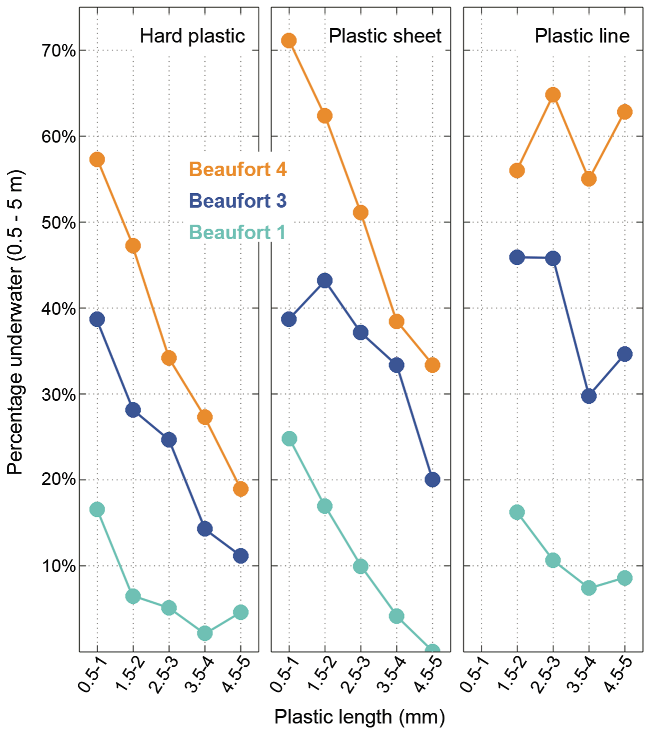

Figure 7: Percentage of plastic pieces of different types and size classes located at depths greater than 0.5 m during sampling at Beaufort scale 1, 3, and 4.