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Microplastics in Southern Ocean sea ice: a pan-Antarctic perspective

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Abstract

Microplastic (MP; plastic particles < 5 mm) pollution is pervasive in the marine environment, including remote polar environments. This study provides the first pan-Antarctic survey of MP pollution in Southern Ocean sea ice by analyzing sea ice cores from several diverse Antarctic regions. Abundance, chemical composition, and particle size data were obtained from 19 archived ice core samples. The cores were melted, filtered, and chemically analyzed using Fourier-transform infrared spectroscopy and 4,090 MP particles were identified. Nineteen polymer types were found across all samples, with an average concentration of 44.8 (± 50.9) particles·L^{-1}. Abundance and composition varied with ice type and geographical location. Pack ice exhibited significantly higher particle concentrations than landfast ice, suggesting open ocean sources of pollution. Winter sea ice cores had significantly more MPs than spring and summer-drilled cores, suggesting ice formation processes play a role in particle incorporation. Smaller particles dominated across samples. Polyethylene (PE) and polypropylene (PP) were the most common polymers, mirroring those most identified across marine habitats. Higher average MP concentrations in developing sea ice during autumn and winter, contrasting lower levels observed in spring and summer, suggest turbulent conditions and faster growth rates are likely responsible for the increased incorporation of particles. Southern Ocean MP contamination likely stems from both local and distant sources. However, the circulation of deep waters and long-range transport likely contribute to the accumulation of MPs in regional gyres, coastlines, and their eventual incorporation into sea ice. Additionally, seasonal sea ice variations likely influence regional polymer compositions, reflecting the MP composition of the underlying waters.

Keywords: Microplastic, marine debris, sea ice, plastic pollution, Antarctica, Southern Ocean

INTRODUCTION

Despite the ubiquity of microplastics (MPs; plastic particles < 5 mm) in the global oceans and their noted presence within remote polar regions, the majority of polar reports have come from the Arctic Ocean, where significant levels of MPs have been recorded in surface waters[1], snow[2], and sea ice[3,4]. In the Southern Ocean, the subtropical front (STF) and the Antarctic circumpolar current (ACC) have long been considered active barriers[5], specifically to buoyant MPs at the sea surface[6,7], thus potentially limiting MP contamination being transported to the Southern Ocean from lower latitudes. However, since their discovery in the Southern Ocean, there have been an increasing number of contrasting MP reports in the region[8-10], suggesting higher exchange across the ACC than previously thought[11]. Plastic contamination has been noted in Antarctic surface waters[12,13], sea ice[14,15], snow[16], and deep-sea sediments[17]. The geography and oceanographic processes in the Arctic and Antarctic vary widely, and thus, we focus solely on the Antarctic in this work when speculating on incorporation and transport mechanisms. To date, there has been a significant lack of comprehensive research surrounding MPs in Antarctic sea ice, with only three previous studies (totaling four ice cores) having been published to date. One of the three studies is our initial work, which first indicated the presence of MPs in Southern Ocean sea ice[14]. However, our methodology was significantly different, making cross-study comparisons difficult. Cunningham *et al.* (2022) did not identify MPs down to their polymeric composition, only noting their presence and confirming the particles were synthetic in nature[18]. Similarly, Materic *et al.* (2022) analyzed one ice core for nanoplastics[15], and thus, our studies are incompatible for comparison. As such, this research truly provides a foundation for subsequent sea ice MP studies and future comparisons.

The remoteness of the ice-covered Southern Ocean and its total encompassment within the ACC provide unique insights regarding marine debris in isolated regions and its transport to areas largely devoid of human activity. Global contaminants have been known to reach the Southern Ocean via long-range atmospheric transport (LRAT) and oceanic currents[19,20]. The ACC is an eastward-flowing current, dividing the Southern Ocean from the surrounding Indian, Atlantic, and Pacific oceans[21]. If MPs from lower latitudes are transported past the ACC - or locally sourced from research, tourist, and fishing activities - they can be pulled toward the continent by southern-flowing tracts of regional gyres such as in the Ross or Wedell Sea[13,22,23] and drawn further into coastal waters as a result of localized eddies, storm-forced surface waves, wave-driven advection such as Stoke’s drift, and frontal meandering[11,24]. MPs directed nearest the continent can then interact with the westward-flowing Antarctic coastal current, leading to further dispersal and their exposure to local processes like tidal interactions, eddies, and seawater convection[25]. Therefore, it should be noted that while it is easier for plastics to enter the Antarctic than previously thought, it is unlikely that MP debris is being moved out of the Southern Ocean at a rate of equal exchange once it has found its way there, but rather is being captured by marine mediums and cycled through Antarctic food webs.

The Antarctic sea ice growth cycle is one of the largest seasonally driven events on Earth, exhibited by the vast changes to sea ice extent from ~3 million km^2 in late austral summer to ~19 million km^2 at its height in early spring[26]. Antarctic sea ice has been suggested to serve as a temporal sink for MP debris[14], and the large seasonal variability in sea ice coverage may facilitate a large and recurring particle flux for MP debris into the global ocean. Sea ice has been suggested to serve as a temporal sink for MPs in polar regions. In autumn and winter, MP particles may be harvested from surface waters during frazil ice formation, where they adhere to and are scavenged by ice crystals as the crystals rise in the water column to become incorporated in newly formed sea ice[27]. As ice continues to form, MPs can become incorporated into growing sea ice via basal accretion until their release in spring when sea ice melts[6]. Additionally, in a well-established ice column, the ice-water interface allows for the sieving of particulate matter in and out of the ice[28,29]. Lastly, MP accumulation may occur by means of LRAT of snow or aerosols[16]. Small, lightweight particles (often fibrous) are easily carried by southward-moving air masses where they can be deposited onto the ice and incorporated into its upper layers, e.g., by snow metamorphic processes, including snow-ice formation[2,30].

To our knowledge, no study has assessed the abundance of MP pollution in sea ice from a pan-Antarctic perspective. This study sought to assess the distribution, abundance, polymer composition, and size spectra of MPs to determine if MP contamination varied significantly across sampling sites, geographical regions, and ice types. We conducted the first comprehensive analysis of MP particles in Antarctic sea ice from near-shore fast ice and open-ocean pack ice. Antarctic landfast ice is sea ice attached to the coastline or grounded icebergs, remaining stationary, while pack ice consists of free-floating sea ice that drifts with wind and ocean currents. Sampling both allows us to compare the sources, transport mechanisms, and temporal deposition of MPs, as landfast ice is stationary and may capture local inputs over time, while pack ice is dynamic and integrates materials from diverse regions, offering insights into the distribution and fate of MPs in polar environments. We conducted MP analysis on 19 sea ice cores from 10 individual research expeditions across distinct Southern Ocean regions: The Antarctic Peninsula, the Bellinghausen Sea, the Weddell Sea, Queen Maud Land, Prydz Bay, Wilkes Land, Mawson Sea, the Ross Sea, and McMurdo Sound, and sampled during austral summers spanning 2004-2022 [Figure 1]. From this analysis, we report the average MP concentration in Antarctic sea ice and analyze the spatial variability of MPs around the Southern Ocean to attain a broader understanding of MP contamination in the Southern Ocean.

MATERIALS AND METHODS

Core collection

The 19 archived sea ice cores used for this study were collected between 2004 and 2022 [Figure 1]. Cores were drilled in austral autumn/winter (March-Aug), spring (Sept-Nov), and late summer season (Dec-Feb) under trace-metal-clean conditions. Of these, 10 cores were first-year pack ice and 9 were first-year landfast ice [Table 1]. Cores drilled during the DML campaign were collected using a Kovacs Mark II corer with an internal diameter of 9 cm, while the rest of the cores were drilled with an electropolished stainless steel corer, suited for trace metal analysis[31], with an internal diameter of 8 or 14 cm. Ice cores were stored in PE plastic bags for transport and freezer storage and decontaminated for MP analysis, as outlined below.

Laboratory processing

All chemicals and reagents used in this study were pre-filtered over 1.2 µm Whatman GF/C (glass microfiber, 47 mm) filters to mitigate MP contamination from packaging. A Dupont™ Tyvek full-coverage suit (Bioclean-D non-sterile coverall with hood, manufactured by Cleanroom Garments) was worn during all ice-core cutting and handling in the field, ensuring consistency with the attire used in trace-metal-clean sea ice coring. For laboratory work, 100% cotton clothing was worn as a precaution to minimize contamination from polymer-blend and synthetic textile fibers. Additionally, cotton fibers were excluded

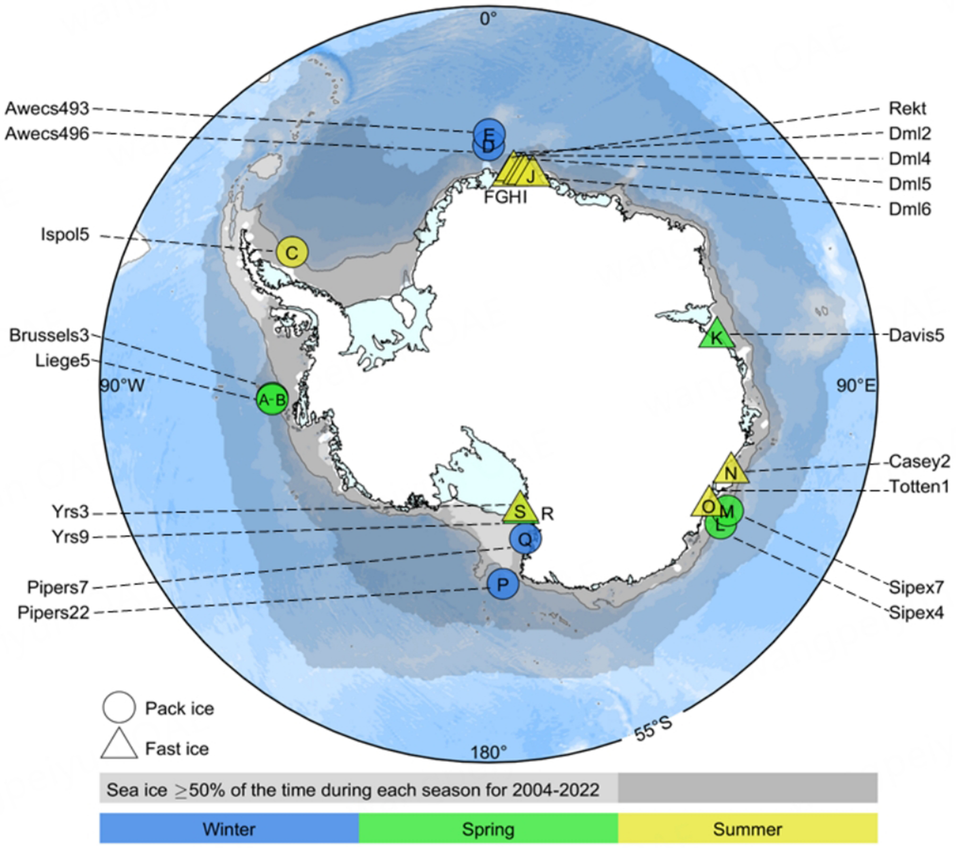

Figure 1. Map of sampling sites for Antarctic ice cores collected from 2004-2022 coupled with mean sea ice concentrations across associated summers. Winter and spring sea ice extent are combined (light gray), while summer sea ice extent is shown in dark gray.

from all analyses to further reduce potential contamination. All glassware was pre-rinsed with ethanol and washed in a glassware-only dishwasher, followed by acid rinses with 1% HCl solution. All glassware was covered in aluminum foil to prevent contamination. Nitrile gloves were not worn during the study, except when handling hazardous chemicals, due to evidence suggesting they can contaminate samples and cause false positives[32]. During each sample transfer step, glassware was thoroughly rinsed with MilliQ™ water to ensure particles had not adhered to the walls of any containers.

As the ice cores were archived samples, processing occurred across three different institutions: the Norwegian Polar Institute (NPI; Tromsø, Norway), the Institute for Marine and Antarctic Studies (IMAS; Hobart, Tasmania), and the Université Libre des Bruxelles (ULB; Brussels, Belgium). Therefore, ice core handling varied slightly based on laboratory infrastructure. The following is a brief overview of the ice-core processing method used to isolate and identify MPs.

All ice cores were cut with individual consideration for the ice crystal structure and ice algal biomass (chlorophyll *a* and particulate organic carbon) within the ice. The cutting of the 19 cores resulted in a total of 60 ice-core horizons for processing and analysis. To ensure there was no contamination due to ice-core storage in LDPE bags for transport and storage, the outside of the core (approx. 1-2 mm) was scraped off with a ceramic knife (Kyocera) pre-cleaned with MilliQ™ water. Core horizons were melted in glass containers at room temperature. Oxidative digestions using 2% sodium dodecyl sulfate (SDS; BDH Laboratory Supplies, England) solution and 35% hydrogen peroxide (H_2O_2; Chem-Supply) were performed

Table 1. Ice core data for the 19 archived sea ice cores used for analysis

Core ID	Original campaign	Sample location	Sampling date	Latitude (°N)	Longitude (°E)	Core length (m)	Ice type
Brussels3	SIMBA	Bellingshausen Sea	11 Oct 2007	-70.06	-93.68	0.59	Pack
Liege5	SIMBA	Bellingshausen Sea	21 Oct 2007	-70.04	-94.08	0.98	Pack
Ispol5	ISPOL	Weddell Sea	19 Dec 2004	-68.06	-55.30	0.95	Pack
Awecs493	AWECS	Weddell Sea	21 June 2017	-66.44	0.12	0.58	Pack
Awecs496	AWECS	Weddell Sea	24 June 2017	-67.46	-0.02	0.59	Pack
Rekt	REKT	Queen Maud Land	12 Jan 2021	-70.18	5.61	1.73	Fast
Dml2	DML	Queen Maud Land	12 Jan 2022	-69.66	6.47	1.385	Fast*
Dml4	DML	Queen Maud Land	13 Jan 2022	-69.84	8.49	1.65	Fast*
Dml5	DML	Queen Maud Land	13 Jan 2022	-69.84	9.62	1.26	Fast*
Dml6	DML	Queen Maud Land	14 Jan 2022	-69.86	11.62	1.85	Fast*
Davis5	DAVIS	Prydz Bay, Davis Station	29 Nov 2015	- 68.57	77.96	1.68	Pack
Sipex4	SIPEX II	Mawson Sea	7 Oct 2012	-65.08	121.67	0.75	Pack
Sipex7	SIPEX II	Mawson Sea	19 Oct 2012	-65.15	118.55	0.80	Pack
Casey2	AAV2	O'Brien Bay, Wilkes Land	23 Dec 2016	-66.30	110.50	1.30	Fast
Totten1	AAV2	Moscow University Ice Shelf, Wilkes Land	31 Dec 2016	-66.80	119.50	1.05	Fast
Pipers7	PIPERS	Terra Nova Bay Polynya, Ross Sea	1 May 2017	-74.97	166.95	0.29	Pack
Pipers22	PIPERS	Central Ross Sea	28 May 2017	-71.07	176.02	0.45	Pack
Yrs3	YROSIAE	Cape Evans, McMurdo Sound	8 Dec 2011	-77.63	166.38	1.48	Fast
Yrs9	YROSIAE	Cape Evans, McMurdo Sound	7 Nov 2012	-77.38	166.23	1.7	Fast

Ice type* indicates cores that were drilled as part of free-floating pack ice, but ice texture analysis and high platelet content indicate they may have originated as landfast sea ice.

over the course of 48 h at 50 °C to reduce biological material in each sample. Next, the treated meltwater was filtered through silica sand (50-70 µm particle size, Sigma-Aldrich) and the filtrate was discarded to waste. Density separations were then performed on the sand mixture (and potentially entrapped MPs) by being placed in a supersaturated NaCl solution (NaCl > 99%, Sigma-Aldrich), stirred for approximately 15 min, and left to settle for about 3 h. NaCl was chosen based on its sufficiency in MP isolation following Quinn *et al.* (2017), even for denser polymers such as polyvinyl chloride (PVC) and polyethylene terephthalate (PET)[33]. The supernatant was filtered onto Whatman anodisc aluminum oxide filters (0.2 µm porosity, 25 mm diameter). Each filter was then placed in an oven to dry for 24 h at 50 °C, following an established oxidative digestive protocol shown to have minimal impact on polymers[34].

Cores processed at NPI (Rekt, Dml2, Dml4, Dml5, Dml6) and ULB (Brussels3, Liege5, Ispol5, Awecs493, Awecs496, Pipers7, Pipers22, Yrs3, Yrs9) were cut in cold rooms; therefore, additional cold gear was necessary. Thin PE gloves were worn over wool gloves. This additional precaution was not found to increase MPs found in blanks at either institution (see next section). Additionally, ULB cores were cut using a powered band saw, and the outside ice layer of each core horizon was removed with the band saw blade.

Blanks and recovery tests

As cores were cut under slightly different circumstances, laboratory blanks were run at all three institutions in triplicate to ensure reliable MP data from our environmental samples. At each institution, blank ice cores were created with ultrapure MilliQ™ water and cylindrically frozen. They were then processed identically to our real samples, allowing us to identify potential laboratory contamination and avoid polymer overestimation. Noted total MPs in blanks by institution are as follows: one polyurethane (PUR) and one polystyrene (PS) particle at NPI (mean 0.22 ± 0.38 particles·L^{-1}), one polyamide (PA) and five PP particles at

IMAS (mean 0.67 ± 0.67 particles·L^{-1}), one PUR, one PS, and two PP particles at ULB (mean 0.44 ± 0.38 particles·L^{-1}). These particle numbers were subtracted from their relevant samples for final calculations and statistical tests.

Three additional blanks, referred to as "spiked blanks", were prepared for recovery rate testing. These blanks were made by spiking 1 L of MilliQ^{TM} water with 50 blue PE beads (20-27 μm diameter; 1.08 g·mL^{-1}) (Cospheric LLC). The recovery samples were processed in the same manner as the previous blanks and environmental samples. The PE beads were identified and counted using a light microscope, and the average recovery rate was determined to be 96 (±3)%. One of the filters was used for micro-Fourier-transform spectroscopy (μFTIR) analysis to verify that the Purency Microplastic Finder (PMF; Purency; version 4.17) accurately detected the beads and corresponded with visual observations.

μFTIR/chemical imaging and data analysis

Data were collected via μFTIR spectroscopy. A Hyperion 3000 microscope attached to a Vertex 70 spectrometer (both Bruker Optics) was used for chemical imaging of all sample filters. Sample analysis was conducted with OPUS 8.7 software (Bruker), using 128 scans for the background and 16 scans for each frame, with an IR microscope objective of ×3.5 magnification. The 64 × 64 FPA detector was selected (no binning), resulting in 64 × 64 spectra per frame (784 × 784 μm^2) with a pixel resolution of ~12.25 × 12.25 μm^2. Each filter was analyzed by combining 16 × 16 FPA frames to create a hyperspectral image containing over 5 million spectra per filter (12.544 × 12.544 mm^2).

The collated OPUS data were exported as an ENVI file and particle analysis was conducted with PMF, an automated analysis software for μFTIR imaging. Machine learning is used in conjunction with an integrated spectral library to directly compare OPUS spectral data and the spectra of known polymers. A baseline confidence rate (hit level) of 90% was set for PA to ensure the software could differentiate true PA particles from similar-looking biological spectra, while 60% was set for all remaining polymer types. For each particle categorized as an MP, software-provided particle area was used to calculate the equivalent spherical diameter (ESD) of each MP. Polymer-dependent false-color images were then generated by PMF to map polymer types, sizes, and locations on each sample filter.

To determine whether variables had normal distributions prior to correlation analyses, the Shapiro-Wilk test was conducted. The non-parametric Mann-Whitney-U test was performed to determine if there was a significant difference in median MP abundances by sampling season and ice type, as well as investigating differences in median particle size between pack and fast ice, and across the ice core's sampling seasons. All tests were performed using the statistical analysis software R (version 4.4.1).

RESULTS AND DISCUSSION

MP abundance in entire sea ice cores

MP contamination was identified in every sampled sea ice core [Figure 2]. In total, 4,090 MP particles were found in this study, averaging a concentration of 44.8 (± 50.8, median = 23.3) particles·L^{-1}. There was a significant difference in median particle abundance between autumn/winter vs. spring cores ($P = 0.038$) and autumn/winter *vs.* summer cores ($P = 0.019$), though there was no statistical difference found between spring and summer concentrations ($P = 0.529$).

Cores collected during austral spring (Brussels3, Liege5, Davis5, Sipex4, Sipex7, Yrs9) and summer (Ispol5, Rekt, Dml2, Dml4, Dml5, Dml6, Casey2, Totten1, Yrs3) reported median MP quantities of 10.1 and 16.4 particles·L^{-1}, respectively [Figure 2]. These are much lower quantities than those recorded in our winter

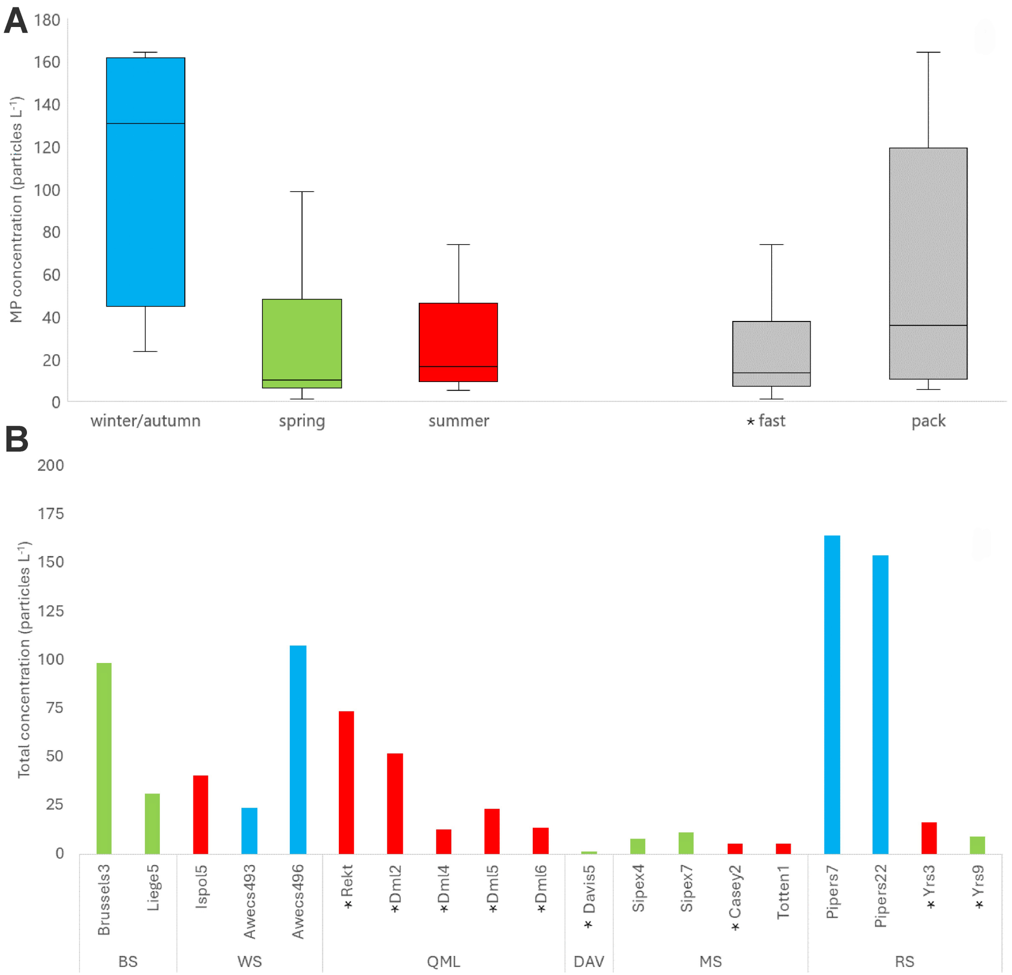

Figure 2. (A) MP concentrations (particles·L^{-1}) grouped by season (winter samples colored in blue, spring in green, and summer in red) and ice type (*denotes landfast ice cores); and (B) presented as the total concentration of MPs per ice core delineated by region: BS, WS, QML, DAV, MS, and RS. MP: Microplastic; BS: Bellinghausen Sea; WS: Weddell Sea; QML: Queen Maud Land; DAV: Davis Station; MS: Mawson Sea; RS: Ross Sea.

cores (Awecs493, Awecs496, Pipers7, Pipers22) at 130.6 particles·L^{-1}. Landfast cores showed a lower median concentration of MPs at 13.4 particles·L^{-1}, compared to pack ice, which had a median of 35.8 particles·L^{-1}, though this was not found to be statistically significant ($P = 0.133$).

Across all 19 cores, we calculate an average integrated MP concentration of 2.2 × 10^{5} (± 2.6 × 10^{5}) particles·m^{-2} in Antarctic sea ice. Our results do not suggest differences in MP counts between years, with no clear temporal trend or variation based on sampling location. Instead, the time of year appears to be the major driver of MP dynamics in sea ice. Integrated concentrations by seasonality are as follows: 3.3 × 10^{5} (± 2.8 × 10^{5}) particles·m^{-2} in autumn and winter ice, 9.7 × 10^{4} (± 4.3 × 10^{4}) particles·m^{-2} in spring, and 2.3 × 10^{5} (± 3.2 × 10^{5}) particles·m^{-2} in summer. The median integrated concentration of MPs in pack ice is 1.2 × 10^{5} particles·m^{-2}, compared with 1.8 × 10^{5} particles·m^{-2} in fast ice, though this difference was not statistically significant ($P = 0.242$).

Polymeric composition

A total of 19 polymer types were identified across all samples (see Table 2 for polymer abbreviations and contributions). Polymer types in pack versus fast ice were largely the same. Polyoxymethylene (POM) (19 particles), silicone (2 particles), and polyphenylsulfone (PPSU) (1 particle) were only noted in fast ice samples, while polyetheretherketone (PEEK) (1 particle) was only found in pack ice; the presence of all other polymers was noted in both ice types. PP and PE consistently dominated across the majority of ice core horizons, with only one exception in which PET was the dominant polymer (Pipers22).

Polymer abundance across pack and fast ice was similar but exhibited a few notable differences. The top ten polymers identified for both ice types were the same (PE, PP, PET, PUR, PAN, PVC, PS, PBT, PA, ABS). Pack ice had slightly higher relative concentrations of all polymers, but most notably PET and PUR, which comprised ≈21% of MPs, compared to ≈11% in fast ice. Compositionally, over 18% of MPs found in fast ice were PAN (350/1,927 particles) compared to 4% in pack ice (88/2,163 particles).

Overall, polymer composition across individually sampled sea ice cores was highly variable. However, when regionally grouped, the relative contribution of each polymer was fairly similar between regions [Figure 3].

Particle size

Over 80% of identified particles were ≤ 1,000 μm^2 and the average particle area for all polymers was 1,033.73 (± 4,501.83) μm^2. ESD of particles ranged from 13.0 to 506.6 μm, with a mean ESD of 27.4 (± 23.7) μm. A significant difference in median particle size was found between pack and landfast ice cores ($P = 0.0015$). The mean particle area of landfast cores was 769.4.0 (± 1,640.7) μm^2, and a mean ESD of 25.6 (± 18.0) μm. Pack ice exhibited a larger mean particle area of 1,258.5 (± 5,747.6) μm^2, and a mean ESD of 28.9 (± 27.7) μm. The median particle area by season is as follows: 365.1 μm^2 in winter cores, 315.1 μm^2 in spring cores, and 265.2 μm^2 in summer cores. As such, significant differences were found between the median particle area for autumn/winter *vs.* summer cores ($P = 2.6 \times 10^{-5}$) and for spring *vs.* summer cores ($P = 0.002$); however, no significant difference in median particle area was found between winter and spring cores ($P = 0.366$).

We found that, in general, particles increased in abundance with decreasing size [Figure 4], and this remained true for both pack and fast ice. The smallest noted particle size was 121 μm^2 in area (several different polymers) and constituted over 51% of all identified particles (2,099/4,090). The largest particle found in our samples was a piece of PS with an area of 201,561 μm^2. In fact, PS had the largest mean area across samples [Table 2].

Spatial and seasonal variability

The spatial and seasonal presence of MPs in sea ice is variable, as seen in Figure 2. Our analysis indicates that coastal sea ice exhibits lower MP abundances than open ocean sea ice. Ice textures are indicative of sea ice growth history, and could help elucidate the mechanisms of MP incorporation, enrichment, and release, as well as the varying levels of MP contamination across drill sites. Pack ice generally has higher frazil ice contributions compared to landfast ice which is mostly made of columnar ice[35]. The more turbulent conditions associated with open ocean regions due to strong winds and wave action lend themselves to frazil ice formation[36], in which randomly shaped ice crystals rise from up to 100 m depth[37] through the water column in autumn and winter, congealing into slush or pancake ice at the ocean surface. We suspect that MPs may get scavenged by frazil ice crystals as they rise to the sea surface, similar to processes suggested for algae and Fe incorporation[38-41]. Alternatively, frazil ice crystals may use MPs as condensation nuclei and subsequently rise to the ocean surface[42], leading to MP incorporation into newly formed ice. It has also been suggested that the number of times an ice crystal encounters a particle will determine how

Table 2. Total polymeric composition and particle size data for all 19 sea ice cores

Abbr.	Polymer	Particle count	Mean area (stdev) (μm^2)	Total area percentage	Mean ESD (stdev) (μm)
PP	Polypropylene	1,338	1,049 (± 3,649)	33.4%	28 (± 24)
PE	Polyethylene	969	758 (± 1,424)	18.2%	26 (± 18)
PAN	Polyacrylonitrile	438	1,750 (± 5,134)	17.5%	35 (± 31)
PET	Polyethylene terephthalate	376	862 (± 1,485)	9.4%	27 (± 19)
PUR	Polyurethane	298	899 (± 1,948)	7.7%	28 (± 19)
PVC	Polyvinyl chloride	228	702 (± 1,882)	6.4%	23 (± 20)
PS	Polystyrene	200	1,972 (± 14,480)	3.8%	29 (± 41)
PBT	Polybutylene terephthalate	55	368 (± 358)	0.5%	20 (± 9)
ABS	Acrylonitrile butadiene Styrene	53	1,551 (± 3,246)	0.5%	35 (± 27)
PA	Polyamide	47	326 (± 1,087)	0.4%	16 (± 13)
PMMA	Polymethyl mathacrylate	19	662 (± 1,032)	0.3%	23 (± 18)
EVOH	Ethylene-vinyl alcohol copolymer	19	192 (± 157)	0.09%	15 (± 5)
POM	Polyoxymethylene	19	140 (± 30)	0.06%	13 (± 1)
EVAc	Ethylene vinyl acetate	12	885 (± 1,886)	0.3%	26 (± 22)
PPSU	Polyphenylsulfone	8	133 (± 0)	0.02%	13 (± 0)
PC	Polycarbonate	5	816 (± 658)	0.1%	30 (± 12)
CA	Cellulose acetate	3	221 (± 77)	0.02%	17 (± 3)
silicone	Silicone	2	199 (± 94)	< 0.001%	16 (± 4)
PEEK	Polyetheretherketone	1	265	< 0.001%	19

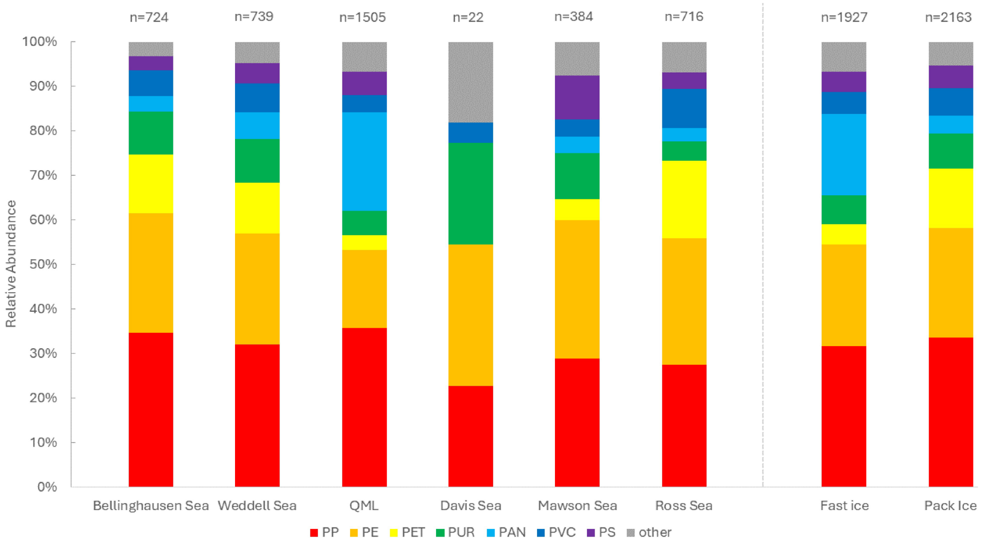

Figure 3. Polymer composition by geographic region and by ice type, where n equals the total particle abundance.

much material gets entrained in sea ice[43], and that convection of sea ice brines and under-ice water, as well as wave action, contribute to particle entrapment[44]. In contrast, landfast ice often forms in calmer conditions and exhibits higher inclusions of columnar ice growing at the bottom of an existing ice cover[45]. The bioaccumulation of MPs by algal growth and associated exopolymeric substances (EPS) in the skeletal layer could explain the incorporation of MPs into columnar ice, as suggested in the case of iron, macronutrients, and ice algae[39,46-49]. Additionally, some of the landfast cores (Yrs and Dml) consisted of

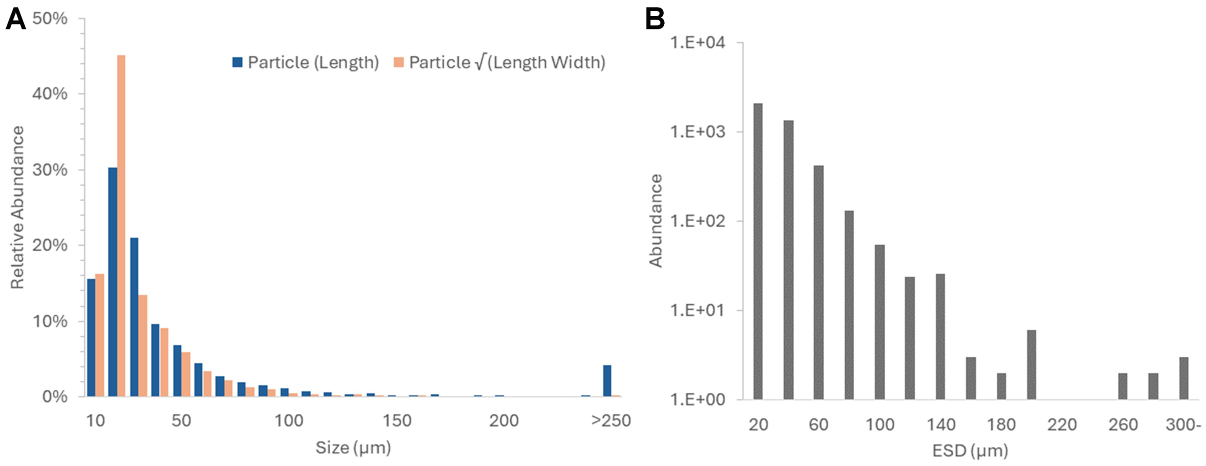

Figure 4. (A) Relative MP particle size distribution from all analyzed stations (n_p = 4,090). Dark blue bars represent particles by length. Light orange bars represent the geometric mean of particle size based on length and width. Particle lengths and widths were measured using PMF; (B) Polymer size abundance across all sea ice samples shown as ESD on a logarithmic scale. MP: Microplastic; PMF: Purency Microplastic Finder; ESD: equivalent spherical diameter.

platelet ice, which facilitates further incorporation mechanisms for MPs. Basal melting can occur when glacial ice comes into contact with relatively warmer waters, leading to underlying supercooled seawater, which may create favorable conditions for platelet ice formation, buoyant rise, and accumulation under the adjacent landfast sea ice[50] along with potential entrapment of any MPs present.

We noted that cores collected in spring and summer had significantly lower MP quantities than in winter. Because samples were not obtained from one site across different seasons, it is difficult to make assumptions about the seasonal MP flux during the sea ice growth/melt cycle. However, ice sampled in late winter/early spring is likely to have the highest levels of MP contamination, as suggested for other sea ice variables such as macronutrients and trace metals[51-53]. This was true for our study as the autumn and winter cores (Awecs493, Awecs496, Pipers7, Pipers22) exhibited the highest mean MP concentrations of all samples [Figure 2]. Sea ice growth rate is fastest in winter and the ice itself is often more frazil-dominant, which, as discussed above, could result in autumn/winter ice cores having higher incorporation rates of MPs than cores collected later in the year. Additionally, turbulent sea ice growth conditions in winter could help explain why the average MP size was significantly larger in winter cores compared to summer cores. Based on mean particle size results from Chen *et al.* (2023), larger particles are more easily entrapped in ice, and the fast and tumultuous growth conditions for sea ice in winter might assist with particle incorporation into a growing ice column[54]. Furthermore, our theory on MP flux in the seasonal ice cover is supported through a deeper look at cores sampled later in the sea ice season. As sea ice melts in spring, ice porosity increases, and brine channels can expand and connect with underlying seawater, where particulate matter such as algae (and suspected MPs) may get released from the ice[55]. Casey2 and Totten1 from late summer in the eastern Antarctic are a prime example of this. Both cores were collected off Wilkes Land in late December, by which point the ice exhibited highly permeable textures with typical characteristics of decaying ice, such as large brine channels and melt holes[56]. These two cores were among those with the lowest mean concentrations of MPs. Time series are needed to test these hypotheses. Alternatively, mesocosm experiments could be conducted to simulate both sea ice growth and melt phases (e.g., Geilfus *et al.*, 2019)[27].

Transport mechanisms

MPs in the Southern Ocean may originate from both local and distant sources. While the ACC is thought to keep the Southern Ocean from accumulating MPs from northern latitudes[19], it has been suggested that both its surface and sub-surface waters are penetrable to MPs[13,57]. Passive MP transport is heavily influenced by ocean currents and mixing such as meridional overturning circulation (MOC) and Southern Ocean upwelling. Baroclinic wind instability transports mass to the poles and yields southward eddy advection[58]. Therefore, MPs in surface waters in mid to low latitudes in the upper cell of the MOC are being drawn down into the Southern Ocean and across the axis of the ACC. We noted higher abundances of MPs in pack ice than fast ice may support the theory that contamination is likely coming from northern latitudes, rather than as a direct result of local and intercoastal activities from research bases or fishing ventures. The presence of MPs in Southern Ocean air samples further indicates that MPs can be transported by diffuse sources[18,59]. The dominance of smaller MPs across our samples was consistent with other Antarctic MP studies that found MP abundance decreased with increasing size[12,60]. Concurrently, the majority of MPs are less than 10 μm in length, indicating that atmospheric and oceanic long-range transport may assist in MP accumulation across our sea ice sampling sites[59,61]. In addition, snow deposition may also play a role in depositing MPs into sea ice as MP fragments and fibers are likely to be incorporated into snow mixtures due to their low particle density and pre-enrichment in materials entrained by winds, as it has been observed on the continent at DML stations and reported elsewhere in the literature[16,62]. However, small MP sizes could simply indicate that particles - whether they originate from local sources or not - are being mechanically degraded over time via marine consumption[63] or in highly dynamic atmospheric and oceanic conditions[61,64] and re-enriched into sea ice and surface waters during subsequent seasons. The abundance of MPs in the autumn/winter cores of the Weddell and Ross Seas could indicate that these large oceanic gyres allow for the accumulation of MP contamination during sea ice formation, rather than their re-dispersal in more open ocean regions. Both these regions are characterized as major areas where northern-sourced deep waters cross the ACC before upwelling southward and toward the surface[23]. The upwelling of deep waters in the Weddell and Ross gyres is a good source candidate of MPs for the surface waters (hence the pack sea ice) in the Southern Ocean since the highest concentration of MPs is found between 200 and 600 m depth in offshore waters of the World's ocean (e.g., Choy *et al.*, 2019)[65]. For example, Isobe *et al.* (2017) observed higher MP concentrations in surface waters south of the Polar Front than in waters north of it[12]. This hypothesis is further supported by the significantly higher MP concentration found in offshore waters of the Weddell Gyre (where deep-water upwelling prevails) compared to waters on the Weddell Sea continental shelf by Leistenschneider *et al.* (2024)[66]. On the contrary, waters on the Antarctic Shelf may be protected from this MP contamination by the Southern Ocean slope front, just north of the continental slope, which partially protects the continental shelf from the intrusion of deeper waters. Further research on pathways of particle transport in the Southern Ocean and sea ice is needed to garner a deeper understanding of contamination levels, and to accurately predict MP sinks as plastic production continues to increase.

In conjunction with seasonal ice characteristics, sampling locations may also help explain the disparity between volumetric MP concentrations in the autumn/winter cores versus the summer/spring cores. We suspect accumulation trends may result from a combination of faster sea ice growth during autumn/winter (and thus more efficient MP entrapment), proximity to external sources of pollution transported by means of wind, subsurface waters (particularly for neutrally buoyant MPs), and local hydrographic features. An MP accumulation model[6] showed that the Antarctic was initially reasonably well protected from MPs sourced externally to the Southern Ocean, but at the end of the 50-year time span, MP contamination had heavily penetrated the Southern Ocean and was present around the entire Antarctic coastline, with MP abundance remaining most dense in Pacific Ocean sectors during winter. This corresponds with our findings, as Pipers7 and Pipers22 sampled during winter near the Ross Sea[67] accounted for the highest particle abundances across all our cores (163.1 and 153.8 particles·L^{-1}, respectively). The remaining cores collected during the sea ice growth phase in the Weddell Sea (Awecs493 and Awecs496)[68] also exhibited higher MP concentrations than any spring/summer cores. As the model progressed, the region with the highest winter accumulation was the Bellinghausen Sea. Brussels3 and Liege5 were drilled during austral spring in this region and maintained significantly higher MP abundances than any other spring/summer cores (average of 98.4 and 31.1 particles·L^{-1}, respectively). Researchers noted that sea ice permeability was significantly reduced for Brussels3 in particular, which could explain the high concentration of particles within this core[69], despite cycles of warming beginning in early spring, thus retaining MPs that were enriched during winter. In contrast, cores drilled in East Antarctica during the sea ice melt phase (Davis5, Sipex4, Sipex7, Casey2, Totten1) exhibited the lowest mean concentrations of MPs among all samples. This could be because the largest hydrological features in the eastern Antarctic remain the ACC and the Antarctic Coastal Current, and the region lacks a large gyre system that can potentially entrap MPs. Simultaneously, we speculate that this could be a result of low vessel traffic, and greater distance from tourist and research hotspots. Cunningham *et al.* (2022) demonstrated that air masses and wind are transport mechanisms for MP entering the Southern Ocean and noted that MPs in their study were likely to have originated from South America[18], which would likely be the case for some of our Weddell Sea ice cores. Perhaps because the eastern Antarctic is further removed from the southern land masses of Africa and South America, airborne MP pollution is not as significant of a factor. This, coupled with the lower rates of tourism and marine activities, could explain the lower MP counts in these cores.

Potential sources for MPs in sea ice

We suspect MP particles are scavenged from surrounding environmental media and incorporated into the sea ice matrix during its growth phase. Based on comparisons with MP studies in surface and subsurface waters, sea ice is a temporary sink for MPs. The mean concentrations of particles·L^{-1} across our cores were consistently four to six orders of magnitude higher than concentrations in seawater [Table 3]. Note that at the time of the current study, there are no comparable reports of MP concentrations in the Bellinghausen or Mawson Seas. In general, the lack of standardized methods for MP extraction from seawater and chemical identification remains a hindrance to consistent cross-study comparisons. Additionally, most studies in the Antarctic are focused on regions with long-standing research stations or those experiencing higher levels of anthropogenic pressures. As such, there have been mixed reports of MP presence in Antarctic surface waters, with some studies finding high levels of MPs in offshore surface waters[19] while others reporting little to no presence of MPs at all[7,73]. Thus, MP incorporation during initial sea ice growth may coincide with the higher abundances of MPs we noted in our autumn/ winter cores compared to those sampled during spring and summer. It may also account for why studies reporting contamination continually note MPs in Antarctic sub-surface waters[60] and sediments[17,74] but vary widely in their findings for upper-surface waters in both coastal and offshore regions.

Air masses may also contribute MPs in sea ice. To date, little remains known about the presence of airborne MPs in Antarctica, though it remains highly probable that at least some portion of MPs found in Southern Ocean Sea ice arise from atmospheric contributions. Backwards, air mass trajectories from the first study of MPs in Antarctic snow indicated that MPs entering the Southern Ocean likely arrive via long-range transport, most notably from South America, upwards of 6,000 km away from their sampling sites in the Ross Sea region, though local sources from Scott Base and McMurdo Station contributed as well[16]. Similarly, air mass trajectories conducted for a cruise from East Asia to Antarctica indicate that MPs likely originated from the continents of South Asia and Oceania[61], with non-fibrous MP concentrations decreasing with increasing latitude. Finally, the ocean-atmosphere exchange of MPs may also contribute locally to our sea ice concentrations[75]. Particles - particularly in coastal surface waters - can be re-entrained in the atmosphere via sea mist[75]. With these combined conclusions, it may be that long-range transport

Table 3. Study summaries of MP concentrations in Antarctic seawater and air masses compared to findings in sea ice in the corresponding regions for our study sites

Ref.	**Location**	**Sample medium**	**Mean MP concentration (particles·L^{-1})**	**Regional sea ice concentration (particles·L^{-1})**
Leistenschneider *et al.*, 2024[66] Leistenschneider *et al.*, 2021[70]	Weddell Sea	Surface waters Subsurface waters	1.0×10^{-5} 4.35×10^{-2}	57.1
Pakhomova *et al.*, 2022[71]	Weddell Sea	Subsurface waters	4.3×10^{-4}	57.1
Cincinelli *et al.*, 2017[72]	Ross Sea	Subsurface waters	1.7×10^{-4}	85.8
Zhang *et al.*, 2022[60]	Ross Sea Davis Sea	Subsurface waters Subsurface waters	1.85×10^{-3} 1.91×10^{-3}	85.8 1.1
Aves *et al.*, 2022[16]	Ross Sea	Air	29	85.8

MP: Microplastic.

facilitates MP contamination across the STF, where a portion of airborne MPs become incorporated into surface waters for inclusion into growing ice. An additional portion of MP particles that remain or become airborne could integrate into sea ice via snow deposition. Cunningham *et al.* (2022) found MP types consistent in air masses and seawater, and thus, they similarly speculate that atmospheric and oceanic processes influence Antarctic MP presence in tandem[18].

It is difficult to pinpoint specific sources of MP contamination. However, the MP fragments found in our samples are typically abundant in the marine environment and have several uses in and out of a marine context. PP, PE, PUR, PVC, PET, and PS are the most abundant marine MPs, comprising approximately 80% of total plastic production[76], and all six polymers were found in high abundance in our study, totaling 78.9% of all MPs identified [Table 2]. The most abundant polymer types were PP and PE and were present in all 19 ice cores. This coincides with PP and PE being the most abundant marine MPs globally and around the Southern Ocean[7,66,72], and aligns with global production rates[77,78]. PP and PE are commonly associated with maritime and fishing activities and land-based beach litter, and this, combined with their low density, makes them readily abundant in surface waters[79]. Additionally, PP was the most abundant polymer found in atmospheric deposition samples inland of the Ross Sea region (coastal Victoria Land), and was linked to potential human activities at nearby research stations[80]. PET accounted for 49% of polymers found in a study of Antarctic snow, with the authors suggesting that both local and distant sources could be contributing to this phenomenon[16]. PET and PA are commonly used in textiles and have high correlations with wastewater[81,82]; thus, while all polymers could penetrate the Southern Ocean via long-range transport, there is potential that these polymers originate from local Antarctic stations or - what is more likely - vessels. Interestingly, PAN and PVC were also found in relatively high quantities across our samples, ranked in the top three for marine polymers of concern[83]. Despite their densities being higher than that of seawater, they have been found in other Southern Ocean samples[7,84]. For cores collected over shallower water depths, we suspect that plastic-laden marine sediments may be resuspended during storms or other turbulent conditions, allowing for the incorporation of these denser MPs into sea ice. Compositionally, PAN was the third most prevalent polymer in fast ice, accounting for over 22% of all MPs, compared to just 6% for pack ice. Ultimately, the high variability in abundance and polymeric composition across our samples makes it difficult to draw conclusions regarding the immediate sources of this debris.

CONCLUSION

Here, we have provided the first pan-Antarctic study of MPs in Southern Ocean sea ice. MP concentrations across our ice cores were high, particularly when compared to concurrent regional seawater studies, indicating sea ice is a reservoir for plastic pollution in the Southern Ocean. High MP concentrations in growing sea ice during autumn and winter, compared to lower average MP abundances in spring and summer, indicate that turbulent and faster growth processes are a likely driver for particle incorporation. The increase in ice porosity and the widening of brine channels as sea ice melts could allow for a return of MPs to surrounding surface waters, suggesting that while sea ice is a sink for MPs, it is a highly seasonal one. It is suspected that Southern Ocean MP contamination is originating from both local and distant sources, but that circulation of northerly deep waters and long-range transport have a heavy impact on MP accumulation across Southern Ocean regional gyres, coastlines, and their eventual inclusion into sea ice. Finally, due to strong seasonal components in the Southern Ocean sea ice cycle, regional polymer compositions are likely largely dependent on the MP composition of underlying waters.

MPs in the Southern Ocean have the potential to accumulate over time. While we know MPs are incorporated into the ice during sea ice growth in autumn and winter, the fate of MPs remains unknown once they are released from the ice again. The low density and small sizes of MPs give them the ability to remain in surface waters to be further broken down by consumption[63] or re-incorporated into sea ice during the following growth season. Even particles that have sunken out of the surface waters to settle in sediments can be resuspended in the water column during storms[39,85] in shallower coastal areas, and thus again have the potential to become entrapped in a growing ice column. Currently, there is a lack of data to conduct analyses on Southern Ocean MP accumulation trends. This could be remedied by conducting time-series sampling, where sea ice is analyzed from subsequent years to determine if there is accumulation over time, as well as further analysis of Southern Ocean sediments to determine if they are an ultimate sink for MPs. The Southern Ocean is known for its variable and highly dynamic conditions, which may make it difficult to pinpoint individual transport and enrichment mechanisms for MPs in sea ice. However, this work provides a step toward particle flux modeling of MPs in sea ice and their effects on the rest of the biogeochemical cycle, both locally and more broadly, around the Southern Ocean.

DECLARATIONS

Authors' contributions

Methodology, validation, writing - original draft, investigation, formal analysis: Kelly A
Conceptualization, data curation: Kelly A, Rodemann T
Funding acquisition: Lannuzel D
Supervision: Lannuzel D, Rodemann T, Meiners KM, Auman HJ, Moreau S, Fripiat F
Writing - review and editing: Lannuzel D, Rodemann T, Meiners KM, Auman HJ, Moreau S, Fripiat F, Dellile B
Resource acquisition: Lannuzel D, Meiners KM, Dellile B, Fripiat F, Moreau S

Availability of data and materials

All data relevant to this study are available via the Australian Antarctic Data Center (doi: 10.26179/qzf5-tr20).

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Kanhai DK, Gardfeldt K, Krumpen T, Thompson RC, O'Connor I. Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. *Sci Rep* 2020;10:5004. DOI PubMed PMC
2. Bergmann M, Mützel S, Primpke S, Tekman MB, Trachsel J, Gerdts G. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. *Sci Adv* 2019;5:eaax1157. DOI PubMed PMC
3. Obbard RW, Sadri S, Wong YQ, Khitun AA, Baker I, Thompson RC. Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earth's Future* 2014;2:315-20. DOI
4. Peeken I, Primpke S, Beyer B, et al. Arctic sea ice is an important temporal sink and means of transport for microplastic. *Nat Commun* 2018;9:1505. DOI PubMed PMC
5. Fraser CI, Kay GM, Plessis MD, Ryan PG. Breaking down the barrier: dispersal across the Antarctic Polar Front. *Ecography* 2017;40:235-7. DOI
6. Mountford AS, Morales Maqueda MA. Modeling the accumulation and transport of microplastics by sea ice. *JGR Oceans* 2021;126:e2020JC016826. DOI
7. Suaria G, Perold V, Lee JR, Lebouard F, Aliani S, Ryan PG. Floating macro- and microplastics around the Southern Ocean: results from the Antarctic circumnavigation expedition. *Environ Int* 2020;136:105494. DOI PubMed
8. De-la-Torre GE, Santillán L, Dioses-Salinas DC, et al. Assessing the current state of plastic pollution research in Antarctica: knowledge gaps and recommendations. *Chemosphere* 2024;355:141870. DOI
9. da Silva JRMC, Bergami E, Gomes V, Corsi I. Occurrence and distribution of legacy and emerging pollutants including plastic debris in Antarctica: sources, distribution and impact on marine biodiversity. *Mar Pollut Bull* 2023;186:114353. DOI PubMed
10. Tirelli V, Suaria G, Lusher AL. Microplastics in polar samples. In: Rocha-Santos T, Costa MF, Mouneyrac C, editors. Handbook of microplastics in the environment. Cham: Springer International Publishing; 2022. pp. 281-322. DOI
11. Fraser CI, Morrison AK, Hogg AM, et al. Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. *Nature Clim Change* 2018;8:704-8. DOI
12. Isobe A, Uchiyama-Matsumoto K, Uchida K, Tokai T. Microplastics in the Southern Ocean. *Mar Pollut Bull* 2017;114:623-6. DOI PubMed
13. Waller CL, Griffiths HJ, Waluda CM, et al. Microplastics in the Antarctic marine system: an emerging area of research. *Sci Total Environ* 2017;598:220-7. DOI
14. Kelly A, Lannuzel D, Rodemann T, Meiners KM, Auman HJ. Microplastic contamination in east Antarctic sea ice. *Mar Pollut Bull* 2020;154:111130. DOI PubMed
15. Materić D, Kjær HA, Vallelonga P, Tison JL, Röckmann T, Holzinger R. Nanoplastics measurements in Northern and Southern polar ice. *Environ Res* 2022;208:112741. DOI PubMed
16. Aves AR, Revell LE, Gaw S, et al. First evidence of microplastics in Antarctic snow. *The Cryosphere* 2022;16:2127-45. DOI
17. Cunningham EM, Ehlers SM, Dick JTA, et al. High abundances of microplastic pollution in deep-sea sediments: evidence from Antarctica and the Southern Ocean. *Environ Sci Technol* 2020;54:13661-71. DOI
18. Cunningham EM, Rico Seijo N, Altieri KE, et al. The transport and fate of microplastic fibres in the Antarctic: the role of multiple global processes. *Front Mar Sci* 2022;9:1056081. DOI
19. Lacerda ALDF, Rodrigues LDS, van Sebille E, et al. Plastics in sea surface waters around the Antarctic Peninsula. *Sci Rep* 2019;9:3977. DOI PubMed PMC
20. Zhang Y, Gao T, Kang S, Sillanpää M. Importance of atmospheric transport for microplastics deposited in remote areas. *Environ Pollut* 2019;254:112953. DOI

21. Nowlin WD, Klinck JM. The physics of the Antarctic circumpolar current. *Rev Geophys* 1986;24:469-91. DOI
22. Ryan S, Schröder M, Huhn O, Timmermann R. On the warm inflow at the eastern boundary of the Weddell Gyre. *Deep Sea Res Pt I* 2016;107:70-81. DOI
23. Tamsitt V, Drake HF, Morrison AK, et al. Spiraling pathways of global deep waters to the surface of the Southern Ocean. *Nat Commun* 2017;8:172. DOI PubMed PMC
24. Pennel R, Kamenkovich I. On the factors controlling the eddy-induced transport in the Antarctic circumpolar current. *J Phys Oceanogr* 2014;44:2127-38. DOI
25. Rintoul SR, Naveira Garabato AC. Dynamics of the Southern Ocean circulation. Ocean circulation and climate - a 21st century perspective. Elsevier; 2013. pp. 471-92. DOI
26. National Snow and Ice Data Center. NOAA/NSIDC climate data record of passive microwave sea ice concentration, version 4. Available from: https://nsidc.org/data/g02202/versions/4. [Last accessed on 23 Dec 2024].
27. Geilfus NX, Munson KM, Sousa J, et al. Distribution and impacts of microplastic incorporation within sea ice. *Mar Pollut Bull* 2019;145:463-73. DOI
28. Spindler M. Notes on the biology of sea ice in the Arctic and Antarctic. *Polar Biol* 1994;14:BF00238447. DOI
29. Leventer A. Particulate flux from sea ice in polar waters. In: Thomas DN, Dieckmann GS, editors. Sea ice. Wiley; 2003. pp. 303-32. DOI
30. Jeffries MO, Krouse HR, Hurst-Cushing B, Maksym T. Snow-ice accretion and snow-cover depletion on Antarctic first-year sea-ice floes. *Ann Glaciol* 2001;33:51-60. DOI
31. Lannuzel D, de Jong J, Schoemann V, Trevena A, Tison J, Chou L. Development of a sampling and flow injection analysis technique for iron determination in the sea ice environment. *Anal Chim Acta* 2006;556:476-83. DOI
32. Witzig CS, Földi C, Wörle K, et al. When good intentions go bad-false positive microplastic detection caused by disposable gloves. *Environ Sci Technol* 2020;54:12164-72. DOI
33. Quinn B, Murphy F, Ewins C. Validation of density separation for the rapid recovery of microplastics from sediment. *Anal Methods* 2017;9:1491-8. DOI
34. López-Rosales A, Andrade JM, Grueiro-Noche G, Fernández-González V, López-Mahía P, Muniategui-Lorenzo S. Development of a fast and efficient method to analyze microplastics in planktonic samples. *Mar Pollut Bull* 2021;168:112379. DOI PubMed
35. Thomas DN, Dieckmann GS. Sea ice - an introduction to its physics, chemistry, biology and geology. London: Wiley Blackwell; 2003. Available from: https://www.wiley.com/en-us/Sea+Ice%3A+An+Introduction+to+its+Physics%2C+Chemistry%2C+Biology+and+Geology-p-9780632058082. [Last accessed on 23 Dec 2024].
36. Barrette PD. Understanding frazil ice: the contribution of laboratory studies. *Cold Reg Sci Technol* 2021;189:103334. DOI
37. Ito M, Ohshima KI, Fukamachi Y, Mizuta G, Kusumoto Y, Nishioka J. Observations of frazil ice formation and upward sediment transport in the Sea of Okhotsk: a possible mechanism of iron supply to sea ice: frazil ice and upward sediment transport. *J Geophys Res Oceans* 2017;122:788-802. DOI
38. Dieckmann GS, Lange MA, Ackley SF, Jennings JC. The nutrient status in sea ice of the Weddell Sea during winter: effects of sea ice texture and algae. *Polar Biol* 1991;11:449-56. DOI
39. Lannuzel D, Schoemann V, de Jong J, et al. Distribution of dissolved iron in Antarctic sea ice: spatial, seasonal, and inter□annual variability. *J Geophys Res* 2010;115:2009JG001031. DOI
40. Garrison DL, Ackley SF, Buck KR. A physical mechanism for establishing algal populations in frazil ice. *Nature* 1983;306:363-5. DOI
41. Spindler M, Dieckmann GS. Distribution and abundance of the planktic foraminifer Neogloboquadrina pachyderma in sea ice of the Weddell Sea (Antarctica). *Polar Biol* 1986;5:185-91. DOI
42. Weeks WF, Ackley SF. The growth, structure, and properties of sea ice. In: Untersteiner N, editor. The geophysics of sea ice. Boston: Springer US; 1986. pp. 9-164. DOI
43. Garrison D, Close A, Reimnitz E. Algae concentrated by frazil ice: evidence from laboratory experiments and field measurements. *Antartic Sci* 1989;1:313-6. DOI
44. Weissenberger J, Grossmann S. Experimental formation of sea ice: importance of water circulation and wave action for incorporation of phytoplankton and bacteria. *Polar Biol* 1998;20:178-88. DOI
45. Fraser AD, Wongpan P, Langhorne PJ, et al. Antarctic landfast sea ice: a review of its physics, biogeochemistry and ecology. *Rev Geophys* 2023;61:e2022RG000770. DOI
46. Roukaerts A, Deman F, Van der Linden F, et al. The biogeochemical role of a microbial biofilm in sea ice. *Elem Sci Anth* 2021;9:00134. DOI
47. van der Merwe P, Lannuzel D, Nichols CM, et al. Biogeochemical observations during the winter–spring transition in East Antarctic sea ice: evidence of iron and exopolysaccharide controls. *Mar Chem* 2009;115:163-75. DOI
48. de Jong J, Schoemann V, Maricq N, et al. Iron in land-fast sea ice of McMurdo Sound derived from sediment resuspension and wind-blown dust attributes to primary productivity in the Ross Sea, Antarctica. *Mar Chem* 2013;157:24-40. DOI
49. Meiners K, Gradinger R, Fehling J, Civitarese G, Spindler M. Vertical distribution of exopolymer particles in sea ice of the Fram Strait (Arctic) during autumn. *Mar Ecol Prog Ser* 2023;248:1-13. Available from: http://www.int-res.com/articles/meps2003/248/m248p001.pdf. [Last accessed on 24 Dec 2024]
50. Hoppmann M, Richter ME, Smith IJ, et al. Platelet ice, the Southern Ocean's hidden ice: a review. *Ann Glaciol* 2020;61:341-68. DOI

51. Fripiat F, Meiners KM, Vancoppenolle M, et al. Macro-nutrient concentrations in Antarctic pack ice: overall patterns and overlooked processes. *Elementa Sci Anthrop* 2017;5:13. DOI
52. Lannuzel D, Chever F, van der Merwe PC, et al. Iron biogeochemistry in Antarctic pack ice during SIPEX-2. *Deep Sea Res Pt II* 2016;131:111-22. DOI
53. Meiners KM, Michel C. Dynamics of nutrients, dissolved organic matter and exopolymers in sea ice. In: Thomas DN, editor. Sea ice. Wiley; 2017. pp. 415-32. DOI
54. Chen Z, Elektorowicz M, An C, Tian X. Entrainment and enrichment of microplastics in ice formation processes: implications for the transport of microplastics in cold regions. *Environ Sci Technol* 2023;57:3176-86. DOI PubMed
55. Tison J, Worby A, Delille B, et al. Temporal evolution of decaying summer first-year sea ice in the Western Weddell Sea, Antarctica. *Deep Sea Res Pt II* 2008;55:975-87. DOI
56. Corkill M, Moreau S, Janssens J, et al. Physical and biogeochemical properties of rotten East Antarctic summer sea ice. *JGR Oceans* 2023;128:e2022JC018875. DOI
57. Reisser J, Slat B, Noble K, et al. The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic Gyre. *Biogeosciences* 2015;12:1249-56. DOI
58. Marshall J, Speer K. Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nature Geosci* 2012;5:171-80. DOI
59. Obbard RW. Microplastics in polar regions: the role of long range transport. *Curr Opin Environ Sci Health* 2018;1:24-9. DOI
60. Zhang S, Zhang W, Ju M, et al. Distribution characteristics of microplastics in surface and subsurface Antarctic seawater. *Sci Total Environ* 2022;838:156051. DOI
61. Chen Q, Shi G, Revell LE, et al. Long-range atmospheric transport of microplastics across the southern hemisphere. *Nat Commun* 2023;14:7898. DOI PubMed PMC
62. Bullard JE, Ockelford A, O'brien P, Mckenna Neuman C. Preferential transport of microplastics by wind. *Atmos Environ* 2021;245:118038. DOI
63. Dawson AL, Kawaguchi S, King CK, et al. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. *Nat Commun* 2018;9:1001. DOI PubMed PMC
64. Andrady AL. Microplastics in the marine environment. *Mar Pollut Bull* 2011;62:1596-605. DOI PubMed
65. Choy CA, Robison BH, Gagne TO, et al. The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Sci Rep* 2019;9:7843. DOI PubMed PMC
66. Leistenschneider C, Wu F, Primpke S, Gerdts G, Burkhardt-Holm P. Unveiling high concentrations of small microplastics (11-500 μ m) in surface water samples from the southern Weddell Sea off Antarctica. *Sci Total Environ* 2024;927:172124. DOI PubMed
67. Tison J, Maksym T, Fraser AD, et al. Physical and biological properties of early winter Antarctic sea ice in the Ross Sea. *Ann Glaciol* 2020;61:241-59. DOI
68. Tison J, Schwegmann S, Dieckmann G, et al. Biogeochemical impact of snow cover and cyclonic intrusions on the winter Weddell Sea ice pack. *JGR Oceans* 2017;122:9548-71. DOI
69. Lewis M, Tison J, Weissling B, et al. Sea ice and snow cover characteristics during the winter–spring transition in the Bellingshausen Sea: an overview of SIMBA 2007. *Deep Sea Res Pt II* 2011;58:1019-38. DOI
70. Leistenschneider C, Burkhardt-Holm P, Mani T, Primpke S, Taubner H, Gerdts G. Microplastics in the Weddell Sea (Antarctica): a forensic approach for discrimination between environmental and vessel-induced microplastics. *Environ Sci Technol* 2021;55:15900-11. DOI PubMed
71. Pakhomova S, Berezina A, Lusher AL, et al. Microplastic variability in subsurface water from the Arctic to Antarctica. *Environ Pollut* 2022;298:118808. DOI
72. Cincinelli A, Scopetani C, Chelazzi D, et al. Microplastic in the surface waters of the Ross Sea (Antarctica): occurrence, distribution and characterization by FTIR. *Chemosphere* 2017;175:391-400. DOI
73. Kuklinski P, Wicikowski L, Koper M, et al. Offshore surface waters of Antarctica are free of microplastics, as revealed by a circum-Antarctic study. *Mar Pollut Bull* 2019;149:110573. DOI
74. Munari C, Infantini V, Scoponi M, Rastelli E, Corinaldesi C, Mistri M. Microplastics in the sediments of Terra Nova Bay (Ross Sea, Antarctica). *Mar Pollut Bull* 2017;122:161-5. DOI PubMed
75. Allen S, Allen D, Moss K, Le Roux G, Phoenix VR, Sonke JE. Examination of the ocean as a source for atmospheric microplastics. *PLoS One* 2020;15:e0232746. DOI PubMed PMC
76. Almroth B, Eggert H. Marine plastic pollution: sources, impacts, and policy issues. *Rev Env Econ Policy* 2019;13:317-26. DOI
77. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. *Sci Adv* 2017;3:e1700782. DOI PubMed PMC
78. Bråte IL, Halsband C, Allan I, Thomas K. Report made for the Norwegian Environment Agency: microplastics in marine environments; occurrence, distribution and effects. Available from: http://www.miljodirektoratet.no/Documents/publikasjoner/M319/M319.pdf. [Last accessed on 24 Dec 2024].
79. Erni-Cassola G, Zadjelovic V, Gibson MI, Christie-Oleza JA. Distribution of plastic polymer types in the marine environment; a meta-analysis. *J Hazard Mater* 2019;369:691-8. DOI PubMed
80. Illuminati S, Notarstefano V, Tinari C, et al. Microplastics in bulk atmospheric deposition along the coastal region of Victoria Land, Antarctica. *Sci Total Environ* 2024;949:175221. DOI
81. Henry B, Laitala K, Klepp IG. Microplastic pollution from textiles: a literature review. 2018. Available from: https://hdl.handle.net/20.

500.12199/5360. [Last accessed on 24 Dec 2024].
82. Šaravanja A, Pušić T, Dekanić T. Microplastics in wastewater by washing polyester fabrics. *Materials* 2022;15:2683. DOI PubMed PMC
83. Yuan Z, Nag R, Cummins E. Ranking of potential hazards from microplastics polymers in the marine environment. *J Hazard Mater* 2022;429:128399. DOI PubMed
84. Barboza LGA, Frias JP, Booth AM, et al. Microplastics pollution in the marine environment. World seas: an environmental evaluation. Elsevier; 2019. pp. 329-51. DOI
85. Dethleff D, Kempema EW. Langmuir circulation driving sediment entrainment into newly formed ice: tank experiment results with application to nature (Lake Hattie, United States; Kara Sea, Siberia). *J Geophys Res* 2007;112:2005JC003259. DOI