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Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition

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A B S T R A C T

While macroplastics have been washing up on Southern Ocean islands for decades and microplastics have been found in seabirds from the region since 1960, there are still relatively few quantitative data on the amount of plastic pollution, especially with regard to floating plastics, at high southern latitudes. We present a baseline estimate of the abundance of floating plastics around the Southern Ocean from a survey of floating macro-, meso- and microplastic pollution conducted during the Antarctic Circumnavigation Expedition in 2016/17. A total of 40 net trawls and 626 h of observation were performed during this survey. Of these, 33 net samples and 552 h of observation were made in polar waters south of the Subtropical Front (STF). Only 5 microplastics and 17 macrolitter items were observed south of the STF, confirming the Southern Ocean as the region with the lowest concentrations of plastic pollution globally. The mean concentrations of floating macrolitter (0.02–0.03 items·km^{-2}) and small plastic fragments (188 ± 589 particles·km^{-2}) south of the STF were one order of magnitude lower than in adjacent temperate waters north of the STF, which suggests that the STF acts as a barrier to the southward transport of floating debris. Despite their much lower density, the mass of macroplastics was similar to that of floating microplastics in the Southern Ocean.

1. Introduction

The global production of plastic materials has increased rapidly over the last 70 years from 2 million tonnes per year in 1950 to over 380 million tonnes in 2015 (Geyer et al., 2017). Of this production, between 60 and 99 million tonnes of plastic waste were disposed of into the environment; a figure which is predicted to triple by 2060 (Lebreton and Andrady, 2019). As a result, plastic items are now widespread in the marine environment. Vast accumulation areas of floating litter have been discovered in all main oceanic gyres and virtually no place on earth can now be considered immune from plastic pollution, including remote islands and deep-sea ecosystems (Barnes et al., 2018; Chiba et al., 2018).

Despite their ubiquitous presence, there are relatively few reports of micro- and macro-plastics in polar regions (Obbard, 2018). Most of these records come from the Arctic Ocean, where significant amounts of microplastics have been recorded in sea-ice cores (Obbard et al., 2014; Peeken et al., 2018), snow samples (Bergmann et al., 2019), on the seabed (Bergmann and Klages, 2012) and floating in surface and sub-surface waters (e.g. Lusher et al., 2015; Còzar et al., 2017). By comparison, the Antarctic region has been considered physically isolated by the strong circumpolar frontal systems that characterise the Southern Ocean and thus relatively unaffected by plastic pollution, even though plastic debris has been washing up on sub-Antarctic islands for decades (e.g. Gregory et al., 1984; Ryan, 1987a; Slip and Burton, 1991; Walker et al., 1997; Convey et al., 2002; Eriksson et al., 2013). Crossing of the Antarctic Polar Front (APF) by driftwood and fishing-related materials has been reported in both directions since the early 1960s (Barber et al., 1959; Coombs and Landis, 1966) and in the 1980s, the presence of microplastics in Antarctic waters was inferred based on the presence of

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ingested plastics in Antarctic (*Thalassoica antarctica)* and snow petrel *(Pagodroma nivea)*, species which remain south of the APF year-round (Ryan, 1987b; van Franeker and Bell, 1988). More recently, our view of the circumpolar fronts as a biogeographic barrier has been challenged by evidence that storm-driven surface waves and ocean eddies facilitate crossing of the polar fronts resulting in more frequent north-south dispersal of drifting materials than previously thought (Fraser et al., 2016, 2018). It is becoming increasingly clear that the Southern Ocean is not exempt from plastic pollution and that Antarctica is not as isolated from the rest of the world as previously considered (Ivar do Sul et al., 2011; Waller et al., 2017). However, global-scale studies highlight the paucity of data about the density of floating plastics around Antarctica (Cózar et al., 2014; Eriksen et al., 2014).

Much of what we do know about the concentration of floating litter in the Southern Ocean is based on a handful of macro-litter (> 25 mm) observations carried out around the Antarctic Peninsula (Barnes and Milner, 2005; Barnes et al., 2009) or in the Atlantic sector of the Southern Ocean (Ryan, 1990; Barnes et al., 2010; Ryan et al., 2014). Much less is known about the occurrence of mesolitter (5–25 mm) and microplastics (< 5 mm) in the region. A few neuston net samples were collected in the 1980s (Gregory et al., 1984; Ryan, 1990), but despite the growing volume of microplastic research and the issue being increasingly recognised globally (Ryan, 2015b), it wasn't until 2017 that the first data about microplastics in Antarctic sediments (Munari et al., 2017; Waller et al., 2017) and surface waters (Cincinelli et al., 2017; Isobe et al., 2017) were published. Microplastics have since been detected in marine sediments near Rothera Research Station (Reed et al., 2018), in surface waters around the Antarctic Peninsula (Lacerda et al., 2019), in Admiralty Bay (Absher et al., 2019), in the Ross Sea and in the Eastern Antarctic Region (Grover-Johnson, 2018), confirming that microplastic pollution has indeed reached the southernmost limits of the Southern Ocean (Waller et al., 2017).

Antarctic and sub-Antarctic wildlife are not immune from the risks caused by plastic pollution. The first records of microplastic ingestion by seabirds were from the Southern Ocean, when prions *Pachyptila* spp. were found to contain plastic in 1960 (Harper and Fowler, 1987). Since then, ingestion of small plastic fibres and fragments has been documented in other seabird species (Ryan, 1987b; Auman et al., 2004; Bessa et al., 2019; Le Guen et al., 2020 this issue) and Southern Ocean fur seals (Eriksson and Burton, 2003; Ryan et al., 2016). Like microplastics, which can be ingested, macroplastics also have negative impacts on Antarctic wildlife, primarily through entanglement of large predators in man-made debris (Bonner and McCann, 1982; Croxall et al., 1990; Arnould and Croxall, 1995; Hucke-Gaete et al., 1997; Nel and Nel, 1999; Hofmeyr et al., 2002; Waluda and Staniland, 2013). Of particular concern is the potential role of stranded plastics as vectors for the spread of exotic species (Barnes & Fraser, 2003) or antibiotic resistances across Antarctic marine environments (Laganà et al., 2018). By 2017, the problem had garnered attention from key scientific bodies responsible for the monitoring and protection of Antarctic environments and marine species, such as the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Microplastics were identified as a 'serious and emerging threat', resulting in the Scientific Committee on Antarctic Research (SCAR) recently creating an action group on the issue of plastic pollution in the Southern Ocean (Waller and Hughes, 2018).

Here we present the results of a circumpolar survey of floating macro- (> 25 mm), meso- (5–25 mm) and microplastic (< 5 mm) pollution performed between 2016 and 2017 during the Antarctic Circumnavigation Expedition (ACE). By combining visual observations for floating macrolitter and neuston net sampling for micro- and mesoplastic particles, we provide a first circumpolar baseline of the abundance of floating plastics around the Southern Ocean across a broad size spectrum. These data contribute to the validation of global floating plastic models and to a better understanding of oceanic litter budgets and transport dynamics, enabling the assessment of future changes in the amounts and types of drifting litter throughout the Antarctic region.

2. Materials and methods

2.1. Study area

Our survey area extends from temperate waters north of the Subtropical Front (STF) to the Southern Ocean, here defined as waters comprised between the STF and Antarctica (Orsi et al., 1995). The Southern Ocean was further subdivided into a Sub-Antarctic Zone (~43–60°S), between the STF and the Antarctic Polar Front (APF), and an Antarctic Zone (> 60°S), between the APF and continental Antarctica. The climatological mean positions of major fronts (STF and APF) were derived from the Southern Ocean Atlas Database after Orsi et al. (1995) retrieved from https://cran.r-project.org/web/packages/orsifronts/vignettes/orsifronts.html.

2.2. Microplastics

2.2.1. Sampling and laboratory analysis

Forty neuston samples were collected around the Antarctic continent between December 2016 and May 2017 (Supplementary Table 1): 33 samples were collected from the R/V *Akademik Tryoshnikov* during the ACE expedition (Legs 1–3) from December 2016 to March 2017, and a further 7 samples were collected between Cape Town and the Prince Edward Islands from the *S.A. Agulhas II* during May 2017, because no samples were collected in this sector of the Southern Ocean during ACE. All samples were collected using the same 200 μm neuston net (Aquatic BioTechnology ©) equipped with a 100 × 30 cm rectangular frame opening, towed for 15 min at a speed of 2–2.5 knots. Net deployments were made in fairly good weather conditions only (i.e. sea state < 6) from the ship's leeward (starboard) side beyond the bow wave, in order to avoid wake turbulence and contamination from the ship. Paint fragments were collected from the ship's deck as contamination controls.

Once on board, the net was rinsed from the outside with running water in order to concentrate all particles in the cod end. Samples were then transferred to 300 ml glass jars, and stored for laboratory analysis. In the laboratory, all samples were examined under a dissecting stereomicroscope (20x magnification). Putative plastic particles were carefully hand-picked using forceps and transferred to aluminum foil. Particles were then oven-dried at 40 °C for 24 h, weighed on an electronic balance (accuracy: 0.1 mg) and classified according to their color and shape (pellets, fragments, foam, films and filaments). Due to the large mesh size of the net and to the high risk of external contamination, textile microfibers were excluded from the analysis. The length of the trawls (mean ± SD: 975.1 ± 261.5 m) and the sampled volume (mean ± SD: 292.53 ± 78.47 m^3) were computed using the net frame dimensions and the tow distance derived from GPS start and stop readings. Microplastic concentrations, expressed as $g{\cdot}L^{-1}$, $g{\cdot}km^{-2}$, $particles{\cdot}L^{-1}$ and $particles{\cdot}km^{-2}$, were then computed (Table 1) and plotted in Fig. 1.

2.2.2. μFTIR analysis

All extracted particles were analyzed using μFTIR (Fourier Transform Infrared Spectroscopy) in order to confirm their polymeric identity. Particle characterization was performed using a LUMOS standalone FTIR microscope (Bruker Optik GmbH), equipped with a motorized XY sample stage and an automated ATR probe (Ge crystal). Following background scans, ATR spectra were recorded by averaging 64 scans per particle with a spectral resolution of 4 cm^{-1} (range 4000–650 cm^{-1}). CO_2 interference (adsorption at 2300–2400 cm^{-1}) was removed for clarity. The infrared spectra were processed and analyzed using OPUS 7.5 software (Bruker). Polymer identification was performed by comparison with commercially available libraries and an

Table 1
Number and concentration of small plastic fragments (< 25 mm) collected using a 200 μm neuston net in the Southern Ocean and adjacent temperate waters off Africa during the austral summer 2016/17 (ACE and Marion cruise).

	Temperate (north of STF)	Southern Ocean	Southern Ocean			All
			43-50°S	50-60°S	> 60°S	
Number of net samples	7	33	7	16	10	40
Number of MP particles	67	5	1	1	3	72
Mean density (items·km^{-2})	8941	188	251	57	353	1719
Mean density (items·L^{-1})	29.8	0.62	0.84	0.19	1.18	5.7
Mean mass (g·km^{-2})	128.1	0.78	3.26	0.06	0.21	23.1
Mean mass (g·L^{-1})	0.4269	0.0026	0.0109	0.0002	0.0007	0.0769

additional custom library compiled within the framework of the JPI-OCEANS project BASEMAN (Primpke et al., 2018). Sample spectra were compared to the database (second-derivative, vector-normalized) and only matches > 75% with reference spectra were accepted as verified polymers. For size distribution analysis, all particles were measured to the nearest 1 μm from the digital images collected by the instrument prior to each scan (OPUS 7.5 software). Particles were measured in length, according to their longest dimension, and width, perpendicular to length. Particle size was then calculated as the geometric mean of the first and second dimension (Fig. 2).

2.3. Macrolitter survey

The count protocol for macrolitter items followed Ryan (2013), as modified in Ryan (2014). Teams of 1–3 observers equipped with binoculars recorded floating debris while the ship was steaming at 10–14 knots. Counts were made on the side of the ship's bow with the best lighting and visibility, either from the bow (elevation 8–9 m above the water line) when weather permitted, or from the bridge or flying bridge (20–22 m). Overall, most observations were made from the ship's bridge (73.9% by time and 75.5% by distance), but observation point had no effect on the number of items recorded in the Southern Ocean (χ^2 = 0.303, df = 1, P = 0.62). All floating debris items were counted, including kelps (Fraser et al., 2018), as well as seabirds and cetaceans, and counts recorded in notebooks for later transcription into a spreadsheet. Counts of marine predators were binned into 10-minute intervals, but all floating debris was scored individually to the nearest minute, and the location determined from the ship's data log. Surveys were conducted throughout daylight hours, irrespective of sea conditions.

Litter items were scored as to size (estimated to the nearest 1 cm), perpendicular distance from the ship (m), buoyancy (at, above or below the water surface), type of material (plastic, metal, glass, worked wood, paper-card, etc.), function (fishing gear, packaging, etc.) and colour. Most items were photographed with a Canon 7D mark II digital SLR and a Canon 500 mm F4 lens to assist in item identification; some were found to be organic material (e.g. pieces of bird skin, kelp, etc.), highlighting the value of photographing suspected litter items.

Litter densities were estimated for items within 50 m of the ship's track, except south of 60°S, where no items were observed within 50 m of the ship. Crude density estimates assumed all items within 50 m of the ship were detected, whereas extrapolated densities used simple size-specific detection functions to estimate the proportion of items not detected at 10-m distance bands from the ship (see Ryan, 2013, 2014

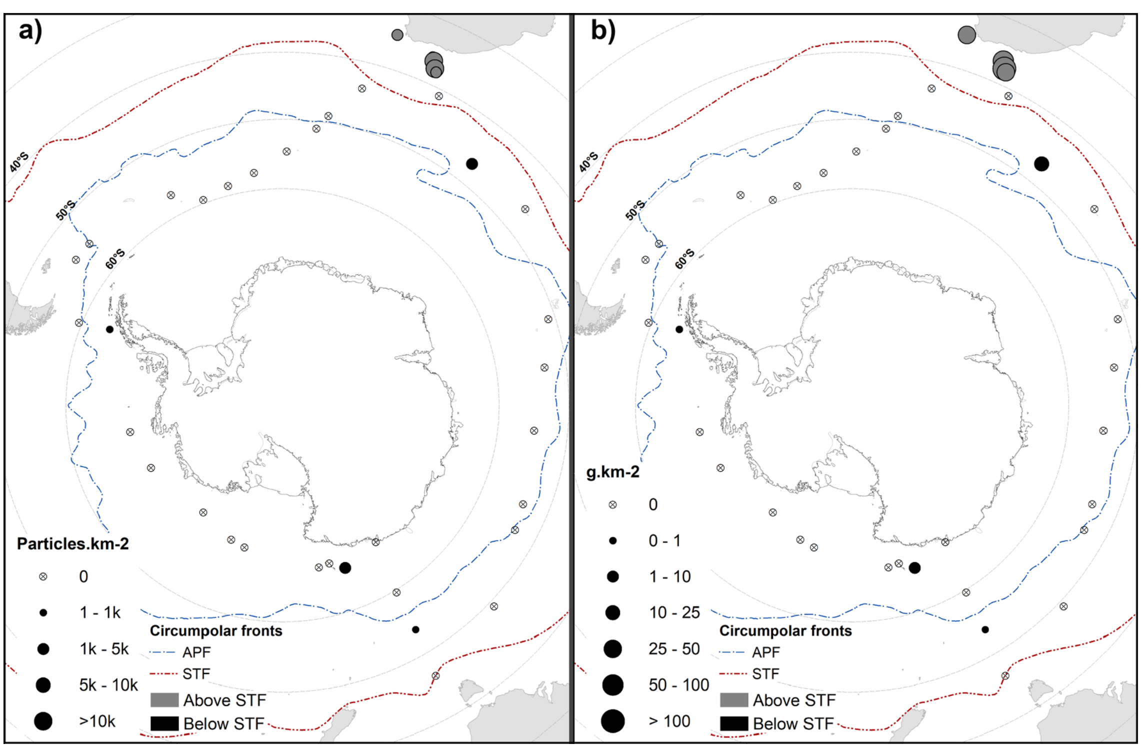

Fig. 1. The concentration of small plastic fragments (< 25 mm) collected around Antarctica expressed in (a) particles·km^{-2} and (b) g·km^{-2} (n = 40 samples). The mean positions of major fronts (APF and STF) are also shown (after Orsi et al., 1995).

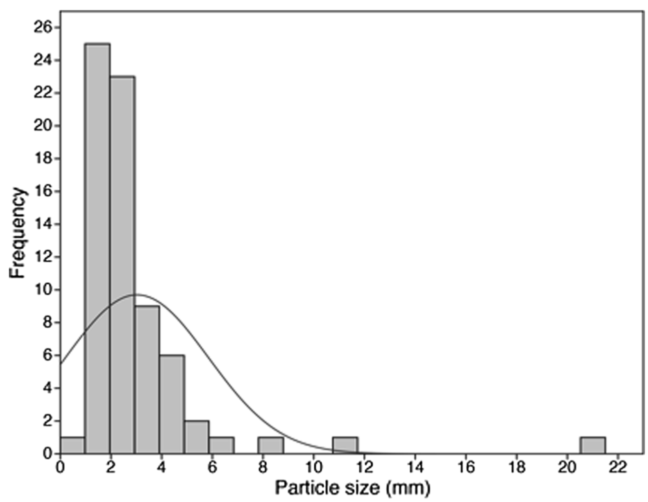

Fig. 2. The size-frequency distribution of all meso and microplastics collected during this survey (n = 72 particles). The size of each item was calculated as the geometric mean of the longest and widest dimension perpendicular to length, measured using the digital images collected by OPUS 7.5 software (Bruker). The line shows a normal fit (parametric estimation).

for details). Because relatively few items were seen during the entire survey, the detection functions were based on data collected on similar cruises in the Bay of Bengal and Southern Ocean (Ryan, 2013, 2014; Ryan et al., 2014), when a similar range of weather conditions was encountered (from Beaufort 1–11, but predominantly 3–8). Size-specific detection functions were estimated for four size classes of litter items: < 5 cm (2.7× the crude count), 5–15 cm (1.8×), 15–30 cm (1.4×), and > 30 cm (1.3×). No litter items were seen within 50 m of the ship south of 60°S, so a crude density estimate was made from the few litter items seen within 500 m of the ship (the maximum detection distance recorded). There is no empirical correction factor for litter items > 50 m from the ship's track, and thus a conservative estimate of 2 was used (assumes half of all items were detected from 50 to 500 m). Litter items seen within 20 km of a port (Cape Town, Hobart and Punta Arenas) were excluded from analyses, as waters close to urban centres tend to support higher than average densities of litter (e.g. Ryan, 2014).

Masses of individual litter items were estimated from surveys of similar items on beaches and urban litter (Eriksen et al., 2014; PGR unpubl. data). Because of the uncertainty in these masses, a lower and upper plausible mass was assigned to each item, and used to estimate a range of macrolitter mass densities. The lower mass density value combined the low mass value per item with the crude density estimate, whereas the upper mass density value combined the high mass value per item with the extrapolated density estimates, thus providing the largest confidence interval for the mass density estimates.

3. Results

3.1. Microplastics

A total of 203 particles were extracted from the 40 neuston samples. μFTIR analysis revealed that most of these particles closely matched the FTIR spectra of the ship's paint or were made of non-synthetic materials such as silica, rust or cellulose. Therefore, all paint fragments (n = 118) and non-synthetic items (n = 13) were removed from our dataset and excluded from calculations, leaving a total of 72 plastic particles (Table 1). Most of these plastic particles were polyethylene (61%), followed by polypropylene (29%), polystyrene (4%), PVC (3%), nylon and PMMA (1 particle each). Of these, 93% were < 5 mm in size (i.e. microplastics), 5 particles were > 5 mm (i.e. mesoplastics) and only 1 particle was < 1 mm (Fig. 2). Mean particle size was 3.03 ± 2.81 mm (range 0.68–21.5 mm; median 2.51 mm). Most particles were secondary hard-plastic fragments (n = 65 items), with 3 filaments, 2 foam items, 1 pellet and 1 film also collected. The most common colour was white (71%), followed by blue (9%), green (7%), black (4%), yellow (3%), transparent (3%) and grey (3%).

Most of the plastic particles (67 out of 72) were retrieved from the seven samples collected in temperate waters north of the Subtropical Front (STF), south of Africa (Table 1, Fig. 1). Only five microplastic particles were found in the 33 samples collected in the Southern Ocean, south of the STF (Table 1); 88% of samples from south of the STF (29 out of 33) contained no plastic. The mean density of plastic north of the STF (8941 ± 14075 particles·km^{-2}) was 48 times higher than in the Southern Ocean (188 ± 589 particles·km^{-2}) and 163 times higher in terms of mass concentrations (128 ± 271 vs 0.78 ± 3.97 g·km^{-2}). Within the Southern Ocean, there were no marked differences between densities collected between 40 and 50°S (1 plastic particle from 7 samples) and 50–60°S (1 plastic particle from 16 samples), but slightly higher concentrations were found south of 60°S (3 particles in 10 samples, mean 353 particles·km^{-2}). Interestingly, no polyethylene fragments were found in the Southern Ocean, where only fragments of PVC (n = 2), polypropylene (n = 1), polystyrene (n = 1) and nylon filament (n = 1) were found (Table 2).

3.2. Macrolitter

Away from urban ports, we observed only 54 macro-litter items (40 within 50 m of the ship's track) during 626 h of observations, covering 15,417 km of transects (Table 3; Supplementary Table 2). By comparison, 10 items were observed during 3.8 h of transects (48.2 km) within 20 km of Cape Town, Hobart and Punta Arenas. Of the litter items observed in the open ocean, most (68.5%) were in temperate waters north of the Subtropical Convergence off Africa and Tasmania (the only areas on the cruise track to traverse temperate waters, Fig. 3). The density of floating artificial debris in temperate waters (0.28–0.51 items·km^{-2}) was an order of magnitude higher than that in the Southern Ocean (0.021–0.030 items·km^{-2}; Table 3), but both were appreciably lower than the density close to urban centres (7

Table 2
Polymer composition of all plastic fragments (< 25 mm) collected using a 200 μm neuston net in the Southern Ocean and adjacent temperate waters off Africa during austral summer of 2016/17 (ACE and Marion cruise).

Polymer	Temperate (north of STF)	Southern Ocean	Southern Ocean			Total
			43-50°S	50-60°S	> 60°S	
Polyethylene (PE)	44	0	0	0	0	44 (61.1%)
Polypropylene (PP)	20	1	0	1	0	21 (29.2%)
Polystyrene (PS)	2	1	0	0	1	3 (4.2%)
Polyvinyl chloride (PVC)	0	2	1	0	1	2 (2.8%)
Polyamide (nylon)	0	1	0	0	1	1 (1.4%)
Poly (methyl methacrylate) (PMMA)	1	0	0	0	0	1 (1.4%)

Table 3
The density of floating debris in the Southern Ocean and adjacent temperate waters off Africa and Tasmania recorded during the ACE cruise in the austral summer of 2016/17 (excluding debris sighted within 20 km of ports).

	Temperate waters (north of STF)	Southern Ocean	Southern Ocean	
			43-60°S	> 60°S
Transect length (km)	1850	13,567	8756	4811
Transect duration (h)	74	552	345	207
Total litter items	37	17	15	2
Items within 50 m	26	14	4	0*
Density of all litter·km^{-2}	0.28–0.51	0.021–0.030	0.032–0.047	0.001
Density of plastic items·km^{-2}	0.26–0.48	0.018–0.025	0.025–0.038	0.001
Mass of all litter g·km^{-2}	16.6–30.1	3.8–8.3	5.9–12.9	0.4–1.3
Mass of plastic g·km^{-2}	7.7–14.1	1.1–2.6	1.7–4.0	0.4–1.3

* Both items south of 60°S were > 50 m from the ship's track (see methods for further details).

items·km^{-2}). Within the Southern Ocean, there was more debris south of the STF to 60°S, with only two items observed south of 60°S (both > 50 m from the ship's track; Table 3).

Most litter items were made of plastic (87%, Table 4), with bottles and pieces of plastic predominating north of the STF and expanded polystyrene (styrofoam) being most abundant in the Southern Ocean, followed by fishing floats (buoys), bottles and fragments of rigid plastic (Supplementary Table 3). Flexible packaging (bags and food wrappings) was scarce south of the STF. Litter items averaged larger in the Southern Ocean than in temperate waters off Africa, and tended to be more buoyant farther south (Table 5).

4. Discussion

Our results show that the density of floating plastics around Antarctica is very low, confirming that the Southern Ocean is characterised by low levels of plastic pollution (Ivar do Sul et al., 2011; Ryan et al., 2014), although not completely free of microplastics as recently suggested by a citizen-science circumpolar survey which failed to detect any plastic fragments in 10 net samples collected around Antarctica south of 60°S (Kuklinski et al., 2019). Our estimates of the concentrations of floating macro- and microplastics in Antarctic waters are one order of magnitude lower than adjacent temperate waters and several orders of magnitude lower than what is generally found in coastal waters or in oceanic accumulation zones (Cózar et al., 2014; Eriksen et al., 2014; Suaria et al., 2015; Campanale et al., 2019; Rothäusler et al., 2019). These findings support previous field observations (Ryan et al., 2014) and oceanographic dispersal models (Lacerda et al., 2019) suggesting that circumpolar fronts, winds and currents limit the southward transport of drifting litter in the Southern Ocean. This hypothesis is supported by the pronounced decrease in the occurrence of floating packaging and single-use items such as bags and food wrappings (Table 4), and by the paucity of polyethylene and polypropylene microplastics in Southern Ocean samples (Table 2), despite being the two most common polymers in single-use applications as well as in surface waters worldwide (as highlighted by Lacerda et al., 2019). Alternatively, as shown by a recent modeling study, the role of Antarctic Circumpolar Currents in preventing transported matter from entering the Southern Ocean weakens significantly with depth (Wichmann et al., 2019). Moreover, wind- and wave-driven mixing and

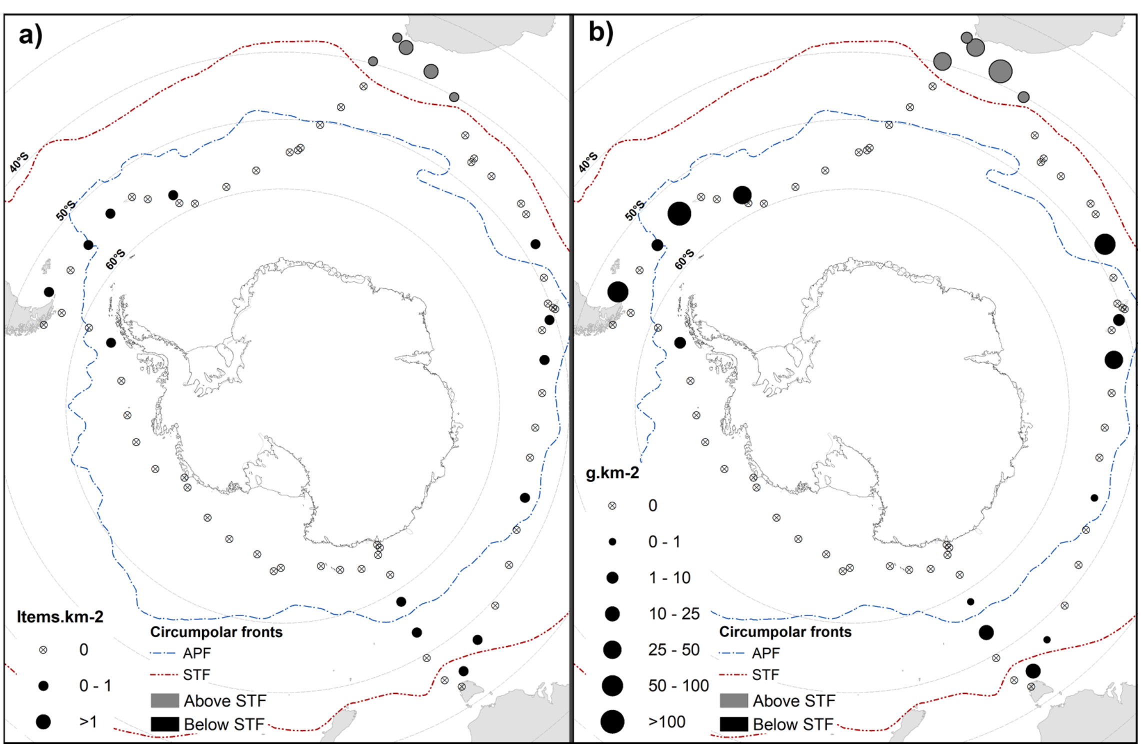

Fig. 3. The concentration of floating macroplastics sighted around the Southern Ocean expressed in (a) items·km^{-2} and (b) g·km^{-2} (n = 15,417 km of transects). The mean positions of major fronts (APF and STF) are also shown (after Orsi et al., 1995).

Table 4
The types of floating debris observed in the Southern Ocean and adjacent temperate waters off Africa and Tasmania during the ACE cruise in the austral summer of 2016/17.

Type of litter item	Temperate (north of STF)	Southern Ocean	Southern Ocean	
			43-60°S	> 60°S
All plastic	**33**	**14**	**12**	**2**
Bottles and canisters	10	2	1	1
Bags and food wraps	4	1	1	0
Lids	2	0	0	0
Styrofoam lumps	4	5	5	0
Fishing floats & ropes	3	2	1	1
Trays and crates	2	1	1	0
Shoes	1	1	1	0
Other user item	1	0	0	0
Pieces (hard fragments)	6	2	2	0
All non-plastic	**4**	**3**	**3**	**0**
Metal cannisters	2	1	1	0
Light bulbs	1	0	0	0
Wood	1	1	1	0
Card/paper	0	1	1	0
All litter items	**37**	**17**	**15**	**2**

Table 5
Size and buoyancy of floating debris observed in the Southern Ocean and adjacent temperate waters off Africa and Tasmania during the ACE cruise in 2016/17.

Litter parameter	Temperate (north of STF)	Southern Ocean	Southern Ocean	
			43-60°S	> 60°S
Size of litter item				
< 5 cm	8	1	1	0
5–15 cm	6	0	0	0
15–30 cm	11	8	7	1
30–60 cm	6	7	7	0
> 60 cm	6	1	0	1
Buoyancy				
Above the surface	15	12	10	2
At the surface	14	3	3	0
Below the surface	8	2	2	0

Langmuir turbulence can greatly enhance the submersion of buoyant plastic debris (Kukulka et al., 2012; Brunner et al., 2015). Therefore, in the highly dynamic Southern Ocean, microplastics can be more prone to be transported to polar regions by subsurface currents, hence explaining the low concentrations usually found in Antarctic surface waters.

Although it is challenging to infer the sources of the observed items, the only piece of cardboard observed, at 57°S, between Tasmania and East Antarctica, presumably came from a ship, as cardboard does not typically float for very long at sea, supporting the conclusion expressed by many authors, that most litter found in Antarctica derives from local sources such as fishing, tourism and research activities (e.g. Ivar do Sul et al., 2011; Waller et al., 2017). Most macrolitter items observed in the Southern Ocean were large, buoyant items such as expanded polystyrene lumps, plastic bottles and fishing buoys (Table 5), which is consistent with long-distant transport favouring larger items, and particularly buoyant items that are unlikely to sink due to fouling (Ryan, 2015a). Highly buoyant items also have significant windage, which presumably aids their dispersal across the Antarctic Circumpolar Current (ACC) (Fraser et al., 2018) as well as allowing them to remain afloat for long periods around Antarctica (Lacerda et al., 2019). However, it also must be noted that buoyant items might be easier to detect during visual surveys, especially in rough seas conditions such as those commonly encountered in the Southern Ocean.

Contrary to what was found by Ryan et al. (2014), the concentration of floating macrolitter in the Antarctic Zone south of 60°S was one order of magnitude lower than in sub-Antarctic waters between the Antarctic Polar Front and the Subtropical Front (Table 3). This is not surprising, given that human impacts (i.e. fishing, tourism and research) are greater in the sub-Antarctic region (Campos et al., 2013) and that litter stranding rates on Antarctic shores are generally lower than those recorded on sub-Antarctic islands (Convey et al., 2002; Ivar do Sul et al., 2011; Eriksson et al., 2013). However, confidence in our estimates of the abundance and distribution of floating macrolitter is limited by the small number of items detected, with no macrolitter items observed within 50 m of the ship's track south of 60°S. We were forced to use detection functions derived from other studies to extrapolate for overlooked debris items, and even though these studies used the same methodology (and mostly the same observers) from similar sized vessels across a similar range of oceanic conditions, the estimates of floating macroplastic densities reported from this study should be treated as indicative rather than precise estimates, especially since using a transect width of 500 m and assuming that all litter items within 500 m from the ship are detected, might lead to severe underestimation of litter densities.

Interestingly, unlike macroplastics, the density of microplastics was if anything greater south of 60°S (Table 1). However, the very small number of microplastics detected limits the statistical power of our results. Isobe et al. (2017) also found higher extrapolated concentrations of microplastics (including several polyethylene and polypropylene fragments) south of the APF (i.e. 136,000–286,000 pieces·km^{-2}) than in samples collected in sub-Antarctic waters between 45°S and 60°S (i.e. 38 of 44 microplastics were extracted by these authors from only two samples collected south of 60°S), suggesting that once beyond the ACC and oceanic fronts, microplastics may be trapped in polar waters around Antarctica. However, the sample size in that study was only five net tows along a latitudinal transect (Isobe et al., 2017). As yet there is no quantitative evidence to determine whether or not microplastics are crossing the ACC, or if the detected particles result from local fishing, tourist and/or research activities, as recently suggested for the Ross Sea (Cincinelli et al., 2017; Munari et al., 2017; Waller et al., 2017). The size-class distribution of the collected particles seemed to follow very closely that originally reported by Cózar et al. (2014), suggesting a removal of particles < 1 mm. Although the causes of this gap in the size distribution are currently unknown, removal of particles this size, either through biofouling or other size-selective processes such as ingestion by planktivorous fish and zooplankton (Dawson et al., 2018), have been suggested as likely explanations (Cózar et al., 2014).

Our estimated density of microplastics in terms of mass (0.78 ± 3.97 g·km^{-2}) is similar to that reported from net samples collected south of the Antarctic Polar Front by Cózar et al. (2014), i.e. 0.1–0.5 g·km^{-2}, but lower than the 27.8 g·km^{-2} (0.21–146 g·km^{-2}) found by Lacerda et al. (2019) around the Antarctic Peninsula, where local human activities are higher. Overall, these concentrations are within the range of concentrations predicted by Eriksen et al. (2014) for surface waters in the Southern Ocean (0.55–56.58 g·km^{-2}) and are of the same order of magnitude as our estimate of macroplastic concentration in the region (1.1–2.6 g·km^{-2}). This paucity of macroplastics in terms of weight is especially remarkable considering that in oceanic waters macro- and megaplastics generally account for 75–78% of all floating plastic mass (Eriksen et al., 2014; Lebreton et al., 2018).

More than half (58%) of the particles collected in our neuston samples were paint fragments, later established as contamination from the survey ships. Lacerda et al. (2019) also reported very large numbers of paint particles in their samples from the Antarctic Peninsula (i.e. 2805 paint fragments vs 78 plastic particles). Although most presumably came from our survey vessels, paint chips are continuously generated during ongoing repair, maintenance and cleaning of all ship decks and superstructures, including research vessels, cruise liners and fishing boats operating in Antarctica (personal observation). Large quantities of synthetic paints, often containing metals and anti-fouling biocides (Turner, 2010), are usually related to intense marine traffic and shipping activities at lower latitudes (Song et al., 2014). Over 180 fishing, tourism and research vessels were active around Antarctica and the sub-Antarctic islands in 2017–2018 (McCarthy et al., 2019), presumably releasing substantial quantities of varnish and paint fragments into the Antarctic environment. Given the projected increase in ship traffic volumes in the Southern Ocean, with 9 new tourist vessels and several new research vessels expected this season alone (IAATO, 2019), these inputs seem set to increase in the coming years with unknown consequences for Antarctic ecosystems.

Our results show that the concentration of macro- and microplastics in the Southern Ocean are an order of magnitude lower than adjacent temperate waters and many orders of magnitude lower than other parts of the world. Nonetheless, although in low quantities, we documented the presence of floating macro- and microplastics at latitudes as high as 65°S. There is ample evidence from other regions that plastic pollution is having detrimental impacts on marine organisms. At present, we do not know to what extent Antarctic species are being affected, and whether they are more susceptible to ingestion or contamination by microplastics. This represents a significant gap in our knowledge, which warrants further consideration. The new data presented here support other recent findings that microplastic debris does indeed pollute the waters surrounding Antarctica. As reported by Waller et al. (2017), the levels of plastic pollution in the Antarctic region, are likely to be negligible at the scale of the Southern Ocean, but may be significant on a local scale, particularly around research stations.

CRediT authorship contribution statement

Giuseppe Suaria: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Resources, Visualization, Writing - original draft, Writing - review & editing. **Vonica Perold:** Methodology, Investigation, Writing - review & editing. **Jasmine R. Lee:** Investigation, Visualization, Validation, Writing - review & editing. **Fabrice Lebouard:** Investigation, Validation. **Stefano Aliani:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **Peter G. Ryan:** Conceptualization, Methodology, Formal analysis, Investigation, Validation, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105494.

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