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Review

Microplastics in the Antarctic marine system: An emerging area of research

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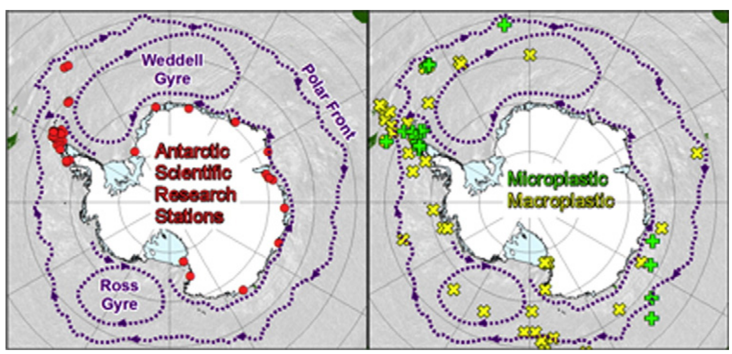
HIGHLIGHTS

- The Antarctic marine system is considered pristine compared to other regions.
- Microplastics are present in Antarctic waters but available data are scarce.
- Local sources of primary microplastic do not explain reported concentrations.
- Plastic originating from outside the region may contribute to Antarctic pollution.
- Standardised monitoring of microplastic in Antarctic waters is needed urgently.

GRAPHICAL ABSTRACT



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ABSTRACT

It was thought that the Southern Ocean was relatively free of microplastic contamination; however, recent studies and citizen science projects in the Southern Ocean have reported microplastics in deep-sea sediments and surface waters. Here we reviewed available information on microplastics (including macroplastics as a source of microplastics) in the Southern Ocean. We estimated primary microplastic concentrations from personal care products and laundry, and identified potential sources and routes of transmission into the region. Estimates showed the levels of microplastic pollution released into the region from ships and scientific research stations were likely to be negligible at the scale of the Southern Ocean, but may be significant on a local scale. This was demonstrated by the detection of the first microplastics in shallow benthic sediments close to a number of research stations on King George Island. Furthermore, our predictions of primary microplastic concentrations from local sources were five orders of magnitude lower than levels reported in published sampling surveys (assuming an even dispersal at the ocean surface). Sea surface transfer from lower latitudes may contribute, at an as yet unknown level, to Southern Ocean plastic concentrations. Acknowledging the lack of data describing microplastic origins, concentrations, distribution and impacts in the Southern Ocean, we highlight the urgent need for research, and call for routine, standardised monitoring in the Antarctic marine system.

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Contents

1. Introduction

The Southern Ocean region south of the Polar Front has a surface area of approximately 22 million km^2 and a volume of over 71.8 million km^3, representing 5.4% of the world's oceans. The area is under increasing threat from fishing, pollution, and the introduction of non-native species, while climate change is leading to rising sea temperatures and ocean acidification (Aronson et al., 2011). Of increasing concern is pollution in the form of floating macroplastic (Barnes et al., 2009, 2010), which has impacts through, for example, entanglement and ingestion by marine predators (Van Franeker and Bell, 1988; Huin and Croxall, 1996; Waluda and Staniland, 2013; Ryan et al., 2016) and deposition of beached debris (Walker et al., 1997; Convey et al., 2002; do Sul et al., 2011; Eriksson et al., 2009). In contrast, microplastic pollution in the Southern Ocean (i.e. plastic particles <5 mm, Arthur et al., 2009) has received little scientific or regulatory attention, despite the issue being increasingly recognised globally (Andrady, 2011; Cole et al., 2011; do Sul and Costa, 2014; Lusher et al., 2015a; Sutherland et al., 2011; Thompson, 2015). In this paper we review the current state of knowledge concerning microplastics in the Southern Ocean. We collate data from existing and new studies, estimate the input of primary microplastics from personal care products and fibres released from synthetic textiles in the region and describe potential sources and transmission routes of plastics into the region with a view to promoting more research to inform policymakers with jurisdiction over the Antarctic and Southern Ocean.

1.1. Microplastics in the global context

Substantial quantities of microplastics are already present in the global marine ecosystem (Liebezeit and Dubaish, 2012; Collignon et al., 2012; Desforges et al., 2014), from the tropics to the poles, including in Arctic sea ice (Obbard et al., 2014; Lusher, 2015, Bergmann et al., 2017; Tekman et al., 2017). Microplastic particles enter the oceans via wastewater and breakdown of macroplastic and have been shown in numerous studies to be persistent in oceanic systems, including surface and deep ocean waters, and in deep sea sediments (Andrady, 2011; Cole et al., 2011; do Sul and Costa, 2014). Microplastics have been shown to accumulate in oceanic gyres (Leichter, 2011; Eriksen et al., 2013; Gross, 2013; Cózar et al., 2014; Ryan, 2014), and find their way into the global deep ocean (Woodall et al., 2014; Fischer et al., 2015) and deep sea sediments and fauna (Van Cauwenberghe et al., 2015; Taylor et al., 2016). However, the extent, quantity and impacts of microplastics in the marine environment around Antarctica remain largely unknown.

Marine microplastic pollution has primary and secondary sources. Primary microplastics are derived from a number of sources including personal care products, such as toothpastes, shampoos and shower gels, and fibres from laundry. Washing synthetic clothing and fabrics may release microplastic fibres in wastewater. It has been shown that a single polyester fleece jacket can release >1900 fibres per wash (Browne et al., 2011). However, approximately 90% of microplastics may be retained in wastewater treatment plants (see e.g. Ziajahromi et al., 2016). The non-retained microplastics can be released in a largely unaltered state, into the nearshore marine environment having passed through sewage treatment facilities (Fendall and Sewell, 2009; Gröndahl et al., 2009). Physical oceanographic processes may then act to retain or further disperse the particles. Plastic microfibre contamination is widespread, with fibres found on the shorelines of six continents, with more fibres found near densely populated areas (Browne et al., 2011).

Secondary microplastics, both particles and fibres, result from the breakdown of macroscopic plastic ocean debris, which is common throughout the world's oceans (see Li et al. (2016) for review). Around half of discarded plastics are buoyant in seawater, and as such may be subject to degradation by ultraviolet (UV) radiation and decomposition (Hammer et al., 2012). Several comprehensive studies of oceans near populated regions have evaluated the contribution of different sources of primary and secondary microplastics to the overall microplastic levels in the marine environment (e.g. Sundt et al., 2014, Essel et al., 2015, Lassen et al., 2015, Magnusson et al., 2016). It was generally concluded that the majority of microplastics in the marine environment are from secondary sources. Secondary microplastics are known to persist both in surface and deep ocean waters and in deep sea sediments across the world oceans (do Sul and Costa, 2014). A recent global estimate put the input of plastic into the oceans at approximately 6.4 million tons per annum (UNEP, 2005). Around 5 million solid waste items are thrown or lost overboard from vessels (UNEP, 2005, 2009) and ships discards and losses are considered to be the major source of marine debris found on remote beaches (Hammer et al., 2012). An even greater source of marine plastic debris, according to many estimates, is from land based sources such as coastal populations, industry and agriculture (Mehlhart and Blepp, 2012).

1.2. Antarctic legislative framework

International legislation controlling the use and release of microplastics has not kept pace with the emerging environmental consequences of their production. The international community, including the United Nations Environment Programme (UNEP), and regional and national legislative bodies are attempting to address the problem by prohibiting the use of microplastics in personal care products worldwide (UNEP, 2015). Currently there is no global regulation of the discharge of wastewater (including bathing and laundry grey water), nor is it being actively considered by the International Maritime Organisation. The International Convention for the Prevention of Pollution from Ships (1973) as modified by the Protocol of 1978 (MARPOL 73/78) aims to prevent pollution of the marine environment. The issue of marine debris is covered in Annex V, which prohibits the deliberate release of plastics (such as plastic ropes, fishing nets and plastic bags) and other waste from ships, but the level of adherence to these regulations may not always be consistent, particularly amongst those participating in illegal, unreported, unregulated (IUU) fishing (Chen, 2015). No international marine legislation mentions microplastic pollution specifically.

Governance of the area south of latitude 60°S is through the Antarctic Treaty System. The Antarctic Treaty (which entered into force in 1961) put territorial claims into abeyance and prohibited testing of nuclear weapons, but said little on environmental management. In 1998 the Protocol on Environmental Protection to the Antarctic Treaty entered into force, containing specific annexes on Waste Disposal and Waste Management (Annex III) and Prevention of Marine Pollution (Annex IV). Release of wastewater from vessels within 12 nautical miles of the coast is prohibited, but Parties are not compelled to treat wastewater released from their scientific research stations. Under Annex I Environmental Impact Assessment Parties are obliged to undertake environmental impact assessments (EIAs) for all activities within the Antarctic Treaty area, with a view to implementing measures to mitigate any impact. However, the Committee for Environmental Protection (http://www.ats.aq/e/cep.htm), which is the body established by the Protocol to provide Antarctic Treaty Parties with advice on environmental issues, has yet to consider the issue of microplastics, due largely

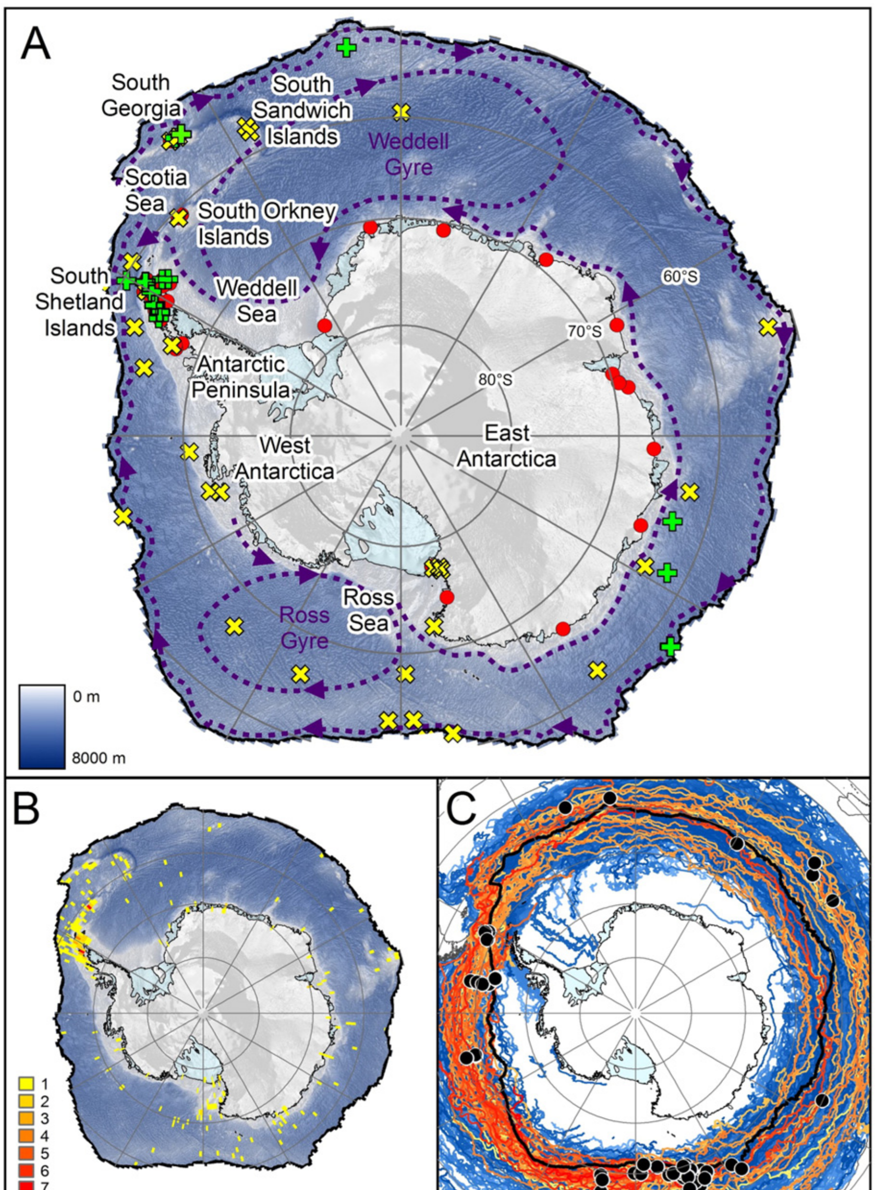

Fig. 1. (A) Main coastal Antarctic facilities operated by National Antarctic Programmes and recorded findings of microplastics and macroplastics in surface waters, on beaches and in sediments south of the Polar Front. Plot boundary: mean position of the Polar Front. Red dots: research stations and facilities. Yellow crosses: records of macroplastics. Green crosses: records of microplastics (see Supplementary Table S1). Purple arrows: direction of major ocean currents. (B) The average number of ships (including fishing, tourism and scientific vessels) within a 1° × 1° spatial grid cell, November 2009–January 2010 (data courtesy of the European Union https://webgate.ec.europa.eu/maritimeforum/). (C) Trajectories of near-surface drifters (1989–2015). All drifters found south of 48°S are shown; those drifters that were deployed north of the mean position of the Polar Front (thick black line) and that are transported southwards across the Polar Front are highlighted in shades of red/orange. The deployment locations of these latter drifters are denoted by black circles.

to a lack of scientific evidence to inform its work and policy development. The Convention for the Conservation of Antarctic Marine Living Resources (CAMLR Convention - https://www.ccamlr.org/) manages marine living resources within the area south of the Polar Front including the Antarctic Treaty area. The CAMLR Commission (CCAMLR) currently monitor for the presence of anthropogenic debris at a small number of sites around the Antarctic continent, but as yet, this does not include monitoring for microplastics. However, the issue of microplastic pollution was presented for the first time to a meeting of the CCAMLR Working Group on Ecosystem Monitoring and Management in 2016, indicating that it is a topic of interest and potential concern.

2. Reports of microplastics in the Southern Ocean

As an emerging area of concern, there are to date few reports of the presence of microplastics in the Southern Ocean and the methods for sampling and reporting are not yet consistent or comparable. Microplastic particles have been found in intertidal sediments from the sub-Antarctic island of South Georgia (Barnes et al., 2009), in deep sea sediments in the Weddell Sea (Van Cauwenberghe et al., 2013) and in the surface waters of the Pacific sector of the Southern Ocean (Isobe et al., 2016). Although not in the peer-reviewed literature, a number of citizen science environmental projects recently found microplastics in surface waters of the Southern Ocean (see Fig. 1A and Table S1) at levels that are consistent with those recorded in more populated areas of the world oceans (AdventureScience.org, 2016). The organisation Adventure Science reported mean values of 22 particles L^{-1} (<5 mm) in seawater samples taken from the western Antarctic Peninsula, with a maximum concentration of 117 particles L^{-1} (AdventureScience.org, 2016). These values are comparable with those collected and analysed by the same project in highly populated regions of the world e.g. east (1–161 particles L^{-1}) and west (1–31 particles L^{-1}) coasts of the USA, New Zealand (2–7 particles L^{-1}) and South Africa (10 particles L^{-1}). The Tara Expeditions Foundation found microplastics in each of four of their samples collected using towed neuston nets in the Southern Ocean, with a concentration of 0.55–56.58 g km^{-2} for particles between 0.335 and 4.75 mm in size (Eriksen et al., 2014; see Fig. 1A and Table S1). Cózar et al. (2014) found concentrations of 0.100–0.514 g km^{-2} at all sample stations south of the Polar Front and Isobe et al. (2016) found values ranging from 46,000–99,000 particles km^{-2} (in the surface 1 m) for particles between 0.16 and 5 mm in size at sample locations south of latitude 60°S.

2.1Quantification of shallow-marine microplastic contamination from within Mackellar Inlet, King George Island, South Shetland Islands, Antarctica

We report shallow-marine microplastic contamination from within Mackellar Inlet, South Shetland Islands (Fig. 1A), close to where the Peruvian Machu Picchu research station is located. Brazilian (Comandante Ferraz) and Polish (Henryk Arctowski) research stations are also found in the wider Admiralty Bay. Sediment and macroalgal material was collected by the Peruvian authors of this study in 2013 and 2015 using Van Veen grab and SCUBA sampling methods at depths ranging from 6 to 60 m at 11 stations across this shallow inlet (see S2 for details of sampling procedure and laboratory analysis).

Samples contained between 16 and 766 synthetic particles m^{-2}, with no clear pattern of abundance or distribution. Plastic particles in the samples ranged from 1 to 23 mm in length (Fig. 2), with microplastics being classified as those smaller than 5 mm, with the most common size being 1–2 mm. The samples contained both secondary microplastic fragments and fibres in a range of colours, implying that particles may have originated from multiple sources including the degradation of larger plastic objects, possibly in the local vicinity.

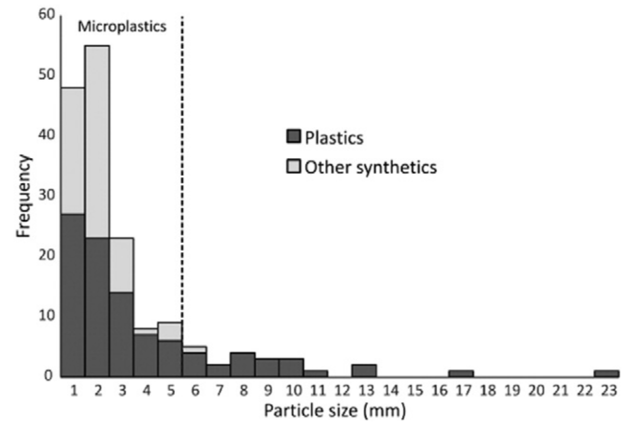

Fig. 2. Frequency of synthetic particles and microplastics from shallow-marine samples taken within Mackellar Inlet, South Shetland Islands sorted by size.

3. Southern Ocean marine ecosystem and potential impact of microplastic

Here we consider the impact of microplastics on four different habitats within the Southern Ocean: pelagic, benthic, sub-littoral and intertidal regions. Pelagic food webs in the Southern Ocean are mobile, patchy and have a rapid turnover (De Broyer et al., 2014). They are characterised by keystone species of diatoms (algal primary producers) and Antarctic krill (*Euphausia superba*) (De Broyer et al., 2014). Within the zooplankton community, suspension filter feeders are predicted, from laboratory experiments using high concentrations of microplastics, to ingest a large proportion as their feeding mode concentrates food from large volumes of water (Kaposi et al., 2014). Antarctic krill, the ecologically important filter feeder, has an uneven population distribution, both spatially and temporally, with ~25% of the biomass concentrated in 10% of its total habitat area, namely the Scotia Sea and Drake Passage (Atkinson et al., 2008). As one of the high traffic areas for shipping in the region (by both the tourism and fishing industries) (Fig. 1B), the Scotia Sea may be a key area for the potential ingestion of microplastics by krill. Evidence from the northern hemisphere shows that microplastics may impact pelagic ecosystems by causing toxicological effects in key species, such as copepods (Lee et al., 2013; Cole et al., 2015) and euphausiids (Desforges et al., 2015), at the base of the food chain as well as potential bioaccumulation and biomagnification through the food chain (Cole et al., 2013; Besseling et al., 2012; Teuten et al., 2009; Ward and Kach, 2009). In turn, these processes could have negative consequences for higher predators such as fish (Lusher et al., 2013; Romeo et al., 2015), seabirds (Furness, 1983; Ryan et al., 2016) seals (Bravo Rebolledo et al., 2013) and whales (Besseling et al., 2015; Lusher et al., 2015b) in addition to the known impacts of macroplastic ingestion and entanglement on marine biota (Derraik, 2002, Gregory, 2009).

Antarctic benthic communities consist predominantly of suspension and deposit feeders with dominant taxa in both shallow and deep water relying on detritus in the water column and sediments to obtain energy and nutrients (Griffiths, 2010). As with the pelagic suspension filter feeding organisms, it is likely that these species will be affected by deposition/settling of microplastic due to the risk of ingestion associated with their feeding strategies (Taylor et al., 2016; Wright et al., 2013b).

Shallow sub littoral habitats are highly heterogeneous, patchy and heavily impacted by ice (icebergs, sea ice and fast ice) (Brown et al., 2004; Smale et al., 2008). The impacts of ice scour, together with advection, result in the resuspension of sediments (Barnes and Souster, 2011; Gutt, 2001), and potentially any microplastics within them, which may increase the likelihood of them being ingested by benthic taxa in coastal areas. Intertidal habitats in Antarctica do exist but are relatively unexplored. Those which have been investigated are surprisingly rich in biodiversity and generally comprise a subset of the local marine community (Waller et al., 2006). Evidence from intertidal habitats elsewhere has shown that animals do ingest microplastics and can suffer detrimental consequences, such as decreased energy reserves and reduced survival rates, for instance in marine worms and amphipods (Wright et al., 2013a; Tosetto et al., 2016).

Although no published data exist concerning microplastic impacts upon Antarctic biota, effects have been observed in similar taxa in other ocean regions, such as the impairment of feeding and a decrease in reproductive output (as described above). At the moment it is not clear whether Antarctic species would respond in the same way, leaving considerable scope for further research.

4. Sources of microplastic within the Southern Ocean

4.1. Microplastics in wastewater

In Antarctic waters, microplastics may be discharged in wastewater from scientific research stations (Fig. 1A) and research, fishing and tourist vessels (Fig. 1B). Gröndahl et al. (2009) reported that of the 71 research stations located in Antarctica, 52% had no wastewater treatment systems. This corresponded to 37% of the permanent stations (occupied year-round) and 69% of stations occupied only during the austral summer. Conventional wastewater treatment, including tertiary treatment techniques such as microfiltration, may fail to fully remove microplastics (Fendall and Sewell, 2009; Ziajahromi et al., 2016) and this situation may be exacerbated in remote polar regions where operational difficulties may reduce treatment efficiency (Tin et al., 2009; Aronson et al., 2011).

4.2. Estimation of microplastic release into the Southern Ocean from personal care products and laundering synthetic fabrics

Information on the volume of wastewater released into the Southern Ocean and empirical data on microplastics in the wastewater are not available. In order to assess the potential input of primary microplastics from personal care products and laundering synthetic fabrics we quantified the human presence in the region, onboard ships and at scientific research stations as ~18.2×10^6 person days per decade (Table 1) using data from:

- The International Association of Antarctica Tour Operators (IAATO) (2004–2014): total number of cruises, their duration and the numbers of passengers and crew on each cruise.
- The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (2004–2014): total number of fishing vessels (licensed), duration of fishing in Southern Ocean and the number of crew.
- The Council of Managers of National Antarctic Programs (COMNAP): summary of coastal scientific research stations and personnel for summer and winter occupancy between 2004/5 and 2014/15, www.comnap.aq (Fig. 1A).

We used published rates of primary microplastic use and production per person for elsewhere in the world to generate values for total local microplastic input (from personal care products and laundry) into the Southern Ocean. Estimates of daily microplastic use per person in personal care products ranged between 2.4 and 27.5 mg day^{-1} (Gouin et al., 2011, 2015). We estimated a maximum potential input (i.e. based on 18.2 million person days per decade) of between c. 44–500 kg of microplastic particles entering the Southern Ocean per decade from personal care products (See Table 2).

Estimates of synthetic fibres given off by laundry were based upon studies where individual items were found to release between 680 and 1900 fibres per wash (polyester blankets and shirts, and fleece clothing respectively; Browne et al., 2011). Napper and Thompson (2016) estimated that a 6 kg wash of acrylic fabric could release over 728,000 fibres. Assuming that each person on ships or research stations washed clothes or bedding once per week, lower and upper estimates were calculated for between three and 11 synthetic fabric items per person per week (based on typical standard issue Antarctic clothing and the values presented by Browne et al., 2011), with the upper value including at least one fleece item. We calculated estimates ranging between 0.5 and 2.3 billion (using Browne et al., 2011) and 25.5 billion (using Napper and Thompson, 2016) plastic fibres released into the Southern Ocean over a decade, assuming that 90% of fibres are removed during water treatment (Ziajahromi et al., 2016). Few reports exist on the presence of microfibres in the water column or sediments of the Southern Ocean, although detection is likely to be possible near the source of wastewater discharge but, due to dilution effects, detection in the open ocean may be more difficult.

Our preliminary calculations indicate that microfibres from laundry released in wastewater may be a more substantial source of microplastic pollution compared with personal care products. Our results suggest that the local input from personal care products and laundry is relatively low, but likely to be concentrated around highly visited and/or populated areas such as the Northern Antarctic Peninsula (Fig. 1A, B).

4.3. Microplastics from the degradation of macroplastic pollution originating in the Southern Ocean

Macroplastic pollution in the Southern Ocean has been recorded by both at-sea observations and shore-based surveys (Fig. 1A). In Antarctic waters, high UV levels in the austral summer may mean that photo-oxidation is a more effective mechanism for degrading floating debris than in regions elsewhere. However, the cold temperatures may reduce the contribution of thermal oxidation in the breakdown of submerged plastics (Hammer et al., 2012). Convey et al. (2002) found that 8–10% of the

Table 1
The estimated number of person days spent on the Southern Ocean or in coastal regions of Antarctica through tourism and legal fishing during the period 2004 to 2014. Tourist data were obtained from the International Association of Antarctica Tour Operators (IAATO) and fishing data from the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), research station data based upon mean occupancy (summer and winter) provided by the Council of Managers of National Antarctic Programs (COMNAP).

Antarctic summer season	Fishing vessels (longline)	Fishing vessels (krill)	Tourist visitors	Research stations	Total
2004/05	39,410	38,502	626,248	(166,164 winter & 649,558 summer) 815,722	1,519,882
2005/06	36,575	65,565	778,017	(166,164 winter & 649,558 summer) 815,722	1,695,879
2006/07	42,840	48,267	815,491	(166,164 winter & 649,558 summer) 815,722	1,722,320
2007/08	36,260	41,757	951,891	(166,164 winter & 649,558 summer) 815,722	1,845,630
2008/09	32,095	73,935	966,366	(166,164 winter & 649,558 summer) 815,722	1,888,118
2009/10	33,530	102,858	771,883	(166,164 winter & 649,558 summer) 815,722	1,723,993
2010/11	31,290	83,235	815,319	(166,164 winter & 649,558 summer) 815,722	1,745,566
2011/12	31,570	72,912	797,209	(166,164 winter & 649,558 summer) 815,722	1,717,413
2012/13	35,455	99,882	735,747	(166,164 winter & 649,558 summer) 815,722	1,686,806
2013/14	27,790	106,578	1,666,107	(166,164 winter & 649,558 summer) 815,722	2,616,197
Total 2004–2014	346,815	733,491	8,924,278	8,157,220	18,161,804

Table 2
Estimates of the total mass of microplastics entering the Southern Ocean (south of the Antarctic Polar Front) due to the release of personal care products by those participating in tourism, legal fishing and scientific research between 2004 and 2014, based upon a total of ~18.2 million person days (~10 million days from fishing and tourism and ~8.2 million days from scientific research stations – see Table 1). Estimates of daily microplastic release per person are based upon values presented in the references (Gouin et al., 2011, 2015).

		Estimated release of microplastics into the Southern Ocean		
		mg/person/day	kg/year	kg/decade
Estimates of daily microplastic release per person	Gouin et al. (2011)	2.4	4.37	43.7
	Gouin et al. (2015) (minimum output per person estimate)	7.5	13.66	136.6
	Gouin et al. (2015) (maximum output per person estimate)	27.5	50.08	500.8

stranded debris on the South Sandwich Islands and 33–50% at South Georgia and the South Orkney Islands was related to the fishing industry. In highly populated parts of the world, terrestrially derived sources of macroplastics may dominate the input into the marine environment, but due to the small scale of human activity in Antarctica this is unlikely to be the case for material originating on the continent, except potentially on a very local scale around some stations with inadequate waste management practices. Within the Antarctic marine system macroplastic distribution is widespread (Fig. 1A) but records are largely limited to beach studies or opportunistic observations and sampling at sea (Table S1) making quantification of total macroplastics in the Southern Ocean unreliable using available datasets (Convey et al., 2002; Barnes, 2005; Barnes et al., 2010).

4.4. Plastics originating outside the Southern Ocean

Recent observations from the Arctic showed that remote Polar Regions were not beyond the reach of microplastic pollution (Lusher et al., 2015a). Bergmann et al. (2017) found high concentrations of microplastics in Arctic sea ice, including fibres potentially originating from the atmosphere. Tekman et al. (2017) linked increased plastic debris at an Arctic deep sea observatory (2500 m depth) to increased numbers of fishing boats in the region. The Arctic is an ocean surrounded by populated landmasses with industrial centres and with ocean currents that enter from both the Pacific and Atlantic in contrast to the more isolated Antarctic. The Antarctic is an almost unpopulated continent, separated geographically from the nearest continents.

The major current systems of the Southern Ocean comprise the eastward-flowing Antarctic Circumpolar Current, the westward-flowing Antarctic Coastal Current, and the clockwise-circulating Weddell and Ross Sea gyres (Fig. 1A). Until recently, it was thought that, in particular, the Polar Front (a deep-reaching ocean front with an associated current jet within the Antarctic Circumpolar Current) provided a substantial barrier to the transfer of biotic and abiotic material from lower latitudes (Fraser et al., 2011, 2016). However, dispersal processes (for example, due to high frequency variability associated with the Polar Front through meandering and the generation of eddies) provide potential mechanisms for the transfer of material southward across the Polar Front, as demonstrated by near-surface satellite-tracked ocean drifters (Fig. 1C). Recent studies investigating floating kelp distribution also confirmed the transfer of biotic material across the Polar Front, most likely via eddies (Fraser et al., 2011, 2016). Areas such as the western Antarctic Peninsula, where the Polar Front is relatively close to the continent, permit a shorter transfer route to near-shore environments for waters from lower latitude oceans. At intermediate depths, deep waters from lower latitudes upwell to shallower depths across the Antarctic Circumpolar Current as Circumpolar Deep Water. Although the timescales of this process are longer than surface transport routes (approximately decadal), it is another potential mechanism for transport into the region from latitudes north of the Southern Ocean.

Material south of the Polar Front can be transferred towards the Antarctic continent by the southward-flowing limbs of regional gyres, e.g. in the Weddell and Ross Seas, where interaction with the Antarctic Coastal Current may lead to further dispersal. Locally, smaller-scale processes such as cross-shelf transfer and retention, tidal interactions and permanent eddies will act to retain or disperse material (Thompson et al., 2009; Young et al., 2014). These processes will be modified by seasonal variability associated with, for example, flux of freshwater and heat, and the presence and drift of sea ice (Thorpe et al., 2007).

As yet, there is no quantitative evidence to determine whether or not plastics are crossing the Antarctic Circumpolar Current or if the detected particles are locally sourced. While we have identified that transport pathways do exist, modelling studies will allow a better resolution of the importance and timescales of these routes, and the level of dispersal from local sources.

5. Conclusions

The threats to marine ecosystems presented by microplastics have been identified as a major global conservation issue and a key priority for research (Sutherland et al., 2011), but major questions concerning plastic in the Southern Ocean remain unanswered. For example, while the presence and impact of macroplastics and other marine debris has been monitored at a limited range of locations in the Southern Ocean, our understanding of the sources and fate of plastics in these waters is limited at best. Given the low numbers of people present in Antarctica and the Southern Ocean, direct input of microplastic from wastewater is likely to be below detectable limits at a Southern Ocean scale. However, microplastics generated from macroplastic degradation or transferred into the Southern Ocean across the Polar Front has yet to be adequately quantified, but may be a major contributor, as found elsewhere in the world, to the high level of microplastics recorded at some open ocean sites.

In addition to tighter regional regulation on the use and release of plastics in the Southern Ocean we believe that a greater understanding of their distribution and impact is required. At present the international scientific community does not regularly sample for microplastics or record at-sea observations of macroplastics in the Southern Ocean region and there are few peer-reviewed scientific publications exist that quantify plastics in Antarctic waters. Our results show where in the Southern Ocean macro and microplastic have been reported to date. As units and methods of existing studies are not comparable a quantitative study of macro and microplastic concentrations around the Southern Oceans is therefore impossible at this time.

To understand fully the sources and scale of this pollution would require an internationally coordinated effort with standardised or comparable sampling and extraction techniques for microplastics and observation and recording methodologies for macroplastics to map and evaluate circumpolar plastics distribution. Given that the required sampling methods are relatively simple (Lusher, 2015; Desforges et al., 2014), we recommend that this could be done by using ships already deployed to the Southern Ocean for scientific and logistical purposes. Such a campaign would be best organised through the existing international collaborative efforts of the Scientific Committee on Antarctic Research, COMNAP and CCAMLR with support from the Antarctic Treaty Parties.

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