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Quantifying potential marine debris sources and potential threats to penguins on the West Antarctic Peninsula☆

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ABSTRACT

Marine pollution is becoming ubiquitous in the environment. Observations of pollution on beaches, in the coastal ocean, and in organisms in the Antarctic are becoming distressingly common. Increasing human activity, growing tourism, and an expanding krill fishing industry along the West Antarctic Peninsula all represent potential sources of plastic pollution and other debris (collectively referred to as debris) to the region. However, the sources of these pollutants from point (pollutants released from discrete sources) versus non-point (pollutants from a large area rather than a specific source) sources are poorly understood. We used buoyant simulated particles released in a high-resolution physical ocean model to quantify pollutant loads throughout the region. We considered non-point sources of debris from the Antarctic Circumpolar Current, Bellingshausen Sea, Weddell Sea, and point source pollution from human activities including tourism, research, and fishing. We also determined possible origins for observed debris based on data from the Southern Ocean Observing System and Palmer Long-Term Ecological Research program. Our results indicate that point source pollution released in the coastal Antarctic is more likely to serve as a source for observed debris than non-point sources, and that the dominant source of pollution is region-specific. Penguin colonies in the South Shetland and Elephant Islands had the greatest debris load from point sources whereas loads from non-point sources were greatest around the southernmost colonies. Penguin colonies at Cornwallis Island and Fort Point were exposed to the highest theoretical debris loads. While these results do not include physical processes such as windage and Stokes Drift that are known to impact debris distributions and transport in the coastal ocean, these results provide critical insights to building an effective stratified sampling and monitoring effort to better understand debris distributions, concentrations, and origins throughout the West Antarctic Peninsula.

1. Introduction

Marine pollution has been observed throughout the ocean (Barnes et al., 2010, 2009; Chiba et al., 2018; Coyle et al., 2020; Jambeck et al., 2015; Thompson et al., 2004; Van Cauwenberghe et al., 2013) and comes in many forms, including glass, metal, wood, and paper (Iñiguez et al., 2016). Plastic is the most abundant type of marine debris by far due to its long degradation time (Barnes et al., 2009) and can therefore persist and accumulate in the environment for decades (Katsanevakis, 2008).

Wildlife can be impacted by debris in a variety of ways. Half of seabird and marine mammal species and 100% of sea turtle species have been affected by ingesting debris, mostly plastic items (Kühn et al., 2015). In seabirds, ingestion risk has been linked to foraging behavior and diet (Roman et al., 2019a) and increases the likelihood of mortality (Roman et al., 2019b). Entanglement in items such as fishing gear and lines is commonly observed in seabirds (Costa et al., 2020; Kuepfer and Stanworth, 2023; Ryan, 2018) and is a well-known cause of mortality in whales (Baulch and Perry, 2014). While most documented impacts of debris on marine life come from plastic pollution, it is important to note that non-plastic debris, such as metal, glass, and wood macro and micropollutants can also impact wildlife (Rochman et al., 2016).

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Debris are observed worldwide and observations are increasing in remote locations, such as Antarctica (Barnes et al., 2010; Ivar do Sul et al., 2011; Lacerda et al., 2019; Rota et al., 2022; Waller et al., 2017). Potential sources of debris, however, are poorly understood because most data come from opportunistic observations of beached debris and systematic surveys of debris both on coastlines and in the ocean environment are rare (Convey et al., 2002; Otley and Ingham, 2003; Waller et al., 2017; Waluda et al., 2020). Entanglements have been observed in Antarctic wildlife, including in pinnipeds (Bonner and McCann, 1982; Croxall et al., 1990; Waluda and Staniland, 2013), whales (Pallin et al., 2023), and penguins (Kuepfer and Stanworth, 2023; Otley and Ingham, 2003; Trathan et al., 2015). Therefore, a better understanding of debris sources and movements are a critical first step to understanding the impacts of debris on the Antarctic ecosystem.

Passive Lagrangian particle simulations across the Southern Ocean have previously illustrated that the Antarctic Circumpolar Current (ACC) serves as an important source and transport mechanism for debris observed in the WAP (Lacerda et al., 2019). The Bellingshausen and Weddell Seas may also serve as potential debris sources for the WAP (Lacerda et al., 2019). These regions may serve as critical sources of diffuse, or non-point, pollution, concentrating debris released elsewhere and transporting them to the WAP through the Antarctic Slope Current, the southern boundary of the ACC, and the Antarctic Coastal Current (CC) (Dawson et al., 2023). In addition, human activity from tourism, a growing krill fishing industry, and research bases could serve as major point sources for marine pollution (Convey et al., 2002; Gallagher et al., 2024; Otley and Ingham, 2003). These activities provide many opportunities for debris to go overboard through accidental release or loss of equipment (Ivar do Sul et al., 2011). To mitigate pollution in the Antarctic, we must identify potential sources and pathways for released debris on fine spatial scales.

Here, we use a high-resolution physical ocean model and debris observations to determine possible sources and sinks for buoyant debris along the WAP during the austral summer. We examined four sources for debris: 1) non-point source pollution from the ACC, coastal Bellingshausen Sea, and Weddell Sea; and point source pollution from human activities, including, 2) tourism, 3) krill fishing, and 4) research bases. We used simulated buoyant particles to represent debris and determined theoretical origins for observed debris. We hypothesize that debris observed along the coast of the Peninsula will originate from point sources on the continental shelf. This would suggest that pollution originates from human activity on the WAP and is then advected throughout the coastal region, as opposed to being sourced from activity outside the region accumulated elsewhere.

To quantify the threats this pollution poses to the local ecosystem, we quantified theoretical debris loads near penguin colonies. We hypothesize that theoretical debris loads around colonies from point source pollution will be higher than loads from non-point source pollution. Data supporting these hypotheses would suggest that rather than being influenced primarily by debris released in other ocean systems, human activities along the Peninsula pose the greatest pollution threat to the local ecosystems.

2. Methods

2.1. Regional Ocean Modeling System

We used the Regional Ocean Modeling System (ROMS) physical ocean model for our analysis. The extent of the model is illustrated in Fig. 1. This iteration of ROMS for the WAP is described in Graham et al. (2016) and Hudson et al. (2021), and has been used to quantify the role of wind in water mass transport (Dinniman et al., 2012), describe krill movement and retention (Gallagher et al., 2023; Hudson et al., 2022), and predict how pinniped habitats will change under future climate conditions (Hückstädt et al., 2020). Briefly, the model has a 1.5 km horizontal resolution and 24 terrain-following vertical layers. At this resolution, the model can resolve mesoscale eddies on the continental shelf (Graham et al., 2016). ROMS is externally forced by atmospheric forcing from the Antarctic Mesoscale Prediction System (AMPS; Powers et al., 2012) and tidal forcing from CATS2008 (Padman et al., 2002). Dynamic sea ice and interactions between floating ice shelves and the underlying waters are included (Budgell, 2005; Holland and Jenkins, 1999). The boundaries of the model are open following Dinniman and Klinck (2004) and Dinniman et al. (2012) and temperature and salinity on these boundaries are controlled by monthly mean climatologies (Graham et al., 2016).

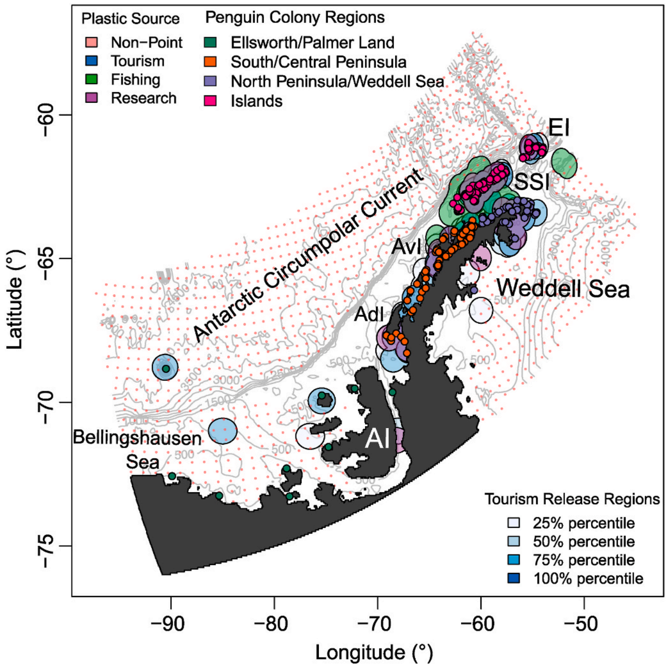

Fig. 1. Map of model domain including penguin colonies from the Mapping Application for Penguin Populations and Projected Dynamics (Che-Castaldo et al., 2023), and particle release regions for non-point, tourism, fishing, and research sources. Particle release densities for tourism sites are included in Table 1. Fishing and research locations used the 100% and 50% release densities, respectively. Major islands and regions of the model domain are highlighted and include: Alexander Island (AI), Adelaide Island (AdI), Anvers Island (AvI), South Shetlands Islands (SSI), and Elephant Island (EI).

We simulated four austral summers (November–March): 2008–2009, 2009–2010, 2018–2019, and 2019–2020. Henceforth, we refer to each austral summer as a season, using the first year of the season to denote each year's simulation. We applied a nodal correction to tidal forcing files to account for different years. The spatial resolution of the AMPS forcing used here was 15–20 km in the 2008 and 2009 seasons and 8 km for the 2018 and 2019 seasons because AMPS resolution improved over time. The model was initialized from initial temperature and salinity conditions and zero velocity and run for a seven year spin up period covering March 2006 through December 2012 (Graham et al., 2016). The final conditions from this simulation were used to initialize the 2008 and 2018 season runs. These runs were extended to the following October to generate the initialization files for the following season.

2.2. Modeling debris

2.2.1. Simulated debris

We modeled buoyant debris, henceforth referred to as simulated debris, using passive Lagrangian floats that are updated at every model time step (50 s) within the ROMS code. We programmed floats to stay in the surface layer, which varied in thickness due to the terrain-following layers. We did not include vertical advective or parameterized turbulent motions. Simulated debris that were advected under an ice shelf were excluded from analysis. We chose to simulate buoyant debris in this study, which for the most part are macrodebris, like water bottles and buoys, since the depth distribution of pollutants in the Antarctic (and elsewhere) is poorly understood.

2.2.2. *Debris release patterns*

Simulated debris were released in four patterns (Fig. 1). In the first pattern, simulated debris were released at 40 km resolution (Fig. 1) and are meant to represent debris that were released from other sectors of the Southern Ocean and transported to the WAP via the ACC, Bellingshausen Sea, or Weddell Seas (Fig. 1). We refer to these as non-point source debris.

The second release pattern represented point source pollution from tourism in the region. We used visitation data for sites by activity for the 2021/2022 field season, which is believed to represent pre-COVID19 pandemic visitation numbers ("Visitor Statistics Downloads," 2023). We considered 208 visited sites within the model domain. Simulated debris were released within 50 km of identified sites at four different densities (Table 1), based on the number of visitors, following methods by Yu et al. (2018). When the 50 km buffer zones around tourist sites overlapped, we released more simulated debris (Fig. 1).

The third and fourth release schemes represented pollution from krill fishing and research bases, respectively. Krill fishing locations from Aker Biomarine, one of the largest krill fishing fleets, between 2004 and 2017 were used. Research station and camp location data from the Council of Managers of National Antarctic Programs (COMNAP; COMNAP Antarctic Facilities data version 3.4.0) were used to represent research bases. We released simulated debris within 50 km of krill fishing locations and research bases (Fig. 1). Simulated debris were released around fishing locations at the same density as the highest tourism percentile (100%; Table 1). We chose to release simulated debris around fishing areas at the same density as in tourism regions due to the high likelihood of objects, such as buoys or nets, being accidently released due to the amount of time they spend in the water. We released particles at the 50 % tourism percentile around research bases (Table 1). We chose a smaller particle release density around research bases due to the increased number of pollution mitigation strategies employed at these locations.

2.2.3. *Debris release protocols*

Simulated debris were released every 2 days from November 1 to the end of February, for a total of 60 releases over 120 days. A total of 1030 non-point source particles were released per event for a total of 61,800 non-point source simulated debris released. A total of 2,025, 1,434, and 561 particles were released per event within tourist, fishing, and research regions, respectively, for a total of 121,500, 86,040, and 33,660 particles released within each area. This high frequency seeding was used to represent potentially high inputs from non-point sources and the near constant cruise ship, fishing vessel, and research presence along the Peninsula during the austral summer. While the most fishing (based on number of trawls) occurs in the austral autumn and winter (Meyer et al., 2020), we simulated the austral summer to examine the potential effects of marine pollution in this region when both human and biological activity are highest. Simulations were run through March such that simulated debris were tracked for at least 30 days.

Table 1
Breakdown of visitation numbers, corresponding horizontal distance between release points, and the number of simulated debris released in buffer areas. The number of visitors were separated into four groups in 25% increments. The number of simulated debris released in each buffer region presented here assumes no overlap with other visitation percentiles and none of the points are on land.

Visitation Percentile	Number of Visitors in 2022/23 Season	Horizontal Distance between Release Points (km)	Number of Simulated Debris Released in Buffer Region
100%	>1213	8	132
75%	383–1212	10	84
50%	113–382	12	59
25%	<112	14	42

2.2.4. *Model limitations*

This iteration of ROMS does not include all physical processes that are known to influence the distributions of buoyant debris. These include Stokes drift and windage, or direct wind transport. Stokes drift is the movement of a buoyant particle in the direction of wave propagation (Stokes, 1847) and windage is the impact of wind on buoyant particles that have an area protruding out of the water. These processes have been shown to influence the distributions of buoyant debris on multiple spatial scales (Lacerda et al., 2019; van Sebille et al., 2020) While Stokes drift has been integrated into previous modeling studies (Lacerda et al., 2019), this iteration of ROMS does not include a wave model. A wave model for this area would need to include interactions with sea ice which have been modeled (Li et al., 2021). These processes, however, have not been modeled with mesoscale eddying over the continental shelf which is included in our simulations, currently poorly predict ice concentrations in the austral summer (Li et al., 2021), at least as currently implemented in ROMS. This is still an area of active research and more work is necessary before we can link an accurate wave model to ROMS to model the effect of Stokes drift.

The Lagrangian drifter code within ROMS does not include direct wind drag for items sticking above the sea surface, therefore, we could not account for windage. Several previously published simulations of buoyant debris did not add any additional wind stress terms to the motion of their particles beyond the wind stress added to the surface ocean (Eriksen et al., 2014; Lebreton et al., 2012), assuming that debris are mostly submerged below the surface. We used this assumption to help account for the lack of windage in our simulations. Since we did not account for windage and Stokes drift, we chose to extend the search radius for our calculated metrics (see Section 2.5) beyond the 1.5 km horizontal scale of the model. By doing so, we attempt to account for some of the stochasticity that these processes produce that is not represented here.

2.3. *Observed debris*

We used the Southern Ocean Observing System (SOOS) database SOOSMap (http://www.soosmap.aq/) to identify debris observations within the ROMS domain. Most of these observations come from opportunistic observations of marine debris along Antarctic coastlines. The Palmer Long-Term Ecological Research (LTER) provided the locations and descriptions of marine debris collected opportunistically during routine seabird surveys. Debris observed in this region are described in Gallagher et al. (2024). While SOOSMap included debris concentrations, a variety of units were used, and the LTER team only noted the location, general size, and type of debris observed. Therefore, to accommodate the heterogeneity of the available data, we only used the location information for all observations, regardless of debris size.

2.4. *Penguin colonies*

To determine which penguin colonies could be exposed to high theoretical debris loads, we identified penguin colonies within one model grid cell of the modeled coastline. We used colony locations from the Mapping Application for Penguin Population and Projected Dynamics (MAPPPD; Che-Castaldo et al., 2023). We considered 288 unique colonies, which consisted of 77 Adélie, 207 chinstrap, 61 gentoo, and 7 emperor penguin colonies. Some colonies contained multiple species.

2.5. Calculated metrics and analyses

2.5.1. Metrics

We calculated two metrics: 1) simulated debris load and 2) number of debris pathways. Simulated debris loads were calculated as the number of simulated debris that entered a region during the simulation. This metric was calculated across the model domain on a 100 km^2 (10 × 10 km) grid and adjacent to penguin colonies, where we used a 6 km (4 grid cell) radius around penguin colony locations. We counted a simulated debris if it entered these regions at any point in their lifetime, which ranged from 30 days to 5 months.

We used simulated debris pathways as proxies for potential pathways of observed debris. A simulated debris track was considered a potential pathway if the simulated debris came within 6 km of an observed debris item during its lifetime, using the R function *point.in.polygon* from the *sp* package (Bivand et al., 2013). Pathways were used to determine the debris' potential origin. Origins were used to construct 95 % kernel densities to illustrate their spatial distributions. Kernels were produced using the *kernelUD* and *getverticeshr* functions in the *adehabitatHR* package in R (Calenge and Fortmann-Roe, 2023).

It is important to note that the true distributions of debris from each of the sources considered here is unknown. This is partially because the distributions of marine debris along the Peninsula is poorly studied, and partially because it is difficult to discern the origins of observed marine debris in the environment. Therefore, these metrics should be considered potential debris loads or potential origins. While imperfect, these are important first steps to understanding the debris loads and origins of marine debris in this remote environment.

2.5.2. Statistical analyses

To account for the different number of simulated debris released from non-point and point sources, all metrics were normalized by subtracting the log-transformed mean from the value and dividing this difference by the standard deviation of the debris source (non-point, tourism, fishing, or research). Data were independently normalized for each source (non-point source metrics normalized to the non-point mean & standard deviation) and are presented such that +1 is equal to 1 standard deviation above the average. We used Kruskal-Wallis tests to compare metrics within and across groups, and Dunn post-hoc tests with Bonferroni corrections as appropriate using the *dunn.test* package in R (Dinno, 2017). The package *multcompView* was used to produce the letters that visualize statistically different pairwise comparisons (Graves et al., 2023).

3. Results

3.1. Debris on the Peninsula

3.1.1. Debris load

Simulated debris from non-point sources were advected throughout the WAP (Fig. 2a). Simulated debris from tourism areas were advected throughout the WAP but those that were released in coastal regions remained confined to the continental shelf (Fig. 2b). The highest concentrations of simulated debris from tourism areas were found in and around the South Shetland and Elephant Islands (Fig. 2b). Simulated debris released around fishing and research areas were concentrated on the continental shelf (Fig. 2c–d) and those released within fishing regions were advected as far south as Adelaide and Alexander Islands and as far north as the Weddell Sea (Fig. 2c). Simulated debris released around research stations were advected farther south, reaching past Alexander Island, and farther into the Weddell Sea to the north and east (Fig. 2d).

3.1.2. Origins of observed debris

Debris observations within SOOSMap were found primarily in coastal regions, and a total of 40 debris observations in SOOSMap were within the model domain (Fig. 3). There were 56 additional debris locations recorded within the Palmer LTER region. We found potential origins for 84 out of 96 observed debris.

Debris found in the North WAP originated from around the tip of the Peninsula (Fig. 3a). The number of potential debris origins from tourism sources was greater than the number of potential origins from non-point sources in the North WAP (Fig. S1). However, the number of potential origins from research and fishing did not differ from non-point sources

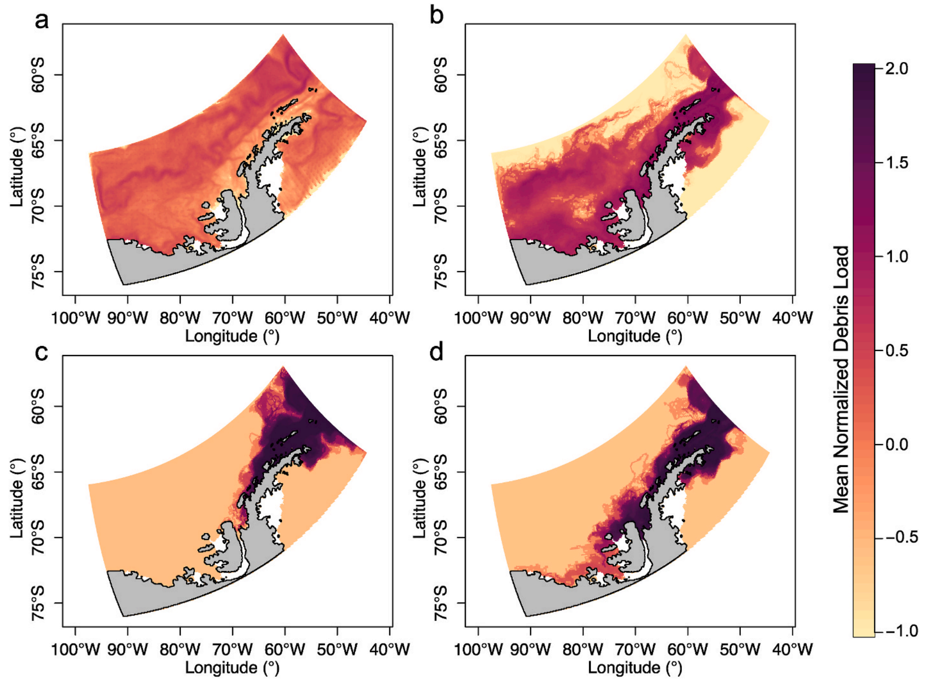

Fig. 2. Mean normalized debris load observed within a 100 km^2 (10 × 10 km) grid for simulated debris released from (a) non-point, (b) tourism, (c) fishing, and (d) research sources.

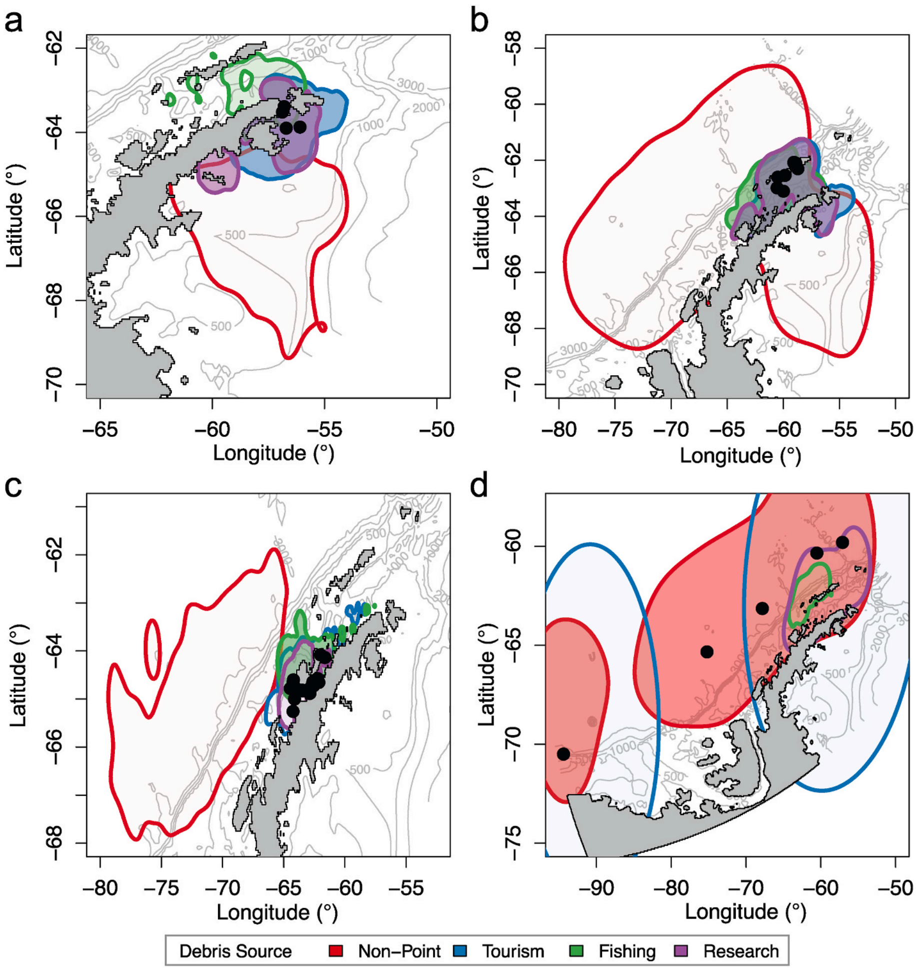

Fig. 3. Maps of observed debris (black points) in the (a) North WAP, (b) South Shetland Islands, (c) Central WAP, and (d) off the continental shelf. Colored shapes illustrate the 95% kernel density estimates of potential origins for observed debris from the four source types considered. More opaque shapes indicate that the median number of normalized potential origins was greater for that debris source within the region, while more transparent shapes indicate a lower median number of origins.

of pollution (Fig. S1) despite having different spatial extents (Fig. 3a).

In the South Shetland Islands, simulated debris from fishing areas provided more potential origins for debris in comparison to non-point sources, but all other comparisons were insignificant (Fig. 3b, Fig. S1). There were no differences in the number of potential origins from the sources considered for debris observed in the Central WAP (Fig. S1). The spatial extent of origins across point sources was similar (Fig. 3c). For non-point sources, potential origins were concentrated off the nearby continental shelf (Fig. 3c). Debris off the continental shelf had the most origins from non-point sources (Fig. 3d) and this was significantly greater than both tourism and research sources (Fig. S1).

The number of potential origins for all point sources was significantly greater in the Central WAP than the number of origins found for debris observed offshore (Fig. S1). The number of origins found for non-point simulated debris was significantly higher for observed offshore debris than the number of origins found for debris observed in the North WAP from non-point sources (Fig. S1).

3.2. Debris near penguin colonies

Theoretical debris loads near penguin colonies only differed within regions in the North WAP and in Ellsworth/Palmer Land (Fig. 4). In the North WAP, debris loads from fishing were significantly higher than those from research (Fig. 4). No other comparisons differed (Fig. 4). In Ellsworth/Palmer Land, debris loads from fishing were significantly lower than those from non-point or tourism sources (Fig. 4). Debris loads from research stations did not differ (Fig. 4).

Within debris types, however, there were significant differences. Predicted debris loads from point sources (tourism, fishing, and research) were greatest in the South Shetland and Elephant Islands, followed by the North WAP, Central WAP, and were the smallest in Ellsworth/Palmer Land (Fig. 4). Predicted debris loads from non-point sources were the greatest in Ellsworth/Palmer Land, which differed significantly from both the North WAP and Island regions (Fig. 4).

These patterns were echoed in the colonies exposed to the highest theoretical debris loads. Cornwallis Island and Fort Point, located on Elephant Island and the South Shetland Islands, respectively, had the highest debris loads from all point sources (Fig. 5, Table S1). While colonies in Ellsworth/Palmer Land, such as Peter I Island, Sims Island, and Jason Peninsula, had the lowest theoretical debris loads from point sources, other colonies in this region (e.g., Pfrogner Point, Bryan Coast, and Smyley) had the highest debris loads from non-point sources (Fig. 5, Table S1). The mean number of simulated debris at all 288 penguin colonies considered here across all 4 sources is included in Supplementary Data and a description of this file is included in Supplementary Text 1.

4. Discussion

Marine pollution is found throughout the world and Antarctica is no

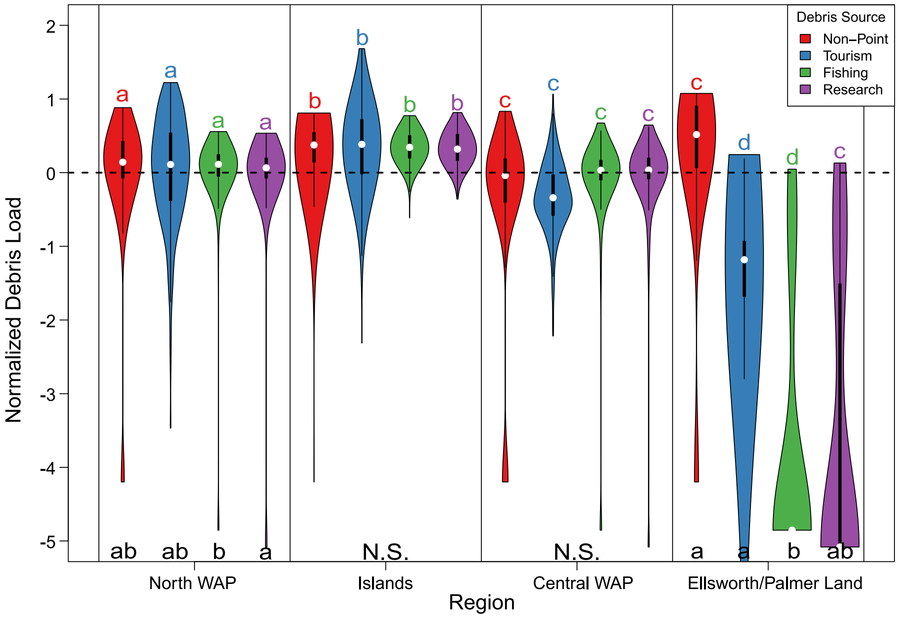

Fig. 4. Distributions of normalized debris loads around penguin colonies along the West Antarctic Peninsula across different regions. Black letters indicate significant differences as indicated by a Kruskal-Wallis test and Dunn test with Bonferroni correction within regions. Non-significant differences are indicated with N.S. Colored letters indicate significant differences indicated by the same tests within debris sources across regions.

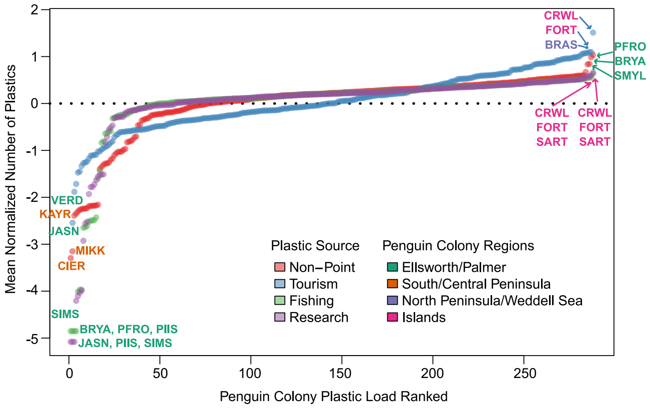

Fig. 5. Mean normalized number of theoretical debris that were advected near penguin colonies from non-point, tourism, fishing, and research sources ordered from fewest number of debris to greatest number of debris. Named colonies represent the 3 colonies that were identified as the colonies at the greatest and least risk for high debris loads for each debris source. Colony abbreviations are defined in Table S1.

longer the exception. Therefore, understanding the origins and potential sources of these debris is critical to protect this region and its inhabitants. Our results demonstrate that pollution from human activities, such as fishing and tourism (Almela and González Herrero, 2020; Waluda et al., 2020), pose a potential threat throughout the WAP.

4.1. Debris origins and pathways on the WAP

We hypothesized that point source pollution from human activities would provide the most debris to the WAP continental shelf. Our results illustrated that debris from point sources provided more potential origins than non-point sources for the observed debris in some regions of the Peninsula, supporting this hypothesis. While tourism and fishing provided significantly more potential pathways for observed debris in comparison to non-point sources in the North Peninsula and Islands regions, respectively, these were the only comparisons within these regions that differed. Therefore, it is difficult to discern how the number of potential origins differed across point sources. This is a common problem in debris monitoring since many debris items have ambiguous origins (water bottles, lines) and it can be difficult to discern exact sources.

Overall, modeled debris from human activity remained on the continental shelf and provided high relative debris loads to the coastal WAP. While some simulated debris from non-point sources were advected onto the continental shelf via the ACC, as suggested by a previous study (Lacerda et al., 2019), the southern boundary of the ACC served as a barrier that prevented most debris from moving onto and accumulating on the continental shelf. However, in addition to wind-induced currents, the canyons and troughs that are known to advect water onto the continental shelf from the ACC served as transport mechanisms for buoyant debris to move onto the continental shelf, especially in the central WAP (Moffat and Meredith, 2018). The CC from the Weddell Sea (Moffat and Meredith, 2018) provided a small number of debris from non-point sources to the northern portions of the WAP.

Unfortunately, these persistent current features also serve as the primary barriers to prevent point source pollutants from exiting the region. From the South Shetland and Elephant Islands to the central WAP, the southern boundary of the ACC strongly limited debris from moving off the continental shelf in our simulation. Similarly, the CC and associated current structures kept debris around the tip of the Peninsula and prevented advection into the Weddell Sea. While previous studies have illustrated that export off the continental shelf in the north Peninsula is possible (Brearley et al., 2019; Castelao et al., 2021; Dawson et al., 2023), our results suggest that observed debris found off the continental shelf most likely originated from the ACC, with non-point sources providing significantly more potential pathways than simulated debris from research areas. Few potential pathways from the continental shelf to points offshore were found. These pathways, both on and off the continental shelf, follow previously defined current pathways on the WAP (Moffat and Meredith, 2018).

4.2. Potential impacts on penguins

We hypothesized that more theoretical debris from point sources would be present around penguin colonies than from non-point sources. This hypothesis was not supported by our results. Relative debris loads from point sources in our simulation did not differ significantly in comparison to non-point sources around penguin colonies throughout the Peninsula.

Debris loads across regions of the Peninsula from different sources, however, did statistically differ, partially supporting our hypothesis. Loads from non-point sources near penguin colonies were greatest in the Ellsworth/Palmer Land regions, whereas loads from all other point sources (tourism, fishing, and research) were highest near colonies in the South Shetland and Elephant Islands. Currents south of this region generally move toward the South Shetland Islands via the Gerlache Strait and northward currents around Low Island, while currents from points to the east move water towards and around these islands (Gallagher et al., 2023; Moffat and Meredith, 2018; Wang et al., 2022). Therefore, debris pollution could easily be concentrated within this region from points south and east. Previous unpublished observations have also frequently observed marine debris around colonies in this region (M. Wethington, personal communication), supporting these results.

The buoyant debris modeled here are more likely to be items like bottles and buoys (Gallagher et al., 2024), which are too large for penguins to ingest until they are broken down to smaller sizes but pose immediate concerns for the entanglement of adults and chicks in the nest. Gentoo chicks have been observed entangled in marine debris in the Falkland Islands and South Georgia (Kuepfer and Stanworth, 2023), which has led to mortality (Otley and Ingham, 2003), and some of these entanglements have been directly linked to fishing (Otley and Ingham, 2003; Trathan et al., 2015). We (HJL) regularly observe plastic debris in penguin nests, including one observation of a chinstrap penguin incubating a 20 oz. plastic soda bottle in the South Shetland Islands. The macroscopic debris modeled thus serves as a source for less-readily observable microplastics and pose direct hazards for penguins; our results suggest that penguins in the South Shetland and Elephant Islands, where fishing activities and the predicted debris loads are greatest, may be at high risk for such impacts.

4.3. Future directions

4.3.1. Study improvements

This study is a critical first step to quantifying the threats of marine debris to the Antarctic ecosystem on broad spatial scales. However, these first attempts at modeling buoyant debris along the WAP are imperfect. We did not model Stokes Drift or windage, two processes that have been shown to impact the distribution of buoyant debris on multiple spatial scales (Lacerda et al., 2019; van Sebille et al., 2020). Therefore, critical next steps to improve on this study would include 1) incorporating a wave model into this iteration of ROMS, and 2) modeling debris pathways as a function of wind speed and direction, as done by previous studies such as Maximenko et al. (2018) to quantify the contribution of wind and wind drag in marine debris accumulation along coasts.

In addition, more information on the distribution of marine debris along the WAP will help improve future simulations. Systematic surveys for debris on beaches and in the coastal ocean are rare in this region (Convey et al., 2002; Waluda et al., 2020). Data from systematic surveys that report absences would allow for more realistic particle release schemes and would improve the validity of our results.

4.3.2. Future monitoring efforts

The distribution of marine debris throughout the WAP and the surrounding coastal ocean is poorly understood. To address this critical gap, systematic beach surveys should be conducted at penguin colonies with high and low predicted debris loads to confirm our results and opportunistically elsewhere on the WAP. We have identified two high threat colonies (Cornwallis Island and Fort Point) and several low threat colonies (e.g., Bryan Coast, Sims Island, Jason Peninsula) that would be good candidates for these surveys.

Conducting surveys at tourist and non-tourist destinations could help determine if visited sites have more debris accumulation. At each location, surveys should be conducted on the leeward and windward side of the coastal region, as winds often influence debris accumulation (MAC, personal observation). Surveys should be conducted at least annually, and for frequently visited sites, multiple surveys across the austral summer would be informative. Extra care should be taken to properly document and identify features (e.g., writing) and describe items reported using standardized categories to help identify debris (e.g. NOAA Marine Debris Monitoring and Assessment Project Categorization Guide: https://marinedebris.noaa.gov/resources/mdmap-protocol-documents-and-field-datasheets).

Long term monitoring and identifying sources of marine pollution are priorities of groups in Antarctica and beyond, such as the Scientific Committee for Antarctic Research, the United Nations Decade of Ocean Science, and working groups within the Scientific Commission on Oceanic Research. Therefore, establishing monitoring programs, and using the data to inform debris pollution mitigation projects and activities, such as improved modeling efforts, should be of high priority for the scientific community to protect Antarctica's coastlines and ecosystems.

5. Conclusions

Here, we present an initial effort to quantify potential marine debris loads along the WAP using a physical ocean model. While we are not able to account for all processes that may impact the transport of marine debris, we illustrate that debris on the continental shelf from known human activities (tourism, research, and fishing) is more likely to remain along the coast, instead of being exported to other regions of the Southern Ocean. Debris observed along the coast likely came from these point sources, rather than diffuse pollution concentrated by the ACC. We determined that penguin colonies in the South Shetland and Elephant Islands may experience the greatest debris loads, due to currents concentrating buoyant debris in this region. We use these results to propose a debris sampling protocol that would help not only confirm these results and further understand which activities are sources of debris in the WAP, but would provide the necessary data to improve future studies of marine debris transport in the Antarctic.

CRediT authorship contribution statement

Katherine L. Gallagher: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Megan A. Cimino:** Writing – review & editing, Methodology, Funding acquisition, Data curation. **Michael S. Dinniman:** Writing – review & editing, Software. **Heather J. Lynch:** Writing – review & editing, Funding acquisition, Conceptualization.

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 the links in the Data Availability Statement

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Appendix A. Supplementary data

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References

Almela, P., González Herrero, S., 2020. Are Antarctic Specially Protected Areas Safe from Plastic Pollution? a Survey of Plastic Litter at Byers Peninsula. Livingston Island, Antarctica.

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.

Bivand, R.S., Pebesma, E., Gomez-Rubio, V., 2013. Applied Spatial Data Analysis with R, second ed. Springer, NY.

Bonner, W.N., McCann, T.S., 1982. Neck collars on Fur seals, Arctocephalus gazelle, at South Georgia. Br. Antarct. Surv. Bull. 57, 73–77.

Brearley, J.A., Moffat, C., Venables, H.J., Meredith, M.P., Dinniman, M.S., 2019. The role of eddies and topography in the export of shelf waters from the West Antarctic Peninsula shelf. J. Geophys. Res. Oceans 124, 7718–7742. https://doi.org/10.1029/2018JC014679.

Budgell, W.P., 2005. Numerical simulation of ice-ocean variability in the Barents Sea region: towards dynamical downscaling. Ocean Dynam. 55, 370–387. https://doi.org/10.1007/s10236-005-0008-3.

Calenge, C., Fortmann-Roe, cfS., 2023. Home Range Estimation.

Castelao, R.M., Dinniman, M.S., Amos, C.M., Klinck, J.M., Medeiros, P.M., 2021. Eddy-driven transport of particulate organic carbon-rich coastal water off the West Antarctic Peninsula. J. Geophys. Res. Oceans 126, e2020JC016791. https://doi.org/10.1029/2020JC016791.

Che-Castaldo, C., Humphries, G., Lynch, H., 2023. Antarctic Penguin Biogeography Project: database of abundance and distribution for the Adélie, chinstrap, gentoo, emperor, macaroni and king penguin south of 60 S. Biodivers. Data J. 11, e101476 https://doi.org/10.3897/BDJ.11.e101476.

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. Pol. 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.

Costa, R.A., Sá, S., Pereira, A.T., Ângelo, A.R., Vaqueiro, J., Ferreira, M., Eira, C., 2020. Prevalence of entanglements of seabirds in marine debris in the central Portuguese coast. Mar. Pollut. Bull. 161, 111746 https://doi.org/10.1016/j.marpolbul.2020.111746.

Coyle, R., Hardiman, G., Driscoll, K.O., 2020. Microplastics in the marine environment: a review of their sources, distribution processes, uptake and exchange in ecosystems. Case Stud. Chem. Environ. Eng. 2, 100010 https://doi.org/10.1016/j.cscee.2020.100010.

Croxall, J.P., Rodwell, S., Boyd, I.L., 1990. Entanglement in man-made debris of Antarctic Fur seals at Bird Island, South Georgia. Mar. Mamm. 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.

Dinniman, M.S., Klinck, J.M., 2004. A model study of circulation and cross-shelf exchange on the west Antarctic Peninsula continental shelf. Deep Sea Res. Part II Top. Stud. Oceanogr. 51, 2003–2022. https://doi.org/10.1016/j.dsr2.2004.07.030.

Dinniman, M.S., Klinck, J.M., Hofmann, E.E., 2012. Sensitivity of circumpolar deep water transport and ice shelf basal melt along the West Antarctic Peninsula to changes in the winds. J. Clim. 25, 4799–4816. https://doi.org/10.1175/JCLI-D-11-00307.1.

Dinno, A., 2017. dunn.test: Dunn's Test of Multiple Comparisons Using Rank Sums.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9, e111913. https://doi.org/10.1371/journal.pone.0111913.

Gallagher, K.L., Dinniman, M.S., Lynch, H.J., 2023. Quantifying Antarctic krill connectivity across the West Antarctic Peninsula and its role in large-scale Pygoscelis penguin population dynamics. Sci. Rep. 13, 12072 https://doi.org/10.1038/s41598-023-39105-6.

Gallagher, K.L., Selig, G.M., Cimino, M.A., 2024. Descriptions and patterns in opportunistic marine debris collected near Palmer Station, Antarctica. Mar. Pollut. Bull. 199, 115952 https://doi.org/10.1016/j.marpolbul.2023.115952.

Graham, J.A., Dinniman, M.S., Klinck, J.M., 2016. Impact of model resolution for on-shelf heat transport along the West Antarctic Peninsula. J. Geophys. Res. Oceans 121, 7880–7897. https://doi.org/10.1002/2016JC011875.

Graves, S., Peipho, H., Selzer, L., Doraj-Raj, S., 2023. multcompView: Visualizations of Paired Comparisons.

Holland, D.M., Jenkins, A., 1999. Modeling thermodynamic ice–ocean interactions at the base of an ice shelf. J. Phys. Oceanogr. 29, 15.

Hückstädt, L.A., Piñones, A., Palacios, D.M., McDonald, B.I., Dinniman, M.S., Hofmann, E.E., Burns, J.M., Crocker, D.E., Costa, D.P., 2020. Projected shifts in the foraging habitat of crabeater seals along the Antarctic Peninsula. Nat. Clim. Change 10, 472–477. https://doi.org/10.1038/s41558-020-0745-9.

Hudson, K., Oliver, M.J., Kohut, J., Cohen, J.H., Dinniman, M.S., Klinck, J.M., Reiss, C.S., Cutter, G.R., Statscewich, H., Bernard, K.S., Fraser, W., 2022. Subsurface eddy facilitates retention of simulated diel vertical migrators in a biological hotspot. J. Geophys. Res. Oceans 127. https://doi.org/10.1029/2021JC017482.

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.

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.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771. https://doi.org/10.1126/science.1260352.

Katsanevakis, S., 2008. Marine debris, a growing problem: sources, distribution, composition, and impacts. In: Marine Pollution: New Research. Nova Science Publishers, New York, pp. 53–100.

Kuepfer, A., Stanworth, A., 2023. Falkland Islands Seabird Monitoring Programme - Annual Report 2022/2023 (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.

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.

Lebreton, L.C.-M., Greer, S.D., Borrero, J.C., 2012. Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull. 64, 653–661. https://doi.org/10.1016/j.marpolbul.2011.10.027.

Li, J., Babanin, A.V., Liu, Q., Voermans, J.J., Heil, P., Tang, Y., 2021. Effects of wave-induced sea ice break-up and mixing in a high-resolution coupled ice-ocean model. J. Mar. Sci. Eng. 9, 365. https://doi.org/10.3390/jmse9040365.

Maximenko, N., Hafner, J., Kamachi, M., MacFadyen, A., 2018. Numerical simulations of debris drift from the Great Japan Tsunami of 2011 and their verification with observational reports. Mar. Pollut. Bull., SI: Jpn Tsunami Debris 132, 5–25. https://doi.org/10.1016/j.marpolbul.2018.03.056.

Meyer, B., Atkinson, A., Bernard, K.S., Brierley, A.S., Driscoll, R., Hill, S.L., Marschoff, E., Maschette, D., Perry, F.A., Reiss, C.S., Rombolá, E., Tarling, G.A., Thorpe, S.E., Trathan, P.N., Zhu, G., Kawaguchi, S., 2020. Successful ecosystem-based management of Antarctic krill should address uncertainties in krill recruitment, behaviour and ecological adaptation. Commun. Earth Environ. 1, 1–12. https://doi.org/10.1038/s43247-020-00026-1.

Moffat, C., Meredith, M., 2018. Shelf–ocean exchange and hydrography west of the Antarctic Peninsula: a review. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 376, 20170164 https://doi.org/10.1098/rsta.2017.0164.

Otley, H., Ingham, R., 2003. Marine debris surveys at Volunteer Beach, Falkland Islands, during the summer of 2001/02. Mar. Pollut. Bull. 46, 1534–1539. https://doi.org/10.1016/S0025-326X(03)00314-X.

Padman, L., Fricker, H.A., Coleman, R., Howard, S., Erofeeva, L., 2002. A new tide model for the Antarctic ice shelves and seas. Ann. Glaciol. 34, 247–254. https://doi.org/10.3189/172756402781817752.

Pallin, L.J., Kellar, N.M., Steel, D., Botero-Acosta, N., Baker, C.S., Conroy, J.A., Costa, D.P., Johnson, C.M., Johnston, D.W., Nichols, R.C., Nowacek, D.P., Read, A.J., Savenko, O., Schofield, O.M., Stammerjohn, S.E., Steinberg, D.K., Friedlaender, A.S., 2023. A surplus no more? Variation in krill availability impacts reproductive rates of Antarctic baleen whales. Global Change Biol. 29, 2108–2121. https://doi.org/10.1111/gcb.16559.

Powers, J.G., Manning, K.W., Bromwich, D.H., Cassano, J.J., Cayette, A.M., 2012. A decade of Antarctic science support through AMPS. Bull. Am. Meteorol. Soc. 93, 1699–1712.

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.

Roman, L., Bell, E., Wilcox, C., Hardesty, B.D., Hindell, M., 2019a. Ecological drivers of marine debris ingestion in Procellariiform Seabirds. Sci. Rep. 9, 916. https://doi.org/10.1038/s41598-018-37324-w.

Roman, L., Hardesty, B.D., Hindell, M.A., Wilcox, C., 2019b. A quantitative analysis linking seabird mortality and marine debris ingestion. Sci. Rep. 9, 3202. https://doi.org/10.1038/s41598-018-36585-9.

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.

Ryan, P.G., 2018. Entanglement of birds in plastics and other synthetic materials. Mar. Pollut. Bull. 135, 159–164. https://doi.org/10.1016/j.marpolbul.2018.06.057.

Stokes, G.G., 1847. On the theory of oscillatory waves. Rep. Br. Assoc. VI.

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.

Trathan, P.N., García-Borboroglu, P., Boersma, D., Bost, C.-A., Crawford, R.J.M., Crossin, G.T., Cuthbert, R.J., Dann, P., Davis, L.S., De La Puente, S., Ellenberg, U., Lynch, H.J., Mattern, T., Pütz, K., Seddon, P.J., Trivelpiece, W., Wienecke, B., 2015. Pollution, habitat loss, fishing, and climate change as critical threats to penguins. Conserv. Biol. 29, 31–41. https://doi.org/10.1111/cobi.12349.

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.

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.

Visitor Statistics Downloads [WWW Document], 2023. IAATO. URL. https://iaato.org/information-resources/data-statistics/visitor-statistics/visitor-statistics-downloads/. (Accessed 13 June 2023).

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., 2013. Entanglement of Antarctic Fur seals at Bird Island, South Georgia. Mar. Pollut. Bull. 74, 244–252. https://doi.org/10.1016/j.marpolbul.2013.06.050.

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.

Wang, X., Moffat, C., Dinniman, M.S., Klinck, J.M., Sutherland, D., Aguiar-González, B., 2022. Variability and dynamics of along-shore exchange on the West Antarctic Peninsula (WAP) continental shelf. J. Geophys. Res. Oceans. https://doi.org/10.1029/2021JC017645.

Yu, X., Ladewig, S., Bao, S., Toline, C.A., Whitmire, S., Chow, A.T., 2018. Occurrence and distribution of microplastics at selected coastal sites along the southeastern United States. Sci. Total Environ. 613–614, 298–305. https://doi.org/10.1016/j.scitotenv.2017.09.100.