Seasonality of marine plastic abundance in central Red Sea pelagic waters

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Highlights

- We conducted a seasonal sampling in an area of surface currents convergence
- We identified the central Red Sea as a hotspot of floating plastic
- Plastic concentrations vary seasonally according to the monsoons, lower in summer
- Plastic composition varies seasonally, with films more frequent in summer
- Most likely, plastic inputs are short-ranged in summer, long-ranged in winter

Abstract

The Red Sea holds one of the lowest concentrations of floating plastic worldwide and no evident congregation zones were identified so far, despite peculiar oceanographic features that candidate the basin as an accumulation area for floating debris. However, the Red Sea exhibits a complex pattern of surface currents, which changes according to the monsoon season, possibly affecting the abundance of plastic throughout the year. To explore the effect of seasonality on plastic concentration in surface waters, we conducted a fortnightly time series sampling, using a neuston net, for 21 months at a pelagic station in the central Red Sea, where the major seasonal overturn of the Red Sea surface circulation occurs. The estimated average abundance ($\pm$ SE) was $58,563 \pm 19,272$ items Km^{-2} (73.5 ± 40.75 g Km^{-2}), highly variable according to season, lower during the summer monsoon. Indeed, the winter monsoon pushes oceanic surface waters inside the Red Sea, transporting alongside floating plastic items, whilst surface currents exit the basin during the summer monsoon, depleting central Red Sea waters from floating plastic. Composition of plastic items also changes through time. Particularly, the higher proportion of films and foams during summer months suggests that the main source of plastic at the sampling station from June to September is a short-range transport, while during winter months, the higher contribution of small fragments indicates that, from October to May, plastic is also transported to the central Red Sea through surface currents for long distances, possibly coming all the way from the Indian Ocean.

Keywords: Microplastic; Marine Debris; Monsoon; Surface Circulation; Red Sea.

1. Introduction

Plastic consumption has increased exponentially over the past decades, leading to parallel growth in mismanaged plastic waste (PlasticsEurope, 2016; Lebreton and Andrady, 2019), which eventually reaches the marine environment (Jambeck *et al.*, 2015; Geyer, Jambeck and Law, 2017). Subjected to mechanical, physical and chemical agents, it fragments into microplastics, items smaller than 5 mm (Moore, 2008; Andrady, 2011). Most of produced plastic is less dense than seawater, therefore derived microplastics float in sea surface waters, unless up-taken by marine biota (Gall and Thompson, 2015) or biofouled by microorganisms which ultimately contribute to its sedimentation (Kooi *et al.*, 2017). Buoyant plastic is either transported by winds and currents back to shore (Thiel *et al.*, 2013) or accumulates offshore in aggregation zones. Seven main marine plastic accumulation zones have been identified so far, 5 corresponding to the 5 oceanic gyres (Lebreton, Greer and Borrero, 2012; Cozar *et al.*, 2014), one in the Arctic (Cózar *et al.*, 2017) and one in the Mediterranean Sea (Cózar *et al.*, 2015; Van Sebille *et al.*, 2015).

Similarly to the Mediterranean Sea and Arctic Ocean, the Red Sea is a semi-enclosed basin, connected to the Mediterranean sea itself through the Suez Canal. Because of the reduced dimension of the channel, the only hydrologically-relevant connection with an external basin is the Bab-el-Mandeb strait, which connects the southern Red Sea with the Gulf of Aden and ultimately the Indian Ocean. At the strait, a mainly inverse estuarine circulation, characterized by an inflow of surface Indian Ocean waters balanced by an output of denser Red Sea waters at depth, occurs for 8 months per year (Sofianos and Johns, 2002). The semi-enclosed nature and inverse estuarine circulation are features that contribute to the accumulation of marine plastic in

the Mediterranean Sea, where plastic floating on Atlantic Ocean surface waters enters and never exits the basin. Likewise, these were expected to lead to high plastic accumulation in the Red Sea, which, in turn, has been shown to sustain one of the lowest concentrations of plastic worldwide (Martí *et al.*, 2017). Together with low inputs, high removal rates were proposed as an explanation of this finding. However, sinks (e.g. sedimentation, coastal deposition, ingestion by marine biota, Law, 2017) mainly justify the significant gap found between waste inputs in the marine environment and estimated marine litter in surface waters (Cozar *et al.*, 2014). Therefore, the scarcity of microplastics in Red Sea surface waters, and the difference with the Mediterranean Sea and other seas, is also to be found within the unique oceanographic features of the Red Sea.

Due to its elongated and narrow shape, with an average width of only 220 km (Sofianos and Johns, 2002), the Red Sea is considered a coastal sea. Horizontal circulation patterns, although complex, appear only at the mesoscale, characterized by an alternation of cyclonic and anticyclonic eddies (Yao *et al.*, 2014). Hence, Marti *et al.* (2017) report rather uniform plastic concentrations in surface waters, with no clear aggregation areas identified.

Because of the coastal nature of the Red Sea, floating plastic items tend to strand back to shore (Martin *et al.*, 2018; Martin, Almahasheer and Duarte, 2019). It appears, in fact, that only objects characterized by high volume-to-surface ratio have the potential to travel long distances to reach the open sea (e.g., Lebreton *et al.*, 2018). As the Red Sea catchment area lacks of perennial rivers, which act as major vectors delivering plastic into the marine environment (Lebreton *et al.*, 2017), wind transport may play a major role in the Red Sea. For example, the frequent dust storms over the Red Sea were already recognized as important carriers of microorganisms and nutrients into the marine environment (Raitsos *et al.*, 2013; Yahya *et al.*, 2019). The dominance

of the wind transport would be expected to result in high inputs of light-weight plastic types with a low volume-to-surface ratio, such as like films (i.e. bags, wrappings, or pieces of them) and fibers (i.e. thin filaments normally originating from textiles, Martí *et al.*, 2017), which however, for the reason exposed above, are unlikely to reach the open sea. Hence the low concentration of plastic found in pelagic waters.

Winds are not uniform during the year in the Red Sea, and experience seasonal patterns, driven by monsoonal dynamics (Patzert, 1974), that should result in seasonality in the transport of plastics to the Red Sea. Winds over the Red Sea experience two contrasting seasons, driven by the Northeast winter monsoon from October to May, and the Southwest summer monsoon from June to September. In winter, winds blow from SE in the Southern Red Sea and from NW in the Northern Red Sea, while in summer, winds blow from NW across the whole of the Red Sea (Patzert, 1974; Murray and Johns, 1997). The same seasonal inversion is also reflected on main surface currents, flowing in the same direction (SE) in summer months all over the basin, but changing towards NW during winter in the Southern half of the Red Sea (Patzert, 1974). The crossing point of these two main currents is located in the central Red Sea, estimated from 19° N to 24° N depending on the model used (Sofianos and Johns, 2003; Yao *et al.*, 2014). At the Bab-el-Mandeb strait, the inverse estuarine circulation occurs only from October to May, contrarily from the Gibraltar strait in the Mediterranean Sea that shows it all year around. During the summer months, it changes to a three-layer circulation with deep and surface waters outflowing to the Gulf of Aden and an intermediate layer of oceanic waters inflowing in the Red Sea (Sofianos and Johns, 2002). This mechanism should therefore drift microplastics floating on surface waters inside the Red Sea from October to May and outside from June to September, affecting plastic concentrations in Red Sea surface waters during the year.

Given these premises, a seasonal pattern in the abundance of buoyant microplastics is expected in the Red Sea.

Because surveys in Marti *et al.* (2017) were conducted at different stations in different times of the year, a seasonal pattern of plastic distribution could not be investigated. In order to examine the hypothesized seasonal variability in the abundance of floating microplastic, we sampled biweekly drifting microplastics at a pelagic station in the Central Eastern Red Sea, where the main surface current overturns according to seasons, during nearly two years (21 months).

2. Materials and Methods

2.1 Field Sampling

The sampling station is located at 22.31 °N 39.0 °E, at <10 Km from the coast, where the small town of Thuwal and the King Abdullah University of Science and Technology (KAUST) are located, inhabited by approximately 8000 people, at about 90 Km N from Jeddah, the main human settlement on Red Sea shores, counting approximately 3 million people. The sampling station, located at a depth of about 50 m, is surrounded by a system of inshore reefs within a radius of 3 Km.

At the sampling station, we deployed a neuston net (Aquatic BioTechnology, Manta net) to collect surface plastic. The net was deployed from a small vessel (< 10 m in length) using a crane which also allowed trawling on the side of the boat. This avoided interferences with the turbulence created by the vessel propellers at the back, which could lead to plastic sinking and consequently underestimation of its abundance in surface waters. The neuston net used was

designed with an opening mouth of 60 x 20 cm and a mesh size of 200 μm . Two floaters on each size of the sustaining aluminum frame allow the net mouth to float at approximately 1/3 above the water surface, by limiting the encumbrance (e.g. compared to a classic manta trawl) and making this type of net more suitable for a sampling on a small-sized vessel (Fig. S1). The net is equipped with a General Oceanics 2030R flowmeter.

Before deployment, time and number indicated by the flowmeter were recorded. The net was towed for 30 min at 2-3 knots. After trawling, the net was retrieved on board, counts on the flowmeter recoded and mesh washed from the outside with seawater to ensure congregation of the sample in the net cod-end. The sample was collected in bottles, after thorough rinsing of the cod-end to ensure complete collection, and saved in a cooler until return. Once back in the lab, the sample was concentrated and fixed in ethanol for further inspection.

We conducted a total of 41 samplings from 4th September 2016 to 28th May 2018, approximately one sampling every two weeks, at around 10 - 11 a.m. Wind speed of the area around Thuwal at the time and date of the sampling was retrieved from <https://www.wunderground.com/>.

2.2 Sample processing

The sample was re-suspended in 45 μm filtered seawater to facilitate a density-based separation of buoyant plastic items. It was then entirely screened under a stereoscope in a petri dish after partition in smaller subsamples. All putative plastic items floating on the surface were sorted. The bottom of the petri dish was also carefully checked to pick sinking plastic items, either because biofouled or of polymers denser than seawater. The petri dish screening was repeated three times at three different magnifications. Sorted plastic items were rinsed with distilled water and once dried photographed and measured using an image analysis software (Image J,

<https://imagej.nih.gov/>). Items were classified in fragments (hard pieces from broken objects), films (bags, wrappings, or pieces of them), foams (expanded cellular plastics), threads (filaments from fishing lines, ropes and nets), beads (e.g. derived from products for cleansing and personal care) and pellets (raw plastic used for manufacturing). A subsample of the sorted items (>50%) was then analyzed with Fourier-transform infrared spectroscopy (we used Nicolet 10 FT-IR for particles $\geq 250 \mu\text{m}$ and Nicolet 6700 $\mu\text{FT-IR}$ for particles $< 250 \mu\text{m}$) to confirm it as plastic. Wave number ranged between 4,000 and 650 cm^{-1} . We first collected the background spectrum which was then subtracted to the object spectrum. We performed at least 16 scans per object, progressively increasing scans if necessary to decrease the noise. We characterized the polymer type against comparison with the OMNIC spectra library and confirmed the result if library match was >50%. The subsample of items that was not analyzed with FT-IR could be visually confirmed as plastic items due to characteristics of shape (e.g. regular edges), color (e.g. brilliant colors) and consistency of the material.

Fibers in the sample were also counted and picked. All the material used for the sample collection and the inspection at the stereoscope was previously rinsed with distilled water and a blank (a petri dish with a thin layer of distilled water) was set close to the working area during sample processing to account for environmental fibers contamination. However, a blank could not be set during sampling operations and fibers sorted could not be confirmed as plastic. Therefore, although we will report the abundance of fibers (after subtraction of number of fibers in the blank), we will exclude fibers from all our analyses.

2.3 Data analyses

Area of water sampled per tow was calculated multiplying flowmeter counts (i.e. difference in counts between tow start and end), rotor constant (retrieved from the flowmeter manual at <http://www.GeneralOceanics.com>) and width of the net. Volume of water sampled was obtained multiplying area sampled and height of the net submerged. Abundance and concentration of plastic were calculated as number and weight (in g) of plastic per Km^2 or m^3 . A correction on the abundance of plastic ($N \text{ items Km}^{-2}$ or m^{-3}) was applied when the friction velocity of water (u^*_w) > 0.6 , based on the effect of wind mixing on the vertical distribution of the buoyant plastic as proposed by Kukulka *et al.* (2012).

To obtain a size distribution of plastic items, sorted pieces of plastic were assigned to 15 size classes, which bins were set following a 0.01-log series of the feret diameter measured with ImageJ. Abundance of items in each size class was normalized per width of the size class. Size distributions of 4 plastic shapes (i.e. films, foams, fragments and threads) were compared using a Anderson-Darling k-sample test and compared in pairs using Kolmogorov-Smirnov (KS) test. The size distribution for beads and pellets was not produced since the sample size ≤ 10 .

Distribution of plastic abundance (wind-corrected) and concentration during the 41 sampling dates were tested using Generalized Additive Models (GAMs). We built models for both untransformed (Fig. S2) and log-transformed + k (Fig. S3 and S4) data, where k is a constant equivalent to the lowest value $\neq 0$, added in order to allow log-transformation in presence of zeros. Models from untransformed and log-transformed data were compared using the Akaike's Information Criteria (AIC) and consequently, the model from log-transformed data was preferred. Models were considered significant when p-value < 0.05 . Differences in the average concentration of plastic between the winter and the summer monsoon were tested with a Wilcoxon rank-sum test. Proportion of each plastic shape (fragments, films, foams, threads,

beads and pellets) was calculated for each sampling date and its distribution in time was tested using GAM models. Differences in composition of plastic by shape between the winter and the summer monsoon were tested with a chi-square test. All statistical analyses were performed in R studio 1.1.383 and comparisons were considered significant if p-value <0.05.

3. Results

We collected a total of 830 plastic items, excluding fibers, in 41 samples (Supplementary Data 1). Retrieved items were mainly fragments (73%) and films (14.9%), in polyethylene (PE, 65.6%) or polypropylene polymers (PP, 26.3%), transparent (35.3%) or white colored (30.4%, Fig. 1a, b, c). Items length ranged from 0.18 mm to 115 mm (mean $\pm$ SE 2.64 $\pm$ 0.22 mm), with most items comprised between 1 and 1.6 mm. However, the highest abundance of items normalized per mm⁻¹ of the size class width falls between 0.6 and 1 mm (Fig. 1d). Plastic shapes showed different size distributions (Anderson-Darling k-sample test, T.AD = 3.0, p-value = 0.02). Particularly, fragments (mean size $\pm$ SE = 1.61 $\pm$ 0.08 mm) were significantly smaller in size than foams (2.54 $\pm$ 0.25 mm, KS test, D = 0.33, p-value = 3×10^{-4}), which were smaller than films (7.04 $\pm$ 1.34 mm, KS test, D = 0.25, p-value = 0.04). Threads (5.33 $\pm$ 0.86 mm) and films showed the same size distribution (KS test, D = 0.13, p-value = 0.6, Fig. 1e).

Abundance of plastic items, excluding fibers, during the 41 sampling dates ranged from 0 (in only one sample, dated 23rd September 2016) to 613,937 plastic items Km⁻² (sample dated 19th February 2018, Table 1), for an average ($\pm$ SE) of 58,563 $\pm$ 19,272 pieces Km⁻² and an average concentration of 73.5 $\pm$ 40.75 g Km⁻² (median 19,777 pieces Km⁻² and 8.05 g Km⁻², Table 1). We

207 obtained an average density of $102,402 \pm 14,358$ fibers Km^{-2} , which we excluded from further
208 analyses for the reasons explained in paragraph 2.2.

209 Plastic abundance during almost two years shows a seasonal pattern at the sampling station, by
210 increasing from September to May on both years, while decreasing from May to September (Fig.
211 2a). Particularly, the GAM model shows the most negative effect in September 2016, turning
212 positive in the following months and reaching a peak in March/April to become negative again in
213 summer 2017. The same pattern repeats in the second year of sampling (Fig S3). Generally,
214 mean plastic abundance in samples collected during the winter monsoon ($54,334 \pm 24,908$ items
215 Km^{-2} , October to May) was significantly higher than that in samples collected during the summer
216 monsoon ($9,673 \pm 2,410$ items Km^{-2} , June to September, Fig 2b; Wilcoxon rank-sum test, $W =$
217 70 , $p\text{-value} = 0.01$). Concentration of plastic (in g plastic Km^{-2}) through time also shows the
218 same seasonal pattern (Fig. S4).

219 The composition of floating plastic by shape also differed through time and, particularly, films
220 reached their highest contribution in August/September, at the end of the summer monsoon,
221 while fragments reached the highest contribution in March, during winter, and the lowest in
222 October, just after the end of the summer monsoon (Fig. 2c). The GAM models confirm a
223 positive effect of film contribution in summer (Fig. S5a), while for fragments it generally shows
224 a positive effect in winter and negative in summer, although during the winter of the second year
225 the positive effect starts with a delay (Fig S5b). Threads had also a significantly different
226 contribution in time, which however did not follow a seasonal pattern (Fig. S5c). The relative
227 contribution of other shapes did not show any significant distribution in time. In general, films
228 and foams were more frequent than expected during the summer monsoon (31.9% and 14.9 %)
229 compared to the winter monsoon (13.9% and 4.5%) and fragments were more frequent that

expected during the winter monsoon (74.5%) than during the summer monsoon (48.9%, Chi-square test, $X = 24.03$, $p\text{-value} = 2.1 \times 10^{-4}$, Fig. 2d). The higher contribution of fragments in winter and their smaller size compared to other plastic shapes, justifies why the difference in plastic weights between seasons is less significant (Fig. S4b) than the difference in abundances (Fig. 2b).

4. Discussion

The data presented identifies the Saudi waters of the Central Red Sea as a plastic hotspot in the Red Sea, where the median abundance and mass of floating plastic fragments (19,777 items Km^{-2} and 8.05 g Km^{-2}) were one and two orders of magnitude higher than the median values estimated for the entire basin (1,030 items Km^{-2} and 0.03 g Km^{-2}), respectively (Marti *et al.* 2017). Current models of surface circulation in the Red Sea (Sofianos and Johns, 2003; Churchill *et al.*, 2014) suggest that the Eastern coast of the Red Sea experiences a convergence of currents at 22° N, where the sampling station was located, during the winter monsoon, from October to May, that would aggregate plastic in the study area during much of the year. In addition to accounting for the high abundance of floating plastic items in the study area, this explanation is also consistent with the significantly higher concentration of floating plastic items found during the winter monsoon compared to the summer months (June to September) when surface currents at the eastern boundary of the central Red Sea drive floating debris South, facilitating their export from the basin. The lowest abundance of plastic is indeed reached in August/September, at the end of the summer monsoon, it starts to increase again in October, when the surface currents revert to NW, reaching a peak in March/April, to later decrease again in May/June at the beginning of the

new summer monsoon. These results suggest that currents drive plastic load patterns at the sampling station during the winter months, while they deplete the central Red Sea surface waters of floating plastic during the summer months.

While the overall composition of floating plastic per shape, polymer and size does not differ from that reported in Marti *et al.* (2017), we found a higher frequency of films and foamed plastics in summer than in winter. These are lightweight plastic forms, unlikely to be transported in the water for long-distances, therefore unlikely to be carried by the main surface currents coming from the South in winter. Fragments instead, having a high volume-to-surface ratio, can reach the station through these long-travelling currents and are indeed less frequent during the summer monsoon, when currents transport floating plastic South and outside the Red Sea. This suggests that the main source of plastic at the sampling station during summer is short-ranged, while floating plastic, mainly fragments, that aggregates in winter are transported from the open sea, possibly originating from the Indian Ocean, conveyed through the surface current inflowing at the Bab el Mandeb strait. The short-range origin of films and foams and the long-range transport of plastic fragments through currents is also supported by the different size distribution of the three plastic types. Indeed, larger sizes, as those reported for films and foams, suggest a slower fragmentation, hence a shorter period spent in the water exposed to wave action, sunlight and other degrading agents.

While the model we propose explains the fluctuation in plastic abundance through time at a seasonal scale, the intra-seasonal variability in plastic abundance and composition also found suggests that there are other environmental factors (e.g. local winds and currents) that might influence plastic distribution at smaller temporal scales. Therefore, although we show here that the seasonal inversion of surface currents in the Red Sea justifies the differences in plastic

abundance and composition across seasons at the sampling station, we do not exclude the role of other variables in determining plastic distribution at other temporal scales.

In summary, the results presented here reveal the presence of a plastic hotspot at a convergence of currents at 22° N in the Central Red Sea. We also show a seasonal pattern of plastic abundance at this location, with monsoon driven currents advecting plastics to the south during the summer, thereby leading to relatively low concentrations, and NW currents transporting plastics into the sampling area during winter, when abundance is highest. Understanding seasonal variability in plastic loads and its drivers provides clues on the sources and fate of plastic that can inform management strategies toward minimizing this risk to the marine ecosystem.

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Table 1 Concentration of plastic items in 41 samples collected from 4th September 2016 to 28th May 2018. Concentrations are reported as abundance (N of items) or weight (g or mg) of plastic per Km² or m³. Abundance is corrected following Kukulka *et al.* (2012), depending on wind speed, also reported.

Sampling date	Wind speed (m/s)	N plastic items Km ⁻² (wind corrected)	N plastic items m ⁻³ (wind corrected)	g plastic Km ⁻²	mg plastic m ⁻³
4/09/2016	3.1	1359	0.01	2.08	0.013
23/09/2016	2.2	0	0	0	0
17/10/2016	3.3	15521	0.10	9.96	0.063
31/10/2016	0	3104	0.02	0.36	0.002
14/11/2016	2.2	23584	0.15	14.77	0.092
28/11/2016	3.9	898	0.01	0.4	0.003
13/12/2016	2.2	848	0.01	0.02	0.0001
23/01/2017	2.8	11022	0.07	8.37	0.052
06/02/2017	6.1	8463	0.14	3.97	0.025
20/02/2017	2.2	13565	0.08	2.61	0.016
06/03/2017	3.3	119822	0.75	98.37	0.615
20/03/2017	5.3	71523	0.45	16.55	0.103
3/04/2017	6.7	52454	0.33	3.42	0.021
17/04/2017	5.0	29126	0.18	7.94	0.05
15/05/2017	1.7	37081	0.23	13.35	0.083
29/05/2017	7.5	51836	0.32	8.48	0.053
12/06/2017	3.1	10271	0.06	2.06	0.013
03/07/2017	4.7	22596	0.14	8.05	0.05
17/07/2017	4.4	10271	0.06	0.34	0.002
1/08/2017	5.0	8702	0.05	1.55	0.01
21/08/2017	3.6	4748	0.03	20.68	0.129
28/08/2017	3.9	3536	0.02	0.04	0.0002
13/09/2017	4.4	18839	0.12	6.15	0.038
25/09/2017	3.3	16408	0.10	30.31	0.189
17/10/2017	6.7	34404	0.22	9.55	0.06
23/10/2017	4.4	27571	0.17	5.61	0.035
6/11/2017	3.9	22253	0.14	10.04	0.063
27/11/2017	3.9	3735	0.02	0.98	0.006
4/12/2017	3.9	29651	0.19	1.66	0.01
18/12/2017	1.4	2194	0.01	0.38	0.002
8/01/2018	10.3	494735	3.09	1432.5	8.953
22/01/2018	3.1	42878	0.27	108.16	0.676
5/02/2018	3.3	19777	0.12	26.73	0.167
19/02/2018	5.8	613937	3.84	923.45	5.772
6/03/2018	2.5	67560	0.42	48.33	0.302
20/03/2018	0.6	252426	1.58	104.22	0.651
9/04/2018	2.8	76723	0.48	47.91	0.299
16/04/2018	2.2	31263	0.20	9.73	0.061

30/04/2018	1.7	132067	0.83	17.99	0.112
14/05/2018	4.7	8105	0.05	2.33	0.015
28/05/2018	2.8	6211	0.04	3.87	0.024
Mean ±SE		58,563 ±19,272	0.37 ±0.12	73.5 ±40.75	0.46 ±0.25

Fig. 1 Composition and size distribution of plastic items. Relative frequency of plastic items, excluding fibers, by shape (A, n = 830), polymer type (B, n = 448) and color (C, n = 830) and size distribution of plastic items (D, n = 825) and of the four main plastic shape (films, foams, fragments and threads, E). In plot B, PE stands for polyethylene, PP for polypropylene, PS for polystyrene, PVPr for polyvinyl propionate and Others include polyamide (PA), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), polyvinyl chloride (PVC), polyvinylidene chloride (PVDC), polyurethane (PUR) and urethane alkyd. Size distribution is reported as abundance of all items per size class (grey line, plot D), abundance normalized per width of the size class (red line, plot D) or cumulative probability that films (n = 120, yellow line, plot E), foams (n = 43, green line, plot E), fragments (N = 605, blue line, plot E) and threads (N = 42, pink line, plot E) with a size X are smaller than a given size x , $F(x) = P[X \leq x]$.

Fig. 2 Seasonality of plastic abundance and composition. **A.** Seasonal distribution of log-transformed plastic abundance (in N items Km^{-2} , wind corrected, $+k$) during a sampling period of 1.75 years (21 months). The grey line represents the loess fit of log-transformed plastic

abundance. The area of the plot shaded in red represent the summer monsoon (June to September). **B.** Plastic concentration (in N items Km^{-2} , wind corrected) in samples collected during the summer monsoon (June to September, N = 10) and the winter monsoon (October to May, N = 31). Difference in abundance between season was tested with a Wilcoxon rank sum test which parameters are reported in figure. Boxplots show the median (line across a box), quartiles (upper and lower bounds of each box) and extremes (upper and lower whiskers). **C.** Proportion of 6 shapes of plastic items (beads, films, foams, fragments, pellets and threads) during a sampling period of 1.75 years. Lines represent the loess fit. The area of the plot shaded in red represent the summer monsoon. **D.** Cumulative percentage of plastic items by shape during the summer (N = 47) and the winter (N = 783) monsoon. Differences in composition between the two seasons were tested with a Chi-square test which parameters are reported in figure.

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