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Baseline

Descriptions and patterns in opportunistic marine debris collected near Palmer Station, Antarctica

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ABSTRACT

Observations of marine debris in Antarctica have been increasing; however, impacts, distributions, sources, and transport pathways of debris remain poorly understood. Here, we describe the spatial distribution, types, and potential origins of marine debris in 2022/2023 near Palmer Station, Antarctica. We opportunistically collected 135 pieces of marine debris with the majority of items found along shorelines (90 %), some found in/near seabird nests/colonies (7 %) and few on inland rocky terrain (3 %). Plastic and abandoned, lost, or discarded fishing gear dominated observed debris. Results suggest that wind and the Antarctic Coastal Current may be a major pathway for debris. This study is the first assessment of marine debris in this region and suggests that oceanography, weather patterns, and shoreline geomorphology could play a role in determining where debris will accumulate. Continued tracking of debris and development of structured surveys is important for understanding the impacts of human activities in a biological hotspot.

1. Introduction

Plastic and marine debris are ubiquitous in ocean environments. Debris are often found in coastal environments, where they are easy to identify and collect, but have also been observed in environments as deep as the Marianas Trench, and as remote as the poles and the middle of ocean basins (Barnes et al., 2009, 2010; Chiba et al., 2018; Thompson et al., 2004; Van Cauwenberghe et al., 2013; Waluda et al., 2020). Antarctica is marketed to tourists as the world's final pristine frontier even as observations of marine debris in the region are increasing (Barnes et al., 2010; Ivar do Sul et al., 2011; Lacerda et al., 2019; Rota et al., 2022; Waller et al., 2017; Waluda et al., 2020).

Debris can encompass a variety of materials, including wood, paper, metal, glass, and plastic, and can enter the environment through a variety of ways (Iñiguez et al., 2016). Items can originate from a single point, such as a particular fishing vessel or boating activity, or can be collected from many sources over a broad area, such as a watershed, and released into the marine environment through estuaries and rivers. In Antarctica, the Antarctic Circumpolar Current may also concentrate marine debris from other ocean basins and transport them to coastal environments (Dawson et al., 2023; Lacerda et al., 2019; Lozoya et al., 2022; Murphy et al., 2021). As a result of the variety of materials and potential sources of marine debris, as well as the potential for ocean currents to transport debris over long distances, it can be difficult to discern their source, especially as larger items break down into smaller, unrecognizable pieces (van Sebille et al., 2020; Suaria et al., 2020).

Marine debris can range in size from microscopic material to items that are meters long, which can have different impacts on species across the food web. The accumulation of large debris in the environment, specifically macroplastics (> 10 mm; Hartmann et al., 2019) and other similarly sized debris, can pose significant risks for larger animals such as seabirds, sea turtles, and marine mammals (Kühn et al., 2015; Rochman et al., 2016). These risks can come from entanglement in the debris, and has been directly linked to mortality (Kuepfer and Stanworth, 2023; Baulch and Perry, 2014; Kühn et al., 2015). In addition, some animals may purposefully ingest debris, mistaking them for food items (Bessa et al., 2019; Fragão et al., 2021; van Franeker, 1985; van Franeker and Bell, 1988). Smaller microplastics (< 1 mm; Hartmann et al., 2019) can also be unintentionally consumed by animals throughout the food web and have a plethora of impacts on physiology

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and overall fitness (Santos et al., 2021; Tuuri and Leterme, 2023). Therefore, the accumulation and persistence of these debris items in the marine environment can pose significant risks to ecosystem health.

While the number of studies describing debris of all sizes and their impacts throughout the Antarctic food web from amphipods to penguins are increasing (Barnes et al., 2010; Ivar do Sul et al., 2011; Lacerda et al., 2019; Mancuso et al., 2023; Rota et al., 2022; Waller et al., 2017), the distribution and sources of marine debris in the region is poorly understood. Observations of marine pollutants in the Antarctic, especially systematic studies that also report the absence of debris are rare. Most studies to date rely on the opportunistic observation of marine debris on coastlines, such as the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Marine Debris program, and very few studies of debris concentrations are conducted in the coastal ocean (Jones-Williams et al., 2020; Kuklinski et al., 2019; Lacerda et al., 2019; Suaria et al., 2020). Some recent studies have combined observations and modeling efforts to highlight potential sources and transport pathways for observed debris on both circumpolar (Lacerda et al., 2019) and regional (Gallagher et al., in review) scales. However, without information on how much debris is actually present and potentially accumulating in Antarctica, it is difficult to ascertain how true these potential pollutant pathways are. Therefore, more data on the distribution, abundance, and potential sources of marine debris, would be beneficial to improving our understanding on pollutant distribution and designing effective conservation strategies.

Here, we describe marine debris collected over one six-month field season where personnel were based at Palmer Station, Antarctica. This region is not only a biological hotspot, supporting a high abundance of Antarctic krill (*Euphausia superba*) and their predators such as penguins, whales, and seals, but also a hotspot for human activity along the West Antarctic Peninsula. Palmer Station is home to ~40 researchers and support staff during the austral summer, and roughly 20 during winter. Large oceanographic research vessels ferry people to and from the station and also conduct research locally and throughout the Antarctic Peninsula. In addition to research activity, the region is a popular tourism destination and near hotspots for a growing krill fishery and Antarctic toothfish (*Dissostichus mawsoni*) fishery blocks (Finger et al., 2023; Ivar do Sul et al., 2011; Gallagher et al., in review). All of these activities have the potential to introduce marine debris to the local ecosystem. We utilize the opportunistic collection of marine debris on routine seabird surveys to categorize the debris observed within this region and hypothesize potential sources and local pathways for these debris.

2. Methods

2.1. Marine debris collection

Marine debris were collected from 16 November 2022 to 5 April 2023 by a team of three researchers. Researchers were based at Palmer Station, Anvers Island, Antarctica (64.7743°S, 64.0538°W; Fig. 1), and were conducting routine seabird monitoring protocols as a part of the Palmer Long-Term Ecological Research (LTER) program that required visits to nearby islands via small boats. The main seabird species under study include: Adélie (*Pygoscelis adeliae*), gentoo (*P. papua*), and chinstrap (*P. antarcticus*) penguins, brown (*Stercorarius antarcticus*) and south polar skuas (*S. maccormicki*), blue-eyed shags (*Phalacrocorax atriceps*) and southern giant petrels (*Macronectes giganteus*). These seabirds generally nest on higher elevation terrain where nest sites will not be flooded by high tides or storm surge, and based on island-specific geomorphology, higher elevation ridges or regions can be various distances from the coast (meters to 100 s of meters). The team worked on 32 islands in the vicinity of Palmer Station, and some islands were visited as many as 84 (Humble Island) and 72 (Torgersen Island) times, while others were only visited once (e.g., Rosenthal Islands, some of the Joubin Islands). There were 21 islands visited less than five times, and four islands visited between ~20 to 30 times.

During island visits, when marine debris were observed they were picked up. However, marine debris surveys were not conducted, meaning we were not specifically looking for debris and all shorelines or

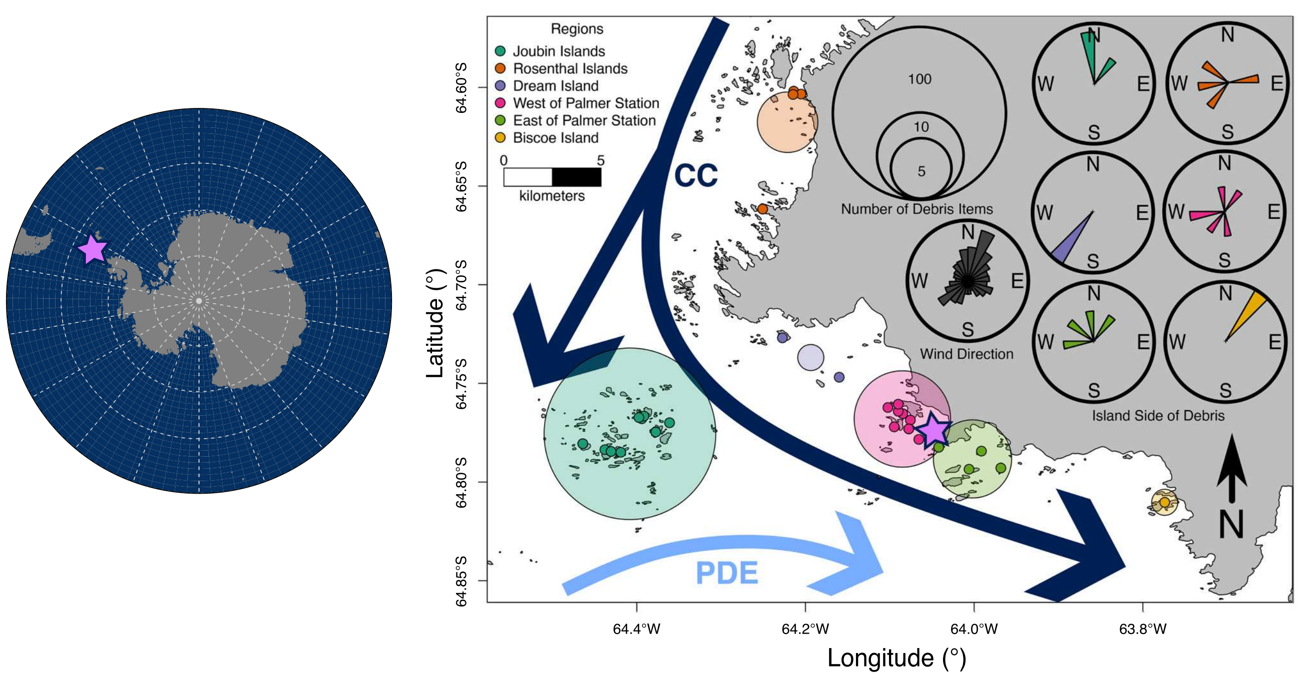

Fig. 1. Locations of marine debris collected near Palmer Station, Anvers Island, grouped into six regions with the total number of debris items represented by the larger circles. The rose plots show the side of the island where debris were collected by region for each unique GPS location (i.e., items from the same location were grouped) and wind directions from 1989 to 2023. General current patterns are shown by the blue arrows, including the Antarctic Coastal Current (CC) and Palmer Deep Eddy (PDE) that sometimes has a surface signature. The map of Antarctica is included on the left and the star is the location of Palmer Station in both maps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

areas were equally visited. Further, we did not record when an area was visited and no debris were found. Therefore, this is a presence-only dataset, where no debris observations does not equate to absences.

When debris were found, we recorded the item type (as specific as possible, and grouped into more general categories following CCAMLR categorizations), approximate size, and location (i.e., latitude/longitude, and water/beach/nest/rocks). CCAMLR size categories are: small (< 2.5 cm), medium (2.5–10 cm), large (10 cm - 1 m), and very large (> 1 m). CCAMLR item categories include plastic, metal, rubber, fabric, wood, rope, glass, and fishing gear. The CCAMLR Marine Debris form provides subcategories, based on the item category ("Marine Debris | CCAMLR", 2017). This data was submitted to CCAMLR using their opportunistic debris collection form.

In the Palmer Station region, all shorelines/beaches are rocky, consisting of pebbles, various sized rocks and large boulders (similar to Anfuso et al., 2020). In the austral winter to spring and sometimes into summer, beaches or regions near the high tide line can be fully or partially covered in snow and ice. Island shape and geomorphology is variable with islands ranging in size from <200 m to ~2 km in length (Fig. 1). The coastal perimeter of the islands exhibits diverse features, ranging from flat rocky beaches to steep rock walls and narrow coves/channels. We considered an item to be along the shoreline/on a beach when it was within a few meters of the high tide line. Other items were considered to be on "inland" rock if it was not in or near a seabird nest or colony. We also manually identified which side of the island the items were collected on (at a 45° resolution) and recorded general features that may facilitate debris washing ashore at that location (e.g., bays, channels).

This preliminary study documents the spatial distribution, types and potential origins of marine debris in the Palmer Station region to track and understand how debris could impact marine flora and fauna. Therefore, we map and provide simple summaries of marine debris that were collected over this one field season.

2.2. Environmental data

We obtained wind speed and direction from April 1989 to June 2023 from the Environmental Data Initiative (LTER, 2023). We chose to display long-term wind patterns because we do not know when debris washed ashore, and the predominant long-term wind direction was relatively consistent despite known interannual and decadal variability.

3. Results and discussion

3.1. Spatial patterns

We collected 135 pieces of marine debris that were grouped into six regions around Palmer Station (Fig. 1). All marine debris were found on land except for one large pink buoy (diameter 1.5 m) that was drifting towards land in the Dream Island region. The majority of items were found along beaches or shorelines ($n = 122$) but a few items were found in/near seabird nests/colonies ($n = 9$) or on inland rocky terrain ($n = 4$).

The six different regions had various amounts of marine debris (not including items in/near nests/colonies): Rosenthal Islands ($n = 5$), Joubin Island ($n = 96$), Dream Island ($n = 2$), West of Palmer ($n = 13$), East of Palmer ($n = 8$), and Biscoe Island (n = 2) (Fig. 1). By determining the side of the island where debris were found using cardinal directions, preliminary regional patterns were apparent (Fig. 1). Debris in the Rosenthal Islands were found on the western and eastern flanks of islands, whereas debris on the Joubin Islands were found on the northern sides of the islands. Around Dream Island and west of Palmer Station, debris were primarily found on the west side of the islands, and further east in the study region, debris were found on the northwest to northeast sides of islands. However, we acknowledge that all shorelines were not surveyed equally and all sides of the surveyed islands do not have beaches where debris could accumulate. Therefore, these debris distributional patterns should be treated as preliminary and confirmed by structured surveys where all shorelines around an island are sampled.

3.2. Possible drivers of accumulation

As debris along shorelines were not uniformly distributed, we considered debris occurrence in relation to general wind and ocean current patterns given the timing of debris accumulation along shorelines was unknown. While wind speed and direction in this region can vary significantly on short temporal (hours) and small spatial scales (kms) (Hudson et al., 2021; Kohut et al., 2018), winds at Palmer Station were predominantly from the north-northeast, east-southeast, and southwest (Fig. 1). Many beached debris items were found in the northern and western sides of islands, suggesting that wind may play a role in these observations by pushing debris onto coastlines that are exposed to the open shelf.

Another factor that likely contributed to these observations was local current patterns. The Antarctic Coastal Current (CC) runs around Anvers Island parallel to the coast, moving south along the Rosenthal Islands and then eastward towards Biscoe Island (Fig. 1). A portion of this current also continues in a southwesterly direction towards and through the Joubin Islands. The distribution of debris in the Joubin Islands suggests that the CC may be a major contributor of debris to this region, with many debris found on the north side of the islands facing the CC. Therefore, debris could be transported to this region by the CC and then advected by nearshore currents, and eventually beached by prevailing winds. Further, the distribution of debris appears to be influenced by island geomorphology. Overall, 83 % ($n = 101$ of 122) of shoreline debris were found in small bays, coves or channels that might aid in debris retention and subsequent accumulation on beaches.

The number of debris found did not appear to be directly related to frequency of island visits. For example, five islands in the Rosenthal Islands region were visited once and only five items were collected along beaches while Joubins Island 76 was also only visited once but 78 items (64 % of total shoreline debris, Fig. 1) were found, potentially facilitated by a narrow channel/bay. Despite the high number of visits to both Torgersen and Humble Islands, only six (four buoys, a glove, and a piece of wood) and two items (a flag on a bamboo stick likely from a Palmer Station cache, and a water bottle) were found, respectively. Thus, it is possible that locations infrequently visited over multiple years may accumulate more debris while locations that are frequently visited and as a result have debris removed more frequently will not accumulate debris because items will be removed annually. Compiling data collected over multiple years would aid in understanding this.

3.3. Description of marine debris collected

The number and types of debris varied by location. The debris found near seabird nests/colonies included mostly small items (~1 to 5 cm) that the birds likely picked up, such as small pieces of hard plastic or glass ($n = 3$, in giant petrel nests), what looked like a piece of a balloon ($n = 1$, near gentoo penguin colonies), a screw ($n = 1$, in giant petrel nest), pieces of styrofoam ($n = 2$, in/near south polar skua nests), a ~ 10 cm candle ($n = 1$, in a south polar skua nest), and a 16 oz. water bottle ($n = 1$, vicinity of gentoo penguin colonies). We assume flying seabirds (e.g., skuas) dropped items near gentoo colonies enroute to their nest sites, although it is possible that the water bottle was wind blown from the shore to the colony area.

The items that were not found in nests/colonies were generally larger, predominantly plastic or classified as fishing gear (Fig. 2). There were four pieces of styrofoam found at three different locations (Joubins Island 8 and two islands west of Palmer Station) that were not along the shoreline. We assume these lightweight items were wind blown to locations where they were found. Along the shorelines, fishing gear was found in each region, plastics were found in four regions and wood was found in three of the six regions. We admit we could not pick up all wood

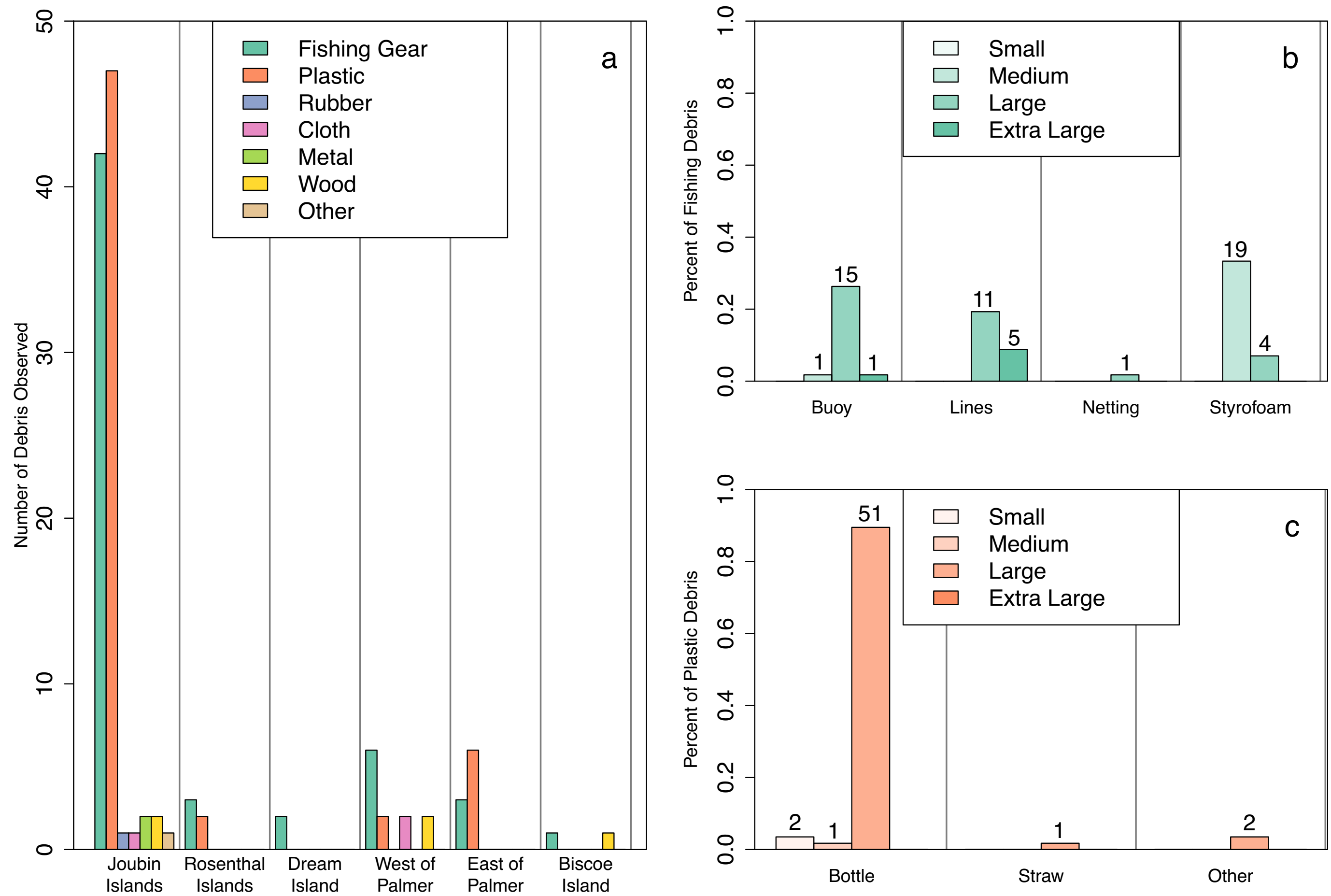

Fig. 2. The number and type of debris observed a) by region. b) The percent of fishing debris that were buoy, lines, netting or styrofoam in each size category, and c) the percent of plastic debris that were bottles, straws or other in each size category. Numbers over each bar in b and c indicate the number of debris in each category. The size categories are small (<2.5 cm), medium (2.5 cm - 10 cm), large (>10 cm - 1 m) and very large (>1 m) following CCAMLR groupings.

debris (especially, in the Joubin Islands) due to the sheer number and size (e.g., long, heavy planks), and thus, the actual number of wood debris may be underestimated. The types of fishing gear were diverse, and included materials across almost all categories other CCAMLR debris categories, including plastic buoys, lines, netting and styrofoam (actual buoys, and presumed pieces of buoys) (Fig. 2b). Of the plastic debris, nearly all (91 %) of the items were bottles (large jugs, but mainly water bottles).

3.4. Notable items

Some of the items found were more unique than others (Fig. 3). For example, there were items with writing in different languages that may help identify origin. This included a fertilizer bottle in Russian; a pain relief spray in Spanish; and water bottles made in China (Fig. 3a, b, e). The Master Kong (Fig. 3e) water bottle cap was the most common type of water bottle, collected 11 times in all regions except Dream and Biscoe Island. The steel toe boot is made for work in cold environments and quite degraded, possibly indicating it was not lost recently (Fig. 3c). Possible origins for these debris include fishing, tourism, and research activities. Countries that fish for Antarctic krill include, but are not limited to, Spanish-speaking Argentina and Chile, Russia, and China (Kawaguchi et al., 2006; Kawaguchi and Nicol, 2020). Antarctic tourism is growing increasingly diverse and includes passengers and ships hailing from China, Chile, Spain, and Russia (Bender et al., 2016; International Association of Antarctica Tour Operators (IAATO), 2022). Chile and Argentina, and Russian-speaking Ukraine also have research stations in the vicinity of Palmer Station (Council of Managers of National Antarctic Programs, 2017).

A large net attached to a buoy was the largest and heaviest gear found, and could have resulted in whale entanglements - a known threat globally (Baulch and Perry, 2014; Brown and Niedzwecki, 2020; Croxall et al., 1990) but only more recently observed in the Antarctic Peninsula (Pallin et al., 2022) (Fig. 3d). This net had a fine mesh and could have originated from fishing (trawl) or research (plankton tow) activities.

4. Conclusions

This is among the first assessments of marine debris over a field season near Palmer Station, a biological and human activity hotspot along the West Antarctic Peninsula. We could not identify a single, definitive source for these debris. Fisheries in the CCAMLR Convention area cover an extensive geographic area and could be a source for some of the debris observed, although some of the nets classified as fishing gear may have come from other sources, such as research activities. Marine debris surveys on the Scotia Arc islands to the north and near Adelaide Island to the south reported a close relationship with local fishery activity at some locations (Convey et al., 2002). While this suggests that analyzing debris accumulation can be a useful indirect measure of local fishery activity and their compliance with CCAMLR regulations, this relationship should be re-evaluated given the spatial consolidation of the Antarctic krill fishery near the South Shetland Islands in recent years.

While Antarctic research stations and scientific activities may lead to unintentional releases, we found only a few items identified as possibly originating from such activities. For example, a flag on a bamboo pole, a

Fig. 3. Photos of example items found (A) A 185 mL bottle of Bona Forte fertilizer for houseplants (in Russian), (B) 100 mL metal bottle of Ethylchloride for pain relief (in Spanish) (left) and an unidentifiable metal bottle (right), (C) what appears to be a Dunlop Mens Purofort Thermo Wellington Boot, which is steel toe and protects under cold conditions, (D) estimated 40 lbs. of line, buoy (~ 2 m diameter) and cloth/mesh (note the human for scale), and (E) a Master Kong plastic water bottle cap (in Chinese). All items pictured were found in the Joubins Islands with BCE, A, and D on island 76, 12 and 18, respectively.

screw and piece of duct tape could have been from station or science activities, but these items made up a small contingent (5 out of 135 total debris observed) of the observed debris. Previous work at the United Kingdom's Peninsula research station has not found debris associated with research activities (Convey et al., 2002). Furthermore, long-term monitoring of debris at South Georgia and the South Orkneys in the Scotia Sea could not identify any debris from local research activities (Waluda et al., 2020). In addition, despite growing concerns about adverse impacts of tourism, including pollution (Ivar do Sul et al., 2011), our investigation reveals no direct evidence of a tourism footprint from the debris that we found. While we did find debris with Chinese text, and Chinese nationals are becoming a growing contingent of Antarctic tourists (Bender et al., 2016; International Association of Antarctica Tour Operators (IAATO), 2022), we did not find any debris that could be directly tied to tourism. However, the absence of evidence does not necessarily negate these concerns; rather, we cannot definitively confirm that tourism poses zero pollution risk to the Peninsula with the available data.

The spatial distribution of debris highlights the potential interaction between oceanography, weather patterns, and shoreline geomorphology in determining the areas where debris may accumulate. Notably, as our group has worked in this region for many years, our visual observations during this study (2022−23) suggest a higher-than-usual debris accumulation. However, it is important to note that the preceding year (2021−22) had limited scientific activities in the region due to the cancellation of Palmer Station science during the construction of a new pier. Since we make every effort to remove debris from the environment during routine seabird surveys, the hiatus may have led to the accumulation of debris during our absence. Continued monitoring efforts and structured surveys in the region will help quantify if this is an anomalous year due to the absence of science at Palmer Station. Future monitoring efforts should also consider saving a portion of plastic debris to determine the composition (i.e. polyethylene, polystyrene, etc).

The anomalous low sea ice in the winter of 2022 (Turner et al., 2022) preceding our study also raises important considerations. Sea ice could act as a barrier preventing items from entering the Palmer region, and its absence may have allowed more debris to drift in and accumulate on beaches. The low sea ice may also allow fisheries to operate in more southerly locations closer to Palmer Station, potentially resulting in an increased presence of debris in nearby waters. Considering these observations, the ongoing monitoring of marine debris and fishing pressure is critical. This continual tracking serves as a tool for assessing compound stressors on wildlife, especially given the backdrop of ongoing rapid climate change. However, further research is required to fully assess the threat that marine debris pose to species in the ecosystem.

CRediT authorship contribution statement

Katherine L. Gallagher: Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Gina M. Selig:** Conceptualization, Visualization, Writing – review & editing. **Megan A. Cimino:** Conceptualization, Data curation, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing.

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.

Data availability

Data are available at https://doi.org/10.6073/pasta/51fb854e151dc00ffcba786080a43dbe.

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References

Anfuso, G., Bolívar-Anillo, H.J., Asensio-Montesinos, F., Portantiolo Manzolli, R., Portz, L., Villate Daza, D.A., 2020. Beach litter distribution in Admiralty Bay, King George Island, Antarctica. Mar. Pollut. Bull. 160, 111657 https://doi.org/10.1016/j.marpolbul.2020.111657.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B Biol. Sci. 364, 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

Barnes, D.K.A., Walters, A., Gonçalves, L., 2010. Macroplastics at sea around Antarctica. Mar. Environ. Res. 70, 250–252. https://doi.org/10.1016/j.marenvres.2010.05.006.

Baulch, S., Perry, C., 2014. Evaluating the impacts of marine debris on cetaceans. Mar. Pollut. Bull. 80, 210–221. https://doi.org/10.1016/j.marpolbul.2013.12.050.

Bender, N.A., Crosbie, K., Lynch, H.J., 2016. Patterns of tourism in the Antarctic peninsula region: a 20-year analysis. Antarct. Sci. 28, 194–203. https://doi.org/10.1017/S0954102016000031.

Bessa, F., Ratcliffe, N., Otero, V., Sobral, P., Marques, J.C., Waluda, C.M., Trathan, P.N., Xavier, J.C., 2019. Microplastics in gentoo penguins from the Antarctic region. Sci. Rep. 9, 14191. https://doi.org/10.1038/s41598-019-50621-2.

Brown, A.H., Niedzwecki, J.M., 2020. Assessing the risk of whale entanglement with fishing gear debris. Mar. Pollut. Bull. 161, 111720 https://doi.org/10.1016/j.marpolbul.2020.111720.

Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., Fujikura, K., 2018. Human footprint in the abyss: 30 year records of deep-sea plastic debris. Mar. Policy 96, 204–212. https://doi.org/10.1016/j.marpol.2018.03.022.

Convey, P., Barnes, D., Morton, A., 2002. Debris accumulation on oceanic island shores of the Scotia Arc, Antarctica. Polar Biol. 25, 612–617. https://doi.org/10.1007/s00300-002-0391-x.

Council of Managers of National Antarctic Programs, 2017. Antarctic Station Catalogue.

Croxall, J.P., Rodwell, S., Boyd, I.L., 1990. Entanglement in man-made debris of Antarctic Fur seals at Bird Island, South Georgia. Mar. Mammal Sci. 6, 221–233. https://doi.org/10.1111/j.1748-7692.1990.tb00246.x.

Dawson, H.R.S., Morrison, A.K., England, M.H., Tamsitt, V., 2023. Pathways and timescales of connectivity around the Antarctic continental shelf. J. Geophys. Res. Oceans 128, e2022JC018962. https://doi.org/10.1029/2022JC018962.

Finger, J.V.G., Krüger, L., Corá, D.H., Petry, M.V., 2023. Habitat selection of southern giant petrels: potential environmental monitors of the Antarctic Peninsula. Antarct. Sci. 35, 256–269. https://doi.org/10.1017/S0954102023000147.

Fragão, J., Bessa, F., Otero, V., Barbosa, A., Sobral, P., Waluda, C.M., Guímaro, H.R., Xavier, J.C., 2021. Microplastics and other anthropogenic particles in Antarctica: using penguins as biological samplers. Sci. Total Environ. 788, 147698 https://doi.org/10.1016/j.scitotenv.2021.147698.

van Franeker, J.A., 1985. Plastic ingestion in the North Atlantic fulmar. Mar. Pollut. Bull. 16, 367–369. https://doi.org/10.1016/0025-326X(85)90090-6.

van Franeker, J.A., Bell, P.J., 1988. Plastic ingestion by petrels breeding in Antarctica. Mar. Pollut. Bull. 19, 672–674. https://doi.org/10.1016/0025-326X(88)90388-8.

Gallagher, K.L., Cimino, M.A., Dinniman, M.S., Lynch, H.J., n.d. Quantifying Potential Marine Debris Sources and Threats to Penguins on the West Antarctic Peninsula. In: Review at Environmental Pollution. doi:10.2139/ssrn.4667894.

Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N. P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53, 1039–1047. https://doi.org/10.1021/acs.est.8b05297.

Hudson, K., Oliver, M.J., Kohut, J., Dinniman, M.S., Klinck, J.M., Moffat, C., Statscewich, H., Bernard, K.S., Fraser, W., 2021. A recirculating Eddy promotes subsurface particle retention in an Antarctic biological hotspot. J. Geophys. Res. Oceans 126, e2021JC017304. https://doi.org/10.1029/2021JC017304.

Iñiguez, M.E., Conesa, J.A., Fullana, A., 2016. Marine debris occurrence and treatment: a review. Renew. Sustain. Energy Rev. 64, 394–402. https://doi.org/10.1016/j.rser.2016.06.031.

International Association of Antarctica Tour Operators (IAATO), 2022. IAATO Overview of Antarctic Tourism: A Historical Review of Growth, the 2021–22 Season, and Preliminary Estimates for 2022–23. XLIV Antarctic Treaty Consultative Meeting, Berlin, p. 2022.

Ivar do Sul, J.A., Barnes, D., Costa, M.F., Convey, P., Costa, E.S., Campos, L., 2011. Plastics in the Antarctic environment: are we looking only at the tip of the iceberg? Oecologia Aust. 15, 150–170. https://doi.org/10.4257/oeco.2011.1501.11.

Jones-Williams, K., Galloway, T., Cole, M., Stowasser, G., Waluda, C., Manno, C., 2020. Close encounters - microplastic availability to pelagic amphipods in sub-Antarctic and Antarctic surface waters. Environ. Int. 140, 105792 https://doi.org/10.1016/j.envint.2020.105792.

Kawaguchi, S., Nicol, S., 2020. Krill fishery. In: Fisheries and Aquaculture. Oxford University Press, pp. 137–158. https://doi.org/10.1093/oso/9780190865627.003.0006.

Kawaguchi, S., Nicol, S., Taki, K., Naganobu, M., 2006. Fishing ground selection in the Antarctic krill fishery: trends and patterns across years, seasons and nations. CCAMLR Sci. 13, 117–141.

Kohut, J.T., Winsor, P., Statscewich, H., Oliver, M.J., Fredj, E., Couto, N., Bernard, K., Fraser, W., 2018. Variability in summer surface residence time within a West

Antarctic peninsula biological hotspot. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 376, 20170165. https://doi.org/10.1098/rsta.2017.0165.
Kuepfer, A., Stanworth, A., 2023. Falkland Islands Seabird Monitoring Programme - Annual Report 2022/2023, vol. No. SMP30. Falklands Conservation, Stanley.
Kühn, S., Bravo Rebolledo, E.L., van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine anthropogenic litter. Springer International Publishing, Cham, pp. 75–116. https://doi.org/10.1007/978-3-319-16510-3_4.
Kuklinski, P., Wicikowski, L., Koper, M., Grala, T., Leniec-Koper, H., Barasiński, M., Talar, M., Kamiński, I., Kibart, R., Małecki, W., 2019. Offshore surface waters of Antarctica are free of microplastics, as revealed by a circum-Antarctic study. Mar. Pollut. Bull. 149, 110573 https://doi.org/10.1016/j.marpolbul.2019.110573.
Lacerda, A.L. d F., Rodrigues, L. dos S., van Sebille, E., Rodrigues, F.L., Ribeiro, L., Secchi, E.R., Kessler, F., Proietti, M.C., 2019. Plastics in sea surface waters around the Antarctic Peninsula. Sci. Rep. 9, 3977. https://doi.org/10.1038/s41598-019-40311-4.
Lozoya, J.P., Rodríguez, M., Azcune, G., Lacerot, G., Pérez-Parada, A., Lenzi, J., Rossi, F., de Mello, F.T., 2022. Stranded pellets in Fildes Peninsula (King George Island, Antarctica): new evidence of Southern Ocean connectivity. Sci. Total Environ. 838, 155830 https://doi.org/10.1016/j.scitotenv.2022.155830.
LTER, P.S.A., 2023. Daily weather averages for Palmer Station, Antarctica (1989-2023). https://doi.org/10.6073/PASTA/3EEFB45DBFB784C3CABE3690EA46FE9E.
Mancuso, M., Conti Nibali, V., Porcino, N., Branca, C., Natale, S., Smedile, F., Azzaro, M., D'Angelo, G., Bottari, T., 2023. Monitoring of anthropogenic microplastic pollution in antarctic fish (emerald rockcod) from the Terranova bay after a quarter of century. Sci. Total Environ. 904, 167244 https://doi.org/10.1016/j.scitotenv.2023.167244.
Marine Debris | CCAMLR [WWW Document], 2017. URL. https://www.ccamlr.org/en/science/marine-debris (accessed 11.28.23).
Murphy, E.J., Johnston, N.M., Hofmann, E.E., Phillips, R.A., Jackson, J.A., Constable, A. J., Henley, S.F., Melbourne-Thomas, J., Trebilco, R., Cavanagh, R.D., Tarling, G.A., Saunders, R.A., Barnes, D.K.A., Costa, D.P., Corney, S.P., Fraser, C.I., Höfer, J., Hughes, K.A., Sands, C.J., Thorpe, S.E., Trathan, P.N., Xavier, J.C., 2021. Global connectivity of southern ocean ecosystems. Front. Ecol. Evol. 9.
Pallin, L.J., Botero-Acosta, N., Steel, D., Baker, C.S., Casey, C., Costa, D.P., Goldbogen, J. A., Johnston, D.W., Kellar, N.M., Modest, M., Nichols, R., Roberts, D., Roberts, M., Savenko, O., Friedlaender, A.S., 2022. Variation in blubber cortisol levels in a recovering humpback whale population inhabiting a rapidly changing environment. Sci. Rep. 12, 20250. https://doi.org/10.1038/s41598-022-24704-6.
Rochman, C.M., Browne, M.A., Underwood, A.J., Van Franeker, J.A., Thompson, R.C., Amaral-Zettler, L.A., 2016. The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. Ecology 97, 302–312. https://doi.org/10.1890/14-2070.1.
Rota, E., Bergami, E., Corsi, I., Bargagli, R., 2022. Macro- and microplastics in the Antarctic environment: ongoing assessment and perspectives. Environments 9, 93. https://doi.org/10.3390/environments9070093.
Santos, R.G., Machovsky-Capuska, G.E., Andrades, R., 2021. Plastic ingestion as an evolutionary trap: toward a holistic understanding. Science 373, 56–60. https://doi.org/10.1126/science.abh0945.
van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A., Bergmann, M., Chapron, B., Chubarenko, I., Cózar, A., Delandmeter, P., Egger, M., Fox-Kemper, B., Garaba, S.P., Goddijn-Murphy, L., Hardesty, B.D., Hoffman, M.J., Isobe, A., Jongedijk, C.E., Kaandorp, M.L.A., Khatmullina, L., Koelmans, A.A., Kukulka, T., Laufkötter, C., Lebreton, L., Lobelle, D., Maes, C., Martinez-Vicente, V., Maqueda, M.A.M., Poulain-Zarcos, M., Rodríguez, E., Ryan, P.G., Shanks, A.L., Shim, W.J., Suaria, G., Thiel, M., van den Bremer, T.S., Wichmann, D., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett. 15, 023003 https://doi.org/10.1088/1748-9326/ab6d7d.
Suaria, G., Perold, V., Lee, J.R., Lebouard, F., Aliani, S., Ryan, P.G., 2020. Floating macro- and microplastics around the Southern Ocean: results from the Antarctic circumnavigation expedition. Environ. Int. 136, 105494 https://doi.org/10.1016/j.envint.2020.105494.
Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838. https://doi.org/10.1126/science.1094559.
Turner, J., Holmes, C., Caton Harrison, T., Phillips, T., Jena, B., Reeves-Francois, T., Fogt, R., Thomas, E.R., Bajish, C.C., 2022. Record low Antarctic Sea ice cover in February 2022. Geophys. Res. Lett. 49, e2022GL098904 https://doi.org/10.1029/2022GL098904.
Tuuri, E.M., Leterme, S.C., 2023. How plastic debris and associated chemicals impact the marine food web: a review. Environ. Pollut. 321, 121156 https://doi.org/10.1016/j.envpol.2023.121156.
Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495–499. https://doi.org/10.1016/j.envpol.2013.08.013.
Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227. https://doi.org/10.1016/j.scitotenv.2017.03.283.
Waluda, C.M., Staniland, I.J., Dunn, M.J., Thorpe, S.E., Grilly, E., Whitelaw, M., Hughes, K.A., 2020. Thirty years of marine debris in the Southern Ocean: annual surveys of two island shores in the Scotia Sea. Environ. Int. 136, 105460 https://doi.org/10.1016/j.envint.2020.105460.