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Microplastic sampling with the AVANI trawl compared to two neuston trawls in the Bay of Bengal and South $Pacific^{*}$

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ABSTRACT

Many typical neuston trawls can only be used during relatively calm sea states and slow tow speeds. During two expeditions to the Bay of Bengal and the eastern South Pacific we investigated whether the new, high-speed AVANI trawl (All-purpose Velocity Accelerated Net Instrument) collects similar amounts and types of microplastics as two established scientific trawl designs, the manta trawl and the DiSalvo neuston net. Using a 335 µm net, the AVANI trawl can collect microplastics from the sea surface at speeds up to 8 knots as it "skis" across the surface, whereas the manta and DiSalvo neuston trawls must be towed slowly in a less turbulent sea state and often represent shorter tow lengths. Generally, the AVANI trawl collected a greater numerical abundance and weight of plastic particles in most size classes and debris types than the manta trawl and DiSalvo neuston net, likely because these trawls only skim the surface layer while the AVANI trawl, moving vertically in a random fashion, collects a "deeper" sample, capturing the few plastics that float slightly lower in the water column. However, the samples did not differ enough that results were significantly affected, suggesting that studies done with these different trawls are comparable. The advantage of the AVANI trawl over traditional research trawls is that it allows for collection on vessels underway at high speeds and during long transits, allowing for a nearly continuous sampling effort over long distances. As local surface currents make sea surface abundance widely heterogeneous, widely spaced short-tow trawls, such as the manta and DiSalvo trawls, can catch or miss hotspots or meso-scale variability of microplastic accumulations, whereas the AVANI trawl, if utilized for back-to-back tows of intermediate distances (5-10 km), can bridge variable wind conditions and debris concentrations potentially reducing variance and provide a greater resolution of spatial distribution.

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1. Introduction

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https://doi.org/10.1016/j.envpol.2017.09.058 0269-7491/© 2017 Elsevier Ltd. All rights reserved. Efforts to collect surface microplastics have grown tremendously in the past several years, incorporating traditional, institutional, and citizen scientists (Hidalgo-Ruz and Thiel, 2015; Zettler et al., 2017). For monitoring floating plastics, neuston (surface)

trawls are used to skim the surface of water in oceans, streams, and lakes where positively buoyant plastics (specific density lower than that of surrounding water) tend to concentrate. These trawls are often of similar design, with an opening to funnel the water into the net, a long net with fine mesh opening (typically $335 \mu m$) to filter the water, a cod end to retain the collected materials (including the plastics), some system to keep the trawl at the surface of the water, and a rope system to attach the trawl to a vessel. Two common challenges that inhibit data collection by trawls include challenging marine conditions (weather, chop, etc), and lost opportunities to collect data while traveling between sampling stations or other locations. The AVANI (All-purpose Velocity Accelerated Net Instrument) trawl, a new design by Marcus Eriksen of the 5 Gyres Institute, offers a new method to sample microplastics at the sea surface. This trawl can be towed particularly at high speeds and over long distances, thus increasing opportunities to document the abundance and impact of microplastics in marine and freshwater environments. The new AVANI trawl can complement traditional trawls, such as the manta trawl and the DiSalvo neuston net used in this study. But new technologies must be validated against established ones to ensure samples are comparable.

The issue of plastic pollution has entered mainstream debate largely due to the increased utility of plastic and research describing environmental impacts. Global plastic production exceeded 300 million tonnes per year in 2014 (Plastics, 2015). While estimates vary as to how much plastic ultimately reaches the oceans (Thompson, 2006; Eriksen et al., 2014; Jambeck et al., 2015), the amount is expected to grow over the next decades as production continues to increase. The presence of plastic debris in marine ecosystems has been well documented (Colton et al., 1974; Law et al., 2010; Moore et al., 2001; Thompson et al., 2004; Cózar et al., 2014), including an increasing abundance of microplastics in all marine and freshwater ecosystems (Eriksen et al., 2013; Hoellein et al., 2014; Corcoran, 2015; Dris et al., 2015; Eerkes-Medrano et al., 2015).

The sources of microplastics are diverse, and include both primary and secondary plastics. Primary sources include preproduction pellets and powders (Mato et al., 2001), as well as polyethylene and polypropylene microbeads used in many personal care products such as facial scrubs and toothpastes (Gregory, 1996; Fendall and Sewell, 2009). Secondary sources originate from mechanical and photo-oxidative degradation (Singh and Sharma, 2008) of plastic items such as bags, bottles, fishing line, and nets into smaller fragments (Browne et al., 2007; Cole et al., 2011) and are also found in sewage effluent contaminated by fibers fragmenting from washing clothes (Browne et al., 2011; Hernandez et al., 2017; Napper and Thompson, 2016).

Given their small size, mobility, similarity to typical prey organisms, and widespread distribution, microplastics have high potential to be ingested by aquatic organisms (Browne et al., 2008; Graham and Thompson, 2009; Lusher et al., 2013; Ory et al., 2017). Direct effects of ingestion, such as inflammation, abrasions, or blockages and subsequent starvation are likely to be less pronounced with the smaller particle size, albeit this is not yet well studied (Rochman et al., 2016). Of concern are potential secondary effects, such as the ability of the plastic to transfer inherent or absorbed persistent organic pollutants (POPs) into the organism, leading to a variety of negative impacts (Browne et al., 2013; Rochman et al., 2013; Wright et al., 2013; Chua et al., 2014; Rochman et al., 2014; de Sa et al., 2015; Tanaka et al., 2015), although these effects are variable across species in laboratory tests (Koelmans et al., 2013; 2014; 2016). Because of these reasons, microplastic monitoring is of continued importance.

While most current studies have been done with traditional neuston trawls, their use is limited to comparatively calm sea states and moderately low trawl velocities. This potentially restricts the number of samples that can be obtained during a particular expedition. Therefore, the current study compares two traditional, wide but shallow-mouthed neuston trawls, the manta trawl and the DiSalvo neuston net with the AVANI trawl to ensure that data collected with the newer AVANI can be compared across studies.

2. Materials and methods

Two expeditions, one in the Bay of Bengal and one in the South Pacific, were conducted using the AVANI trawl and one other established scientific neuston trawl. In the Bay of Bengal, a manta trawl was used alternately with the AVANI trawl, whereas in the South Pacific the DiSalvo neuston net was deployed simultaneously with the AVANI trawl at discrete oceanic stations (Fig. 1).

The AVANI trawl (Fig. 2) has a rectangular aperture which is 60 cm high and 14 cm wide, divided into two compartments by an aluminum plate. The plate is on the same plane as the two skis that keep the trawl at the sea surface when towed so that the bottom compartment (20 cm high and 14 cm wide) is beneath the surface. The net is 4 m long and has a mesh size of 335 μ m with a 30 \times 10 cm² cod end. The AVANI trawl may skim across the ocean surface or at times be nearly completely submerged under rough seas and at high speed.

The manta trawl (Fig. 2) has a rectangular aperture that is 16 cm high and 61 cm wide, and has a 3 m long 335 μ m net with a 30 \times 10 cm² cod end. It has two large upward-angled wings, which are hollow to allow for flotation as well as pushing the front of the trawl upward while under tow.

The DiSalvo neuston net (Fig. 2) has a rectangular aperture that is 40 cm high and 80 cm wide, and has a 2.2 m long 300 μ m net with a 30 \times 15 cm² collecting bag. It has one PVC pipe attached to each side which serve as floating devices that dictate the level at which the net sits in the water. Therefore, in calm conditions water is collected with only half of its opening, an area of 20 cm \times 80 cm. This net has been used in Chile since the 1980s, first introduced by Louis DiSalvo (1988).

The main difference between the AVANI design and other neuston trawl designs such as the manta trawl and DiSalvo neuston net is that its opening is much taller than it is wide, creating a stable net opening that captures the surface of the water at high speeds. Video documentation of AVANI trawl performance is publically available and shows the trawl capturing the sea surface up to sea state 5 on the Beaufort scale (Eriksen, 2017).

The AVANI trawl was specifically designed for rough seas and high speeds that typically destabilize other neuston nets, causing them to leap above or descend below the sea surface. The tall, narrow profile on the AVANI trawl means that in more turbulent sea states, the net opening continually captures the surface layer during vertical movement. The AVANI trawl does not leap out of the water or dive below the sea surface, as frequently happens with other, traditional neuston trawls at higher speeds and sea states. Therefore, the AVANI trawl is an 'efficient' tool for sampling the sea surface at higher speeds and sea states. If trawled at 5 knots for about 60 min, the AVANI net would cover a total surface area of ~1300 m², whereas the Manta and the DiSalvo nets, if trawled at 2 knots for about 15 min, sample an area of 1130 m² and 1482 m², respectively.

The Bay of Bengal expedition was conducted aboard the S/V Mir in 2013 and was jointly organized between the 5 Gyres Institute and the Biosphere Foundation. The 11-day expedition began on May 25, 2013 from Galle Harbor, Sri Lanka, and sailed east to Phuket, Thailand (Fig. 1). 36 samples were collected using the AVANI and manta trawl (Table S1), one after the other. The 36 sample sites, 18 from each trawl, were not equidistant. Instead, they

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Fig. 1. Map showing sampling locations in the Bay of Bengal with the AVANI and manta trawl (A) and in the South Pacific with the AVANI and Epineuston trawl (B). AVANI transects in grey. Manta and DiSalvo neuston trawls in black. In the Bay of Bengal long AVANI transects were conducted, interspersed with manta trawls resulting in an almost continuous sampling. In the South Pacific shorter trawls were conducted and around the islands of Salas y Gómez and Rapa Nui several samples were taken. The length of the transects on the main map in panel B is not to scale.

were used in ways that would characterize their use in a regular research settings. Manta trawl deployments were each 60 min long, at an approximate speed of 2.0 knots. The AVANI trawl was deployed for longer times and distances, often overnight; the longest trawl tow exceeded 130 km. The AVANI trawl was towed typically at 4–6 knots, but occasionally would increase to 7–8 knots when wind gusts would occur while under sail. Both trawls were towed along the surface on the downwind side of the vessel using a spinnaker pole to position the towline outside of the ship's wake, as wake downwells surface plastics.

In addition to the trawl surveys, sixteen 60-minute visual surveys were conducted in the Bay of Bengal to determine whether macrodebris densities follow a similar geographic pattern as microplastic densities. Observations were made from the side of

the ship looking up to 20 meters out, and a 90° arc to the bow, utilizing established survey methods (NOAA; Eriksen et al., 2014).

The expedition in the South Pacific from Chile to Rapa Nui (Easter Island) was conducted aboard the research vessel Cabo de Hornos and organized by the CIMAR 21 project of the Chilean Navy (Fig. 1). The 30-day expedition began on the 12th of October in Valparaíso (Chile), sailed west to Rapa Nui (Chile) and returned to Valparaíso on the 10th of November 2015. 18 AVANI trawls and 34 DiSalvo neuston nets were deployed to collect samples with a maximum of 10 km within predefined stations. In most cases, at each oceanographic station, two replicate deployments were done with the DiSalvo neuston net, and these were paired with a single AVANI trawl (see Table S2 for details). Each trawling lasted between 15 and 30 min. The AVANI trawl was towed along the side of the

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Fig. 2. (A) Schematic drawing of the AVANI trawl (A), Manta trawl (B) and DiSalvo neuston net (C). For dimensioned orthographic PDF files visit TestingOurWaters.Net.

main research vessel using a pole at a speed of 4 knots and the DiSalvo neuston net was trawled behind a small inflatable rubber boat at a speed of approximately 2 knots. Different vessels were used because it was difficult to maneuver the main research vessel at the low speeds required for the DiSalvo neuston net. The DiSalvo neuston net was towed approximately 20–40 m behind the vessels to avoid the turbulence generated by their wake, though this distance is determined by visual observation of wake and likely requires additional investigation to understand wake effects. AVANI trawls were launched from the side of the vessel and trawled in parallel to the ship.

The different distances, speeds, and sea states in each study ensured that the validation between trawls captured the variability of normal use. Unlike laboratory comparisons where all variables are isolated and controlled, field tests for validating technologies have to ensure that trawls behave similarly in a wide variety of normally occurring conditions, such as speed, water states, amount of organic matter in the water, weather, and timing.

2.1. Sample preparation

Samples obtained in the Bay of Bengal were preserved with 70% isopropyl alcohol and later rinsed in saltwater, which floated the plastic to the surface for removal, and investigated remaining organic debris for plastics. Using a dissecting microscope (10x to 40x magnification), plastic was removed from preserved natural material, and then sorted by rinsing through Tyler sieves into 3 size classes: 0.355–0.999 mm, 1.00–4.749 mm, >4.75 mm. Samples

from the South Pacific were preserved in 95% ethanol. Samples from both regions were inspected visually to separate microplastics, with ambiguous particles rejected from the final counts and weights. FT-IR was not utilized to confirm polymer identification in either region due to equipment inaccessibility and confidence in laboratory analysis, which was conducted by one experienced technician for each data set. This was followed by all ambiguous particles analyzed by another lab technician and eliminated if not visually confirmed to be plastic with a high degree of confidence.

All AVANI and some DiSalvo neuston net samples from the South Pacific were contaminated with paint fragments, resulting from collision of the trawl with the boat hull. These paint fragments (fragile, soft, and sinking in seawater) were excluded from analysis. The plastic fragments were photographed with a scale and measured with the software ImageJ. Fragments below 0.335 mm were excluded from analysis, as this was the smallest common size of all three trawl nets. Microplastics were weighed individually using an analytical scale with a precision of 0.1 mg. If individual plastics did not register any weight, a weight of half of the scale's precision was assumed (0.05 mg, 25% of all plastics weighted). For a small portion (approx. 4%) of microplastics, which were not available for weighing, the weight was estimated based on similar-sized fragments. Individual pieces of plastic were divided into categories: fragments, foam, line, pellet, film, other; and then counted.

2.2. Data analysis

The distance sampled with each trawl was calculated by using start and stop latitude and longitude (Bay of Bengal) or using the time of the sampling multiplied by the velocity of the towing vessel (South Pacific). The area sampled was calculated by multiplying this distance by the width of each trawl, then scaling the result to km² to express the quantity of microplastics/km². Two DiSalvo neuston net tows were paired with each AVANI trawl at most stations in the South Pacific; therefore, in those cases the quantity of microplastics/km² from the DiSalvo neuston net tows were averaged first.

Results were recorded for the count and weight totals of all plastics in each tow, as well as for each type of plastic (fragments, foam, line, pellet, film). The resulting data were analyzed by performing a paired *t*-test on the weight density and count density difference of the paired AVANI-manta and AVANI-Di Salvo trawls. The analyses were done using the *t.test* function in R version 3.1.2, using zero as our null hypothesis and a significant p-value of 0.05. The bivariate Pearson correlation analysis (two tailed) was conducted in PSPP version 0.8.5 (Pfaff et al., 2012), using a significant p-value of 0.05. Even though the data points do not follow a normal distribution the Pearson correlation seems adequate to identify whether a general relationship exists between the pairs of trawls (Havlicek and Peterson, 1976).

In the case of the South Pacific, it was clear which DiSalvo neuston trawls were paired with which AVANI trawls since they were conducted simultaneously in discrete areas (Table S2). In the Bay of Bengal, trawls where conducted alternately one after the other (Table S1), and we could not *a priori* determine which pairing (manta before AVANI, or manta after AVANI) would be the most suitable order to analyse the data. Therefore, we used count data (total microplastics/km²) to determine which sample pairs would generate the best fit. For this we did a correlation analysis (with and without extreme values) for total microplastic counts in which we paired (i) each manta with the following AVANI trawl, and (ii) each manta with the preceding AVANI trawl. Since there was a high incidence of plastics in one area (hotspot) where the AVANI trawl was towed for an unusually long time, we also ran the correlation analysis without these extreme values (AVANI 22 and manta 23 in

Table S1). After determining the best model for pairing the manta and AVANI trawls (manta with the preceding AVANI), all following detailed analyses were then done with that sample pairing.

3. Results

In the Bay of Bengal, 36 samples were collected, with the AVANI and manta trawls used alternately along the entire linear transect. totaling 18 samples with each trawl type (Fig. 3A, Tables S1 and S3). Microplastic abundances in the Bay of Bengal mostly varied between a few hundred and 20,000 items/km², but in one area abundances were much higher, exceeding 100,000 microplastics/ km^2 (Fig. 3A). These high abundances were found by both the AVANI and the manta trawl. In the South Pacific, a total of 52 samples were collected at predetermined stations with the AVANI (n = 18) and DiSalvo (n = 32) trawls (Fig. 3B, Tables S2 and S4). Microplastic abundances in the S Pacific mostly varied around 10,000 items/km², but reached abundances of >50,000 microplastics/km² near the islands Rapa Nui and Salas & Gomez (Fig. 3B). In addition to the net surveys in the Bay of Bengal, visual observations were conducted to survey macrodebris, with item and count recorded in 12 categories (Table S5). Highest abundances of floating macrodebris were observed at stations 13 and especially station 14 (Table S5), which coincide with the high microplastic counts in that area (Fig. 3A).

Roughly half of the particles counted in all trawls in all regions



Fig. 3. Count densities of microplastics in the two study regions along the sampling transects. (A) AVANI (n = 18) and manta (n = 18) trawls in the Bay of Bengal. (B) AVANI (n = 18) and DiSalvo neuston net (n = 34) trawls in the South Pacific. For the Bay of Bengal transect the quantity of observed macrolitter is also displayed (every circle represents an observation; open circle = 0 litter items, small circle = 1 litter item, medium circle = 2–5 litter items, and large circle = more than 5 litter items observed). The lines represent moving averages for the respective trawls. Size of islands is not to scale.

were in the 1.0–4.75 mm size range, with 0.335–0.999 mm particles being next, and particles larger than 4.75 mm being least in numerical abundance (Table 1). Among the particle types, in the South Pacific 76% of all particles captured by the AVANI trawl were fragments, and 63% in the DiSalvo trawl. Next highest particle abundance was line, then foam, followed by film at 5% or less. Interestingly, in the Bay of Bengal 59% of particles captured by all manta trawl samples were film, as well as 40% of the AVANI trawl samples. In the Bay of Bengal, 41% of the AVANI particles were fragments, nearly identical to the count of film particles. Line, foam, then pellets were the order of abundance for the remaining particles in the Bay of Bengal.

Given the variability of plastic distribution at a local scale, we had to determine which pairings of AVANI and manta trawls in the Bay of Bengal were best correlated. The correlation analysis for the total microplastic counts in the Bay of Bengal revealed that only microplastic counts between the manta trawl and the preceding AVANI trawl (including the extreme values) are significantly correlated. The manta trawl pairing with the subsequent AVANI trawl (with and without extreme values) shows no significant correlation (Table 2). Considering only the pairing with significant correlation from now on, we also found a correlation for total weight and for some (though not all) different plastic categories and size classes (line, film, microplastics below 4.75 mm for count densities; film and microplastics below 4.75 mm for weight densities, Table 3, Fig. 4). In the Bay of Bengal, the AVANI trawl collected a greater overall mass of plastic compared to the manta trawl (Table 4, Table S6a), which mirrors the findings for count. While most differences were not statistically significant enough to be distinguished from random events and natural variation, the AVANI trawl did collect more plastics by weight when plastics were larger than 1 mm in size. That is, while counts may not have been statistically significant between the two trawls, by weight they were (p-value < 0.05, bold values in Table S6a), indicating that both trawls caught a similar quantity of plastics, but the AVANI caught a greater weight of plastics when the plastics were larger in size (for plastics 1.0-4.75 mm, p = 0.0039; >4.75 mm, p = 0.007; total weight p = 0.0057; Table S6A).

In the South Pacific, a significant correlation was found between the AVANI and DiSalvo trawls, considering the total count densities of microplastics/km² (r = 0.5, p < 0.05), though not for weight. There is only one other significant correlation considering different plastic categories and size classes (count densities of microplastics between 0.335 and 0.999 mm; Table 3, Fig. 4). In the South Pacific, there is no clear pattern as to which trawling method collects more plastic by weight between the AVANI and the DiSalvo neuston net (Table 4). Only the foam weight for plastics between 1.0 and 4.75 mm showed statistically significant increases for the DiSalvo neuston net (p = 0.018, Table S6b).

Analysis of the relationship between microplastic densities and Beaufort values (as a proxy for weather conditions) showed no difference of microplastic densities for lower or higher values on the Beaufort scale, neither for the Bay of Bengal nor for the South Pacific (S7).

4. Discussion

4.1. Validation of trawls

The AVANI, manta, and DiSalvo neuston trawls create generally comparable data, particularly between the AVANI and DiSalvo trawls, though some differences between correlative comparisons of count and weight occurred. A lack of correlation for weight density data for the AVANI-DiSalvo pairs may be explained by the comparatively low quantities of microplastics obtained in the

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Table 1

Total number and proportion of microplastics found for each net and region according to type and size of microplastics.

	Plastic description	Bay of Bengal		South Pacific	
Trawl type		AVANI	Manta trawl	AVANI	DiSalvo neuston net
Total count		5439	1388	108	524
Count and % distribution by size	0.335–0.999 mm	2145 (39%)	675 (49%)	31 (29%)	98 (19%)
	1.0–4.75 mm	2545 (47%)	639 (46%)	61 (56%)	313 (60%)
	>4.75 mm	749 (14%)	74 (5%)	16 (15%)	113 (22%)
Count and % distribution by type	Fragments	2255 (41%)	334 (24%)	82 (76%)	330 (63%)
	Foam	359 (7%)	30 (2%)	8 (7%)	74 (14%)
	Line	602 (11%)	201 (15%)	11 (10%)	92 (18%)
	Film	2188 (40%)	821 (59%)	5 (5%)	21 (4%)
	Pellet	35 (1%)	1 (<1%)	2 (2%)	7 (1%)
	Other	0 (0%)	1 (<1%)	0 (0%)	0 (0%)

Table 2

Pearson correlation (Bivariate Correlation test, two tailed) for total microplastic counts for four different scenarios in the Bay of Bengal. p-value in brackets, < 0.05 in bold.

Scenario	Bivariate correlation (p-value)
Manta trawl paired with subsequent AVANI trawl, $n = 18$ pairs	0.20 (0.42)
Manta trawl paired with subsequent AVANI trawl, values with very high litter densities removed, $n = 16$ pairs	-0.17 (0.54)
Manta trawl is paired with preceding AVANI trawl, $n = 17$ pairs	0.95 (< 0.01)
Manta trawl is paired with preceding AVANI trawl, values with very high litter densities removed, $n = 16$ pairs	0.26 (0.33)

Table 3

Pearson correlation (Bivariate Correlation test, two tailed) for particle counts of types of microplastics and size classes between pairs of nets (p-value in brackets, < 0.05 in bold, < 0.1 in italic). AVANI-manta trawl pairs n = 17. AVANI-DiSalvo trawl pairs n = 16. The correlation test was only performed if more than 50% of samples from both nets contained microplastics for the respective microplastic type or size category (others marked with n/a).

	AVANI-manta (Bay of Bengal)	
Count densities for 1 km ² ocean surface		
All microplastics	0.92 (<0.01)	0.50 (0.048)
Pellets	n/a	n/a
Line	0.48 (0.049)	n/a
Fragments	0.37 (0.14)	0.48 (0.06)
Film	0.98 (<0.01)	n/a
Foam	-0.09(0.74)	n/a
Microplastics 0.335–0.999 mm	0.92 (<0.01)	0.54 (0.03)
Microplastics 1.0-4.75 mm	0.96 (<0.01)	0.38 (0.15)
Microplastics > 4.75 mm	0.04 (0.87)	n/a
Weight densities for 1 km ² ocean surface		
All microplastics	0.53 (0.03)	0.01 (0.98)
Pellets	n/a	n/a
Line	-0.05 (0.86)	n/a
Fragments	0.13 (0.61)	0.03 (0.90)
Film	0.95 (<0.01)	n/a
Foam	0.22 (0.40)	n/a
Microplastics 0.335–0.999 mm	0.57 (0.02)	0.10 (0.73)
Microplastics 1.0–4.75 mm	0.74 (<0.01)	0.06 (0.83)
Microplastics > 4.75 mm	0.42 (0.09)	n/a

region (about 1/10 of the plastics found in the Bay of Bengal): at many sampling stations so few plastics were sampled that they failed to register any weight on the balance and therefore weight data fell below the registration threshold.

Of the particle types collected in each region, the South Pacific was dominated by fragments at 76%, and only 5% film, whereas in the Bay of Bengal fragments were 41% and film 40%. According to Lebreton et al. (2017) the Ganges River is the 2nd largest emitter of plastics to the marine environment, and in this study the Bay of Bengal samples had 10 times more plastic particles than the South Pacific. This observation of more plastic film in the Bay of Bengal may be a reflection of coastal population density and their usage of thin film in the form of plastic bags.

Comparing each manta tow with preceding AVANI tow showed that the AVANI collected a statistically significant higher quantity of large plastic items by weight compared to the manta trawl. This may be an indicator that larger microplastic particles may be distributed deeper beneath the surface than smaller microplastic particles, where the AVANI trawl catches them when it vertically descends, and the manta does not. But this was not observed with the DiSalvo trawl, which raises questions about comparability between studies conducted by the different trawls. Because the manta trawl and DiSalvo neuston net have similar designs in terms of where they sample in the water column, the speeds at which they travel, and their stability in different weather, if the manta was significantly different than the AVANI trawl, one would also expect the DiSalvo neuston net to show the same patterns. This was not the case suggesting that the trawls are comparable in general terms. We offer three explanations for the difference of similar counts, but greater overall weight between the manta and AVANI comparison in the Bay of Bengal, all of which account for heavier plastics and denser plastics floating slightly lower in the water column during the Bay of Bengal expedition.

First, the AVANI trawl's tall, narrow mouth reaches deeper into

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Fig. 4. Correlation between microplastic count density in the two study regions. (A) AVANI paired with manta trawl in the Bay of Bengal (n = 17, r = 0.92, p = <0.01), one data point exceeds the scale (marked with arrows). (B) AVANI paired with DiSalvo neuston trawl in the South Pacific (n = 16, r = 0.5, p < 0.05). Thick lines = trend lines. Filled circles represent average values from multiple tows at the same spot and the extending lines mark the lower and upper values (dotted lines exceed the figure scale). Open circles represent values obtained from single tows.

Table 4

Summary table of the count and weight difference of various plastic types and size classes between trawling by Manta and AVANI pairing in the Bay of Bengal, and DiSalvo and AVANI pairing in the South Pacific. The mean is the difference between Neuston (Manta or DiSalvo) and AVANI trawling; when the value is positive, it shows how much more plastic Manta collected, while when the value is negative, it shows how much more plastic AVANI collected. The values in bold are statistically significant (p-value <0.05).

		Mean	SD	p-value
Manta & AVANI	Count (/km ²)	-16107	47077.63	0.18
	Weight (g/km ²)	-105	136.02	0.0057
DiSalvo & AVANI	Count (/km ²)	-726	11984.00	0.8118
	Weight (g/km ²)	-10	78.48	0.6186

the water column than other trawl designs to create stability in rough seas and high speeds. This means it is sampling more of the water column, though calculations for all trawl designs ignore the volume of water sampled and assumes just the surface of water is being sampled because the volume of water constantly fluctuates within the mouth of any trawl during sampling. As such, the AVANI is likely to gather the plastics just below the surface of the water that other trawls pass over. Yet since the AVANI would sample deeper in the water column of both expeditions, an explanation for why the greater weight of plastics was obtained in the Bay of Bengal is required.

Secondly, between any two studies regardless of the scientific instruments used, differences may come from water and weather conditions. If the weather had stirred the water column in the AVANI-manta comparison, then plastics would be pushed farther down into the water column. Wind, wave action, biofouling, and other environmental factors have great effect on where plastics reside in the water column (Kukulka et al., 2012; Guha, 2008; Melville, 1996). The ideal testing environment would be to deploy different trawls in the same sea state in order to reduce the influence of wind on the vertical distribution of microplastic particles, therefore isolating the variable of trawl performance on the count/ weight of microplastics collected. Yet, in the present study, no difference between calmer and rougher seas and microplastic density could be shown (Table S7), although it has to be emphasized that we aimed at a direct comparison between the traditional neuston trawls and the new AVANI trawl, which is why all surveys were done at mostly fine weather conditions suitable for the traditional trawls. Future studies should test the AVANI trawl at higher sea states.

Third, and most importantly for understanding and analyzing findings in neuston microplastic studies, is the tension between small-scale and large-scale variation. By design, the AVANI trawl covered very large transects in the Bay of Bengal (collecting plastics from a great stretch of ocean) versus the much shorter transects of the manta trawl (collecting plastics from a small area). In the Bay of Bengal, the longest AVANI transect conducted exceeded 130 km, while in the South Pacific, none were over 3 km long. Microplastic distribution can vary substantially even in replicate tows at the same spot (Reisser et al., 2013; present study, Table S4), and this spatial variability can be reduced with longer tows across large areas, as longer tows may bridge this meso-scale variability, thus reducing some of the variance observed. However, by reducing spatial variability with very long tows, important information may be lost, such as localization and identification of "hotspots", i.e. high concentrations of plastics, in particular areas.

4.2. Comparisons between sampling techniques

There have been other techniques used in previous studies to sample at the sea surface and just below the surface, including stacked nets that sample at different levels of the water column simultaneously (Reisser et al., 2015), epineuston trawls similar to the DiSalvo neuston net that use catamaran design or other pontoons to stay afloat (Hidalgo-Ruz et al., 2012), repurposed plankton nets such as Bongo nets (Doyle et al., 2011), as well as non-trawl or net methods such as bulk sampling with laboratory filtration (Dubaish and Liebezeit, 2013; Ng and Obbard, 2006; Setälä et al., 2016), *in situ* filtration (Norén and Naustvoll, 2010), repurposing Continuous Plankton Recorder Samples (Thompson et al., 2004), or

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sampling seawater from intake hoses intended to cool engines (Lusher et al., 2014). Several of these techniques capitalize on what would otherwise be missed sampling opportunities (e.g. Lusher et al., 2014; Doyle et al., 2011; Thompson et al., 2004).

Trawls differ widely in their design. An important variable is the net opening, which can range from 75 cm (Isobe et al., 2014) to 100 cm (Kukulka et al., 2012), 157 cm (Ryan, 1988), and 200 cm (van Dolah et al., 1980). The nets with a larger opening might be more suitable for a survey of large items that have a high probability of not being sampled by nets with small openings, though a better method for evaluating macrodebris are visual observations (Ryan et al., 2009), which we performed in the Bay of Bengal (discussed below). Surprisingly, herein we found that the AVANI net collected more (by weight) of the larger (>1 mm) particles, but overall the count densities were similar between the nets, despite the strong differences in opening width (14 cm for AVANI, 61 cm for manta, and 80 cm for DiSalvo neuston net). It is likely that microplastic densities have reached abundances in the open ocean that all microplastic sizes can be collected representatively with these trawls. Most likely mesoplastics and larger plastics, which occur at significantly lower count densities (e.g. Eriksen et al., 2014), require wider net sizes for representative sampling. Similarly, the effective depth of the trawl mouth varies among trawls, from trawls that skim only the upper surface (\leq 10 cm, e.g. manta trawl) to trawls that filter the upper 25 cm of the water column (Kukulka et al., 2012).

While many net-based neuston trawl studies often only sample at specific sampling stations (e.g. Reisser et al., 2015), the AVANI trawl can overcome this limitation. Because the AVANI trawl can sample at high speeds for long periods of time, it can be used when other forms of trawls or sampling protocols are not feasible, including overnight sampling and high-speed ship movements between stations, as well as citizen science scenarios such as routine shipping or pleasure craft voyages, including sailboats. This advantage may allow for long transects between stations where other trawls are to be used, or the AVANI trawl could be utilized continuously for the entire transit from port to port, with only periodic stops to empty the sample from the cod end, in a similar way as the Continuous Plankton Recorder (e.g. Reid et al., 2003). While sampling the sea surface when underway has been extremely challenging to date, the AVANI trawl appears to perform well in conditions of moderate sea state under 8 knots of boat speed over long transects.

Despite these advantages to using the AVANI trawl, there are also disadvantages. It has been observed that biofilms on plastic particles are damaged during use due to turbulence in the cod end (end of the net). After several hours at speeds up to 8 knots, even fish can be severely damaged. Usually, trawls are used at speeds of 1–3 knots (e.g. Ryan, 1988; Kukulka et al., 2012; Isobe et al., 2014), but higher speeds have also been reported (5 knots; Colton et al., 1974). At these high speeds pressure on these trawls can be high and there is concern that some particles are pushed through the mesh (Colton et al., 1974).

Marine organisms associated with plastic using the AVANI trawl may become damaged during sampling, but these undesired effects can be minimized with recovery of the cod end every 60–120 min, rather than extremely long tows as done herein in the Bay of Bengal. Trawl duration in other studies ranged from 2 min (Ryan, 1988) to 30 min (e.g. Kukulka et al., 2010). To our knowledge, no other trawl has been used for comparable durations as the AVANI trawl herein. While long trawl duration (representative of long distances) may be advantageous for some reasons (covering large areas of the ocean), spatial resolution of sampling decreases. It therefore is suggested to reduce trawl duration to 20–40 min of total time (representing ~ 5–10 km at speeds of 8 knots).

4.3. Spatial variation and macrodebris observations

Floating litter accumulates in large areas within the oceanic gyres (e.g. Cózar et al., 2014; Eriksen et al., 2014). Within these accumulation areas plastic abundances are very high, yet there is also substantial meso-scale variation in plastic distribution as evidenced by samples with very high microplastic abundances adjacent to samples with comparatively low abundances (e.g. Goldstein et al., 2013; Eriksen et al., 2013). This meso-scale variability may be due to oceanic fronts and eddies (e.g. Belkin et al., 2009; Cornejo et al., 2015). Herein, our visual observations (Table S5) found significant numbers of large meso- and macro-plastics in the Bay of Bengal flowing southward along the Andaman Islands, in the same area where we found very high abundances of microplastics. Current modeling suggests a large anticyclonic rotation in the Bay of Bengal during the winter season (Potemra et al., 1991), perhaps 'sweeping' debris along coastlines and concentrating where it was observed in this study.

This meso-scale variability in plastic abundances is rarely accounted for in most studies, because determining it would require high spatial resolution of samples (e.g. Goldstein et al., 2013). However, it has important ecological implications because many organisms (including fishes and seabirds) associate with these accumulation fronts where they find food and habitat (e.g. Acha et al., 2015). In these frontal zones, ecological impacts of plastics are likely highest. Herein we identified one of these mesoscale accumulation zones in the Bay of Bengal, with high abundances of micro- and macroplastics. Knowing that macrofauna are associated with macrodebris (Goldstein et al., 2014), the AVANI trawl has an increased potential to capture and damage wildlife that would otherwise escape a manta or DiSalvo trawl. Here we report the first instance of a sea snake captured while sampling microplastics in the Bay of Bengal (Fig. 5) within the area of observed high debris concentrations. Ironically, a plastic "bendy straw" was captured alongside the sea snake.

Given the importance of ecological processes and impacts at oceanic fronts, we suggest that it is necessary to determine their spatial distribution and persistence over time, and how this is related to the meso-scale variability of plastic distribution. The potential of the AVANI trawl to facilitate a greater amount of spatial sampling, e.g. via deployment from vessels of opportunity, offers a unique chance to achieve this goal. Adjustment of the spatial scale of neuston microplastic surveys to the scale provided by typical oceanographic satellite imagery will help in the future to better



Fig. 5. Sample # 32 in the Bay of Bengal captured a plastic straw and sea snake, demonstrating the impact a faster net may have on wildlife.

determine the small- and meso-scale dynamics of microplastics in the open ocean.

5. Conclusions

Given the scalar differences between small sample areas and the large regional transects the AVANI trawl is designed for, and accounting for other variables that influence microplastic abundance (e.g. wind speed, wave action, vertical mixing, water currents, weather; Reisser et al., 2013) our results suggest that the AVANI, manta, and DiSalvo neuston trawl designs yield comparable data, and studies done with each type of trawl can be compared. To aid in the characterization of variability, we recommend that studies routinely report both the count and weight data when using different models of trawl or other sampling techniques.

Data availability statement

These data are available at figshare.com.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2017.09.058.

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