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Thirty years of marine debris in the Southern Ocean: Annual surveys of two island shores in the Scotia Sea

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ABSTRACT

We report on three decades of repeat surveys of beached marine debris at two locations in the Scotia Sea, in the Southwest Atlantic sector of the Southern Ocean. Between October 1989 and March 2019 10,112 items of beached debris were recovered from Main Bay, Bird Island, South Georgia in the northern Scotia Sea. The total mass of items (data from 1996 onwards) was 101 kg. Plastic was the most commonly recovered item (97.5% by number; 89% by mass) with the remainder made up of fabric, glass, metal, paper and rubber. Mean mass per item was 0.01 kg and the rate of accumulation was 100 items km^{-1} $month^{-1}$. Analyses showed an increase in the number of debris items recovered (5.7 per year) but a decline in mean mass per item, suggesting a trend towards more, smaller items of debris at Bird Island. At Signy Island, South Orkney Islands, located in the southern Scotia Sea and within the Antarctic Treaty area, debris items were collected from three beaches, during the austral summer only, between 1991 and 2019. In total 1304 items with a mass of 268 kg were recovered. Plastic items contributed 84% by number and 80% by mass, with the remainder made up of metal (6% by number; 14% by mass), rubber (4% by number; 3% by mass), fabric, glass and paper (< 1% by number; 3% by mass). Mean mass per item was 0.2 kg and rate of accumulation was 3 items km^{-1} $month^{-1}$. Accumulation rates were an order of magnitude higher on the western (windward) side of the island (13–17 items km^{-1} $month^{-1}$) than the eastern side (1.5 items km^{-1} $month^{-1}$). Analyses showed a slight decline in number and slight increase in mean mass of debris items over time at Signy Island. This study highlights the prevalence of anthropogenic marine debris (particularly plastic) in the Southern Ocean. It shows the importance of long-term monitoring efforts in attempting to catalogue marine debris and identify trends, and serves warning of the urgent need for a wider understanding of the extent of marine debris across the whole of the Southern Ocean.

1. Introduction

Anthropogenic marine debris, particularly plastic, has long been recognised as a global environmental concern, affecting even the remote polar regions (Derraik, 2002; Gregory and Ryan, 1997; Barnes et al., 2009; Cózar et al., 2014; Avio et al., 2016; Xanthos and Walker, 2017). Recent studies estimate that between 4.8 and 12.7 million metric tonnes of plastic waste enters the global ocean from the land each year (Jambeck et al., 2015), however a large proportion of floating and stranded plastic debris may originate directly from shipping (Ryan et al., 2019). This oceanic marine debris can cause harm to wildlife (Gregory, 2009; Gall and Thompson, 2015; Li et al., 2016); facilitate the transport of non-native species (Barnes, 2002; Rech et al., 2016; Miralles et al., 2018) and, when washed up onto our beaches, has been shown to reduce the aesthetic appeal and psychological benefits of visiting coastal environments (Wyles et al., 2016).

Despite its remote location and significant distance from human habitation, the impact of marine debris on Southern Ocean wildlife has been reported since the 1970s. This includes entanglement of marine mammals (Payne, 1979; Bonner and McCann, 1982; Arnould and Croxall, 1995; Waluda and Staniland, 2013), and the ingestion and entanglement of debris by seabirds (Van Franeker and Bell, 1988; Huin and Croxall, 1996; Nel and Nel, 1999; Ryan et al., 2016; Phillips and Waluda, this volume). Beached marine debris has been reported from various oceanic shores in the Southern Ocean, including the Ross Sea coast (Gregory et al., 1984); Deception Island (Gregory and Ryan, 1997); Heard and Macquarie Islands (Slip and Burton, 1991); Livingston Island (Torres and Jorquera, 1995); South Georgia, the South

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Orkneys and the South Shetland Islands (Walker et al., 1997; Convey et al., 2002; Monteiro et al., 2018) and Adelaide Island, Antarctic Peninsula (Barnes and Fraser, 2003). Floating debris items such as fishing buoys and packaging bands have also been observed during surveys in the South Pacific Sector of the Southern Ocean (Grace, 1997) and as far south as 73°S, in the Bellingshausen Sea (Barnes et al., 2010). While the majority of these earlier studies focussed on macro-debris (i.e., items > 5 mm), recent work has suggested that microplastics (items < 5 mm; Thompson et al., 2004), from both primary sources (e.g. industrial scrubbers, microbeads in cosmetics, pre-production pellets; GESAMP, 2015) and the breakdown of larger items, are an emerging area of concern in the Southern Ocean (Isobe et al., 2017; Waller et al., 2017; Reed et al., 2018; Bessa et al., 2019). The Southern Ocean has relatively few direct sources of man-made marine waste, so the input of debris is likely to be from local shipping, research station resupply activities or transported from further afield (Walker et al., 1997; Slip and Burton, 1991; Barnes et al., 2010; Waller et al., 2017; Ryan et al., 2019).

1.1. Legislation and international agreements

The development and effective implementation of legislation, applicable at the national and international levels, is essential for the effective management of pollution in the world's oceans, including those around Antarctica. Since the early 1970s, there have been various measures to reduce marine debris in the Southern Ocean. The International Convention for the Prevention of Pollution from Ships (1973) as modified by the Protocol of 1978 (MARPOL 73/78) aims to prevent pollution of the marine environment. The issue of marine debris is covered in its Annex V, which prohibits the deliberate release of plastic and other waste from ships, but the level of adherence to these regulations may not always be consistent, particularly amongst those participating in illegal, unreported, unregulated (IUU) fishing (Chen, 2015).

This study considers debris accumulation on oceanic island shores of the South Orkney Islands which are located within the Antarctic Treaty area (the area south of latitude 60°S) and fall under the governance of the Antarctic Treaty Consultative Meeting (ATCM; https://www.ats.aq/index_e.htm), and South Georgia, which is under the jurisdiction of the Government of South Georgia and the South Sandwich Islands (GSGSSI).

The area south of 60°S is governed by the 29 Consultative Parties to the Antarctic Treaty. The Protocol on Environmental Protection to the Antarctic Treaty designates Antarctica as a 'natural reserve, devoted to peace and science' and contains Annexes on Waste Disposal and Waste Management (Annex III) and Prevention of Marine Pollution (Annex IV). Annex I, Environmental Impact Assessment (EIA), requires Parties to undertake EIAs for all activities within the Antarctic Treaty area, including the implementation of measures to mitigate impacts. Annex IV specifically prohibits the disposal into the sea of all plastics, including synthetic ropes, synthetic fishing nets and plastic bags.

The GSGSSI is the body responsible for the drafting of legislation concerning South Georgia, which includes Bird Island. The Environmental Charter for South Georgia and the South Sandwich Islands, adopted in September 2001, provides a framework for South Georgia to play a part in developing policies on the environment, as well as helping it to implement effectively appropriate multilateral environmental agreements to which the United Kingdom is a party. One guiding principle of the Charter for the United Kingdom and GSGSSI is to control pollution, with the polluter paying for prevention or remediation.

1.2. CCAMLR marine debris programme

All data reported in this study are submitted annually to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Marine Debris programme (https://www.ccamlr.org/). This programme was established in 1989 to monitor debris in the Southern Ocean, with specific regard to fishing debris items, as a response to increasing concerns regarding global marine debris levels. CCAMLR Members monitor marine debris from beach surveys (Torres et al., 1997; Walker et al., 1997), debris associated with seabird colonies (Huin and Croxall, 1996; Nel and Nel, 1999), entanglements of marine mammals (Arnould and Croxall, 1995; Hucke-Gaete et al., 1997; Waluda and Staniland, 2013), and oiling events of mammals and seabirds (Reid, 1995), although these activities are currently limited to only a small number of locations.

Other CCAMLR initiatives to reduce or mitigate marine debris levels include specific measures on general environmental protection policy during fishing, including Conservation Measure 26–01 that prohibits the use of plastic packaging bands (used to secure bait boxes) in order to reduce potential risks of marine mammal entanglements. CCAMLR longline vessels are also required to report gear loss on a haul-by-haul basis to the Secretariat. Additionally, CCAMLR has recently been engaging with other international organisations such as the International Association of Antarctica Tour Operators (IAATO), the Scientific Committee on Antarctic Research (SCAR), the Global Partnership on Marine Litter (GPML), and Oceanites to increase data exchange and coordinate submission of opportunistically collected marine debris data.

1.3. Study aims

To date, the majority of Southern Ocean studies have considered only single point samples (Monteiro et al., 2018). In contrast, at Bird Island monthly surveys have been undertaken during the summer (1989/90 and 1990/91) and year-round since 1991 (Rodwell, 1990; Walker et al., 1997). At Signy Island, South Orkney Islands monthly surveys have taken place (during the summer only) between 1991 and 2019. We present data from these surveys and evaluate trends and variability in marine debris by examining number, mass, composition and rate of accumulation of debris at both sites and for comparison elsewhere.

2. Materials and methods

Surveys to collect all items of beached marine debris (collection of debris items typically limited to items of *macro*- and *meso*-debris, i.e. visible to the naked eye, > 5 mm) were undertaken at two island locations in the Scotia Sea (Fig. 1a). These were Main Bay, Bird Island, which lies off the north-west tip of South Georgia (Lat. 54°0′0″S, Long. 38°2′59″W; Fig. 1b and c) and three sites (Cummings Cove, Starfish Cove and Foca Cove) at Signy Island, South Orkney Islands (Lat. 60°43′0″S, Long. 45°36′0″W) (Fig. 1d and e). Each beach was surveyed once per month (usually at the end of the month) by one or two researchers with all debris items removed and measured in the laboratory.

2.1. Bird Island

Main Bay, Bird Island, is a 291 m stretch of beach comprised of shingle and sand. The bay has an open aspect to the south-east with the prevailing wind direction from the south-west (Fig. 1c). The research station at Bird Island is occupied year-round. Initial debris surveys took place in summer (October to March) 1989/90 and 1990/91, but the high breeding density of Antarctic fur seals *Arctocephalus gazella* (Boyd, 1993) prevented reliable monthly summer collections (Rodwell, 1990). Therefore, from 1991/92 to 2018/19 debris that accumulated during October, November and December was cleared from the beach during January, which, combined with February and March collections formed the summer total for each year (Walker et al., 1997). All items collected in the summer were pooled, therefore the summer rate of accumulation

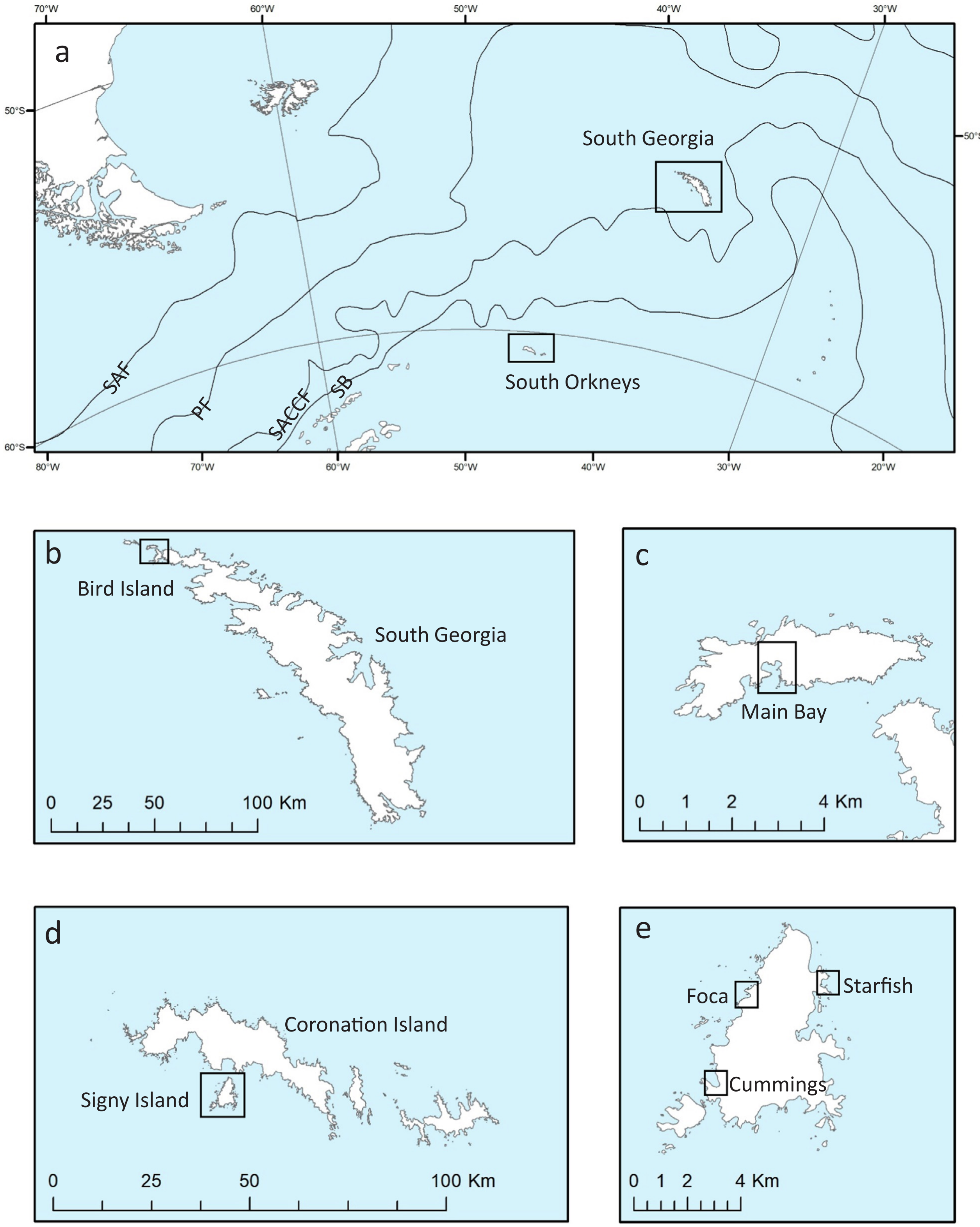

Fig. 1. (a) Map of the Scotia Sea, South Atlantic, with beaches surveyed for marine debris accumulation at Bird Island, South Georgia and Signy Island, South Orkney Islands shown. Location of the fronts of the Antarctic Circumpolar Current (ACC) are indicated, including Sub-Antarctic Front (SAF); Polar Front (PF); Southern Antarctic Circumpolar Current Front (SSACCF) and the Southern Boundary of the ACC (SB). Mean flow is generally northeastward across the Scotia Sea. (b) South Georgia, showing location of Bird Island. (c) Location of Main Bay, Bird Island. (d) South Orkney Islands showing location of Signy Island and Coronation Island. (e) Location of Foca Cove, Starfish Cove and Cummings Cove, Signy Island.

Table 1

Summary data of debris accumulation at Bird Island and Signy Island by site and season. *Bird Island summer rate of accumulation = total debris collected October to March divided by 6. **Bird Island mass data collected from April 1996 onwards.

Location	N surveys	N items	Total mass (kg)**	Rate of accumulation (Items km^{-1} $month^{-1}$)
Bird Island (all)	198	10,112	101.0	99.9
Bird Island (summer)*	30	5638	48.5	107.8
Bird Island (winter)	168	4474	52.5	91.4
Signy Island (all)	333	1304	265.7	3.1
Signy Island (Cummings Cove)	99	689	67.9	17.6
Signy Island (Foca Cove)	117	516	156.3	13.3
Signy Island (Starfish Cove)	117	99	41.5	1.5

was calculated as total debris accumulated over this six month period and divided by six to obtain a monthly mean value. During the winter (April to September), the beaches are generally free from fur seals and monthly sampling has taken place since April 1991. In our analyses, due to the differing sampling regimes, we assessed summer and winter accumulation separately, and then combined data into an annual total that ran from April to March. This has been denoted as the year in which the survey work ends; e.g. the period 1 April 2018 to 31 March 2019 is denoted by the year 2019.

2.2. Signy Island

Debris surveys at Signy Island were undertaken at three sites: Foca Cove, Cummings Cove and Starfish Cove (Fig. 1e). Foca Cove (beach length = 331 m) and Cummings Cove (beach length = 395 m) are both on the western side of the island and are exposed to the prevailing westerly winds. Both beaches consist of boulders, shingle and small areas of sand. Starfish Cove (beach length = 584 m) is on the eastern (leeward) side of the island, facing nearby Coronation Island (Fig. 1d). The beach consists of gently shelving gravel and shingle with some boulders. In contrast to Bird Island Research Station, Signy Island Research Station has been occupied during the austral summer only since 1997; this limits the debris surveys to the months personnel are present. Furthermore, heavy sea ice cover can prevent access to beaches during the winter months. Thus, monthly surveys took place when possible (provided personnel were present and ice cover did not restrict access to beaches; see results) during the months of November to April between 1991 and 2019 at Foca and Starfish Cove, and at Cummings Cove between 1994 and 2019. As sampling was not consistent year to year we calculated the summer rate of accumulation based on the number of sampled months in that summer season.

All surveys at Bird Island and Signy Island were undertaken following the CCAMLR protocols for surveys of beached marine debris (CCAMLR, 1993). Each survey took place on a single tide and, where possible, was carried out at low water. During the survey all debris items of more than 5 mm in largest dimension found between the low water mark and approximately 10 m beyond the high water mark were collected. Mass was recorded for all years for the Signy Island surveys and from 1996 onwards at Bird Island. Small items were weighed to a precision of 0.1 g and heavier items (> 100 g) to the nearest gramme. All items were categorised as fabric, glass, metal, paper, rubber or plastic, with plastic items further subdivided into fishery, consumer and miscellaneous items. Wood items were removed from beaches but are not included here as contemporary anthropogenic sources could not be distinguished from natural or historical items.

2.3. Analyses

For both locations we examine (a) the number and composition of items recovered, (b) the mass of items and (c) the rate of accumulation of debris (items per km of beach per month). At Bird Island we examine seasonal variability (summer and winter), and monthly variability during the winter. At Signy Island we examine the overall summer accumulation and patterns of debris aggregation by month, and compare debris accumulation at the three survey sites. Where possible the provenance of debris items was recorded.

2.4. Modelling of inter-annual trends

Annual debris totals (April to March) were summarized by combining winter collections with those from the following summer and labelled as the year at the end of sampling (e.g. April 2017 to March 2018 was labelled as 2018). Annual samples were expressed as both the total number of items and summed mass, and regressed against year using Generalised Additive Models (GAMs) with negative binomial distributions to detect temporal trends. GAMs were fitted with the mgcv package in R (R Core Team, 2013) using thin plate splines that allow the smoothing term to be reduced to zero if appropriate. Location (Island) was examined as an explanatory factor by testing different smoothers where data allowed and model fits were compared using examination of residuals and using the Akaike Information Criterion (AIC). Temporal trends in the total number and mass of items made of plastic were investigated in the same way. Changes in the mean mass of each item ('all' and 'plastic') were compared using the same methods except that a Gaussian family with a log link was used in the GAMs.

3. Results

3.1. Bird Island

During the 30-year period between October 1989 and March 2019, 168 monthly winter (April to September) and 30 cumulative summer (representing October to March) surveys were undertaken at Main Bay, Bird Island. A total of 10,112 items of beached debris, weighing over 100 kg, were recovered (Table 1). The great majority of these items (n = 9967; 97.6%) were composed of plastic, contributing 89% of the total mass (Table 2). The remainder consisted of metal, fabric, glass, paper and rubber items (Table 2). At least 3980 items (39%) contributing 53 kg (59% by mass) were recognisably fishing gear, comprising lines, nets, floats and ropes (Table 3). Packaging and consumer items, comprising bottles, lids, bags, packaging bands and polystyrene contributed 39% by number and 28% by mass. Miscellaneous plastic items (i.e. broken/unidentifiable items) contributed 23% by number and 13% by mass (Table 3). An average of 337 items weighing 4.21 kg were recovered per year, with a peak in mean number of items observed in 1996 (Fig. 2a) and a peak in mean mass in 1997 (Fig. 2b). The rate of accumulation of debris at Bird Island was on average 100 items km^{-1} $month^{-1}$ (Table 1). Examples of the types of items recovered are shown in Fig. 3. Of 72 items where the origin or language of text was recorded we found 32 to be of South American origin, 23 from Asia and 17 from Europe.

A total of 5638 items (56%) weighing 48.5 kg (48%) were recovered during summer sampling (October to March) and 4474 items (44%) weighing 52.5 kg (52%) during winter sampling (April to September; Table 1). Despite differing sampling regimes, similar amounts and weights of debris were recovered, and similar rates of accumulation

Table 2
Composition of beached marine debris at Bird Island (1989–2019) and Signy Island (summer only; 1991–2019) *Mass data collected at Bird Island from 1996 onwards.

	Bird Island				Signy Island			
Type	number of items	% by number	mass (kg)*	%	number of items	% by number	mass (kg)	% by mass
Plastic	9867	*97.6*	90.0	89.2	1112	*85.3*	212.4	79.9
Metal	51	*0.5*	1.1	1.1	81	*6.2*	37.0	13.9
Fabric	62	*0.6*	6.3	6.3	22	*1.7*	5.4	2.0
Glass	41	*0.4*	1.8	1.8	18	*1.4*	1.2	0.4
Paper	7	*0.1*	0.2	0.2	24	*1.8*	1.3	0.5
Rubber	84	*0.8*	1.5	1.5	47	*3.6*	8.5	3.2
Total	**10,112**		**101.0**		**1304**		**265.7**	

were observed in both seasons, with 108 items km^{-1} $month^{-1}$ during summer (assuming data were representative of the 6 month period, i.e., October-March) and 91 items km^{-1} $month^{-1}$ during winter (Table 1). There was no correlation between accumulation rates during winter and the following summer. Mean monthly debris accumulation was between 15 and 46 items per month (Fig. 4).

3.2. Signy Island

At Signy Island a total of 333 surveys were undertaken, with up to five surveys per beach per year. These were undertaken once per month, usually between November and March. Surveys took place at Foca and Starfish Coves in early April 1991 and were included in the summer totals for that year, but April sampling was not continued in subsequent years. Between six and 15 surveys were completed each year, with surveys not taking place due to logistical reasons, either due to snow and ice preventing access to beaches, or staff not being present due to varying occupation dates of the summer-only research station.

A total of 1304 items of beached marine debris, with a combined mass of 266 kg, were recovered from Signy Island between 1991 and 2019 (Table 1). The majority of these items (n = 1112; 85%) were composed of plastic, with some metal (6%) and rubber (4%) items and the remainder made up of fabric, glass, and paper (Table 2). Plastic (80%) and metal (14%) made up the majority of items by mass (Table 2). One hundred and twelve items (10%) comprised fishing gear, contributing 69% of the overall mass (Table 3). Packaging items such as packaging bands, crates, bags, polystyrene and bottles contributed 50% by number and 19% by mass (Table 3). Plastic packaging bands (n = 306) were the most common item found, contributing 28% by number and 5% of the total mass (Table 3). Miscellaneous (broken/unidentifiable) plastic items contributed 40% by number and 12% by mass (Table 3). The overall rate of accumulation was 3 items km^{-1} $month^{-1}$ (Table 1). An average of 45 items, weighing 9.8 kg, were recovered per year. Mean debris accumulation (by number) was highest during 1994 (Fig. 5a), with a peak in mean mass observed in 2019 (Fig. 5b), although this was mainly due to one large fishing net (> 80 kg) recovered at Foca Cove in December 2019. Debris accumulation was low between 2012 and 2019, and despite monthly surveys during December to February 2015 and November to February 2016, no debris items were recovered in either year (Fig. 5). Of 34 items where the origin or language of text was recorded we found 20 to be of Asian origin, seven from South America, four from Europe, and one each from Africa, Australasia and North America.

A total of 117 months of survey effort were undertaken at each of Foca and Starfish Coves, with 99 months of survey effort at Cummings Cove (with work beginning here in 1994). The vast majority of debris items (92.5%) were recovered from the west coast, with 689 items from Cummings Cove (53%) and 516 from Foca Cove (39.5%); only 99 items (7.5%) were recovered from Starfish Cove on the east coast (Table 1). Total mass of debris was highest at Foca Cove (156.3 kg, 59%), with 67.9 kg (26%) recovered from Cummings Cove and 41.5 kg (16%) from Starfish Cove.

Accumulation rates were an order of magnitude higher on the western coasts (18 items km^{-1} $month^{-1}$ at Cummings Cove and 13 items km^{-1} $month^{-1}$ at Cummings Cove) compared to the east (1.5 items km^{-1} $month^{-1}$ at Starfish Cove) (Table 3). Mean debris accumulation was highest in 1992 at Foca Cove, 1994 at Cummings Cove and 2008 at Starfish Cove. Mean monthly debris accumulation was between 1 and 6 items per month (Fig. 6).

3.3. Modelling of inter-annual trends

In terms of number of items collected per year, location was included in all of the best model fits. At Bird Island, the total number of items collected per year of sampling increased to a peak in 1996 followed by a slight fall then an increase over time (Fig. 7a), with a mean overall increase of 5.7 items per year. In contrast, data from Signy Island showed a slight (non-significant) decrease in items collected per year over time (Fig. 7a). The annual total mass of debris collected at Bird Island showed the opposite trend to the number of items, with a

Table 3
Summary of plastic debris by category and type at Bird Island and Signy Island.

		Bird Island				**Signy Island**			
	Type	N	*% by number*	Mass (kg)	*% by mass*	N	*% by number*	Mass (kg)	*% by mass*
Fishing	fishing line	1178	*11.9*	5.0	*5.5*	9	*0.8*	1.8	*0.8*
	fishing net	1855	*18.8*	21.2	*23.5*	13	*1.2*	103.6	*48.8*
	floats/buoys	20	*0.2*	1.4	*1.5*	12	*1.1*	31.4	*14.8*
	ropes	837	*8.5*	25.7	*28.5*	78	*7.0*	9.9	*4.7*
Packaging/ consumer	packaging bands	347	*3.5*	2.0	*2.2*	306	*27.5*	9.6	*4.5*
	bottles/cups/lids	539	*5.5*	8.4	*9.3*	84	*7.6*	11.1	*5.2*
	packaging bags/sheets	840	*8.5*	8.7	*9.7*	70	*6.3*	7.9	*3.7*
	polystyrene	2022	*20.5*	6.4	*7.1*	96	*8.6*	11.5	*5.4*
Other	miscellaneous	2229	*22.6*	11.3	*12.6*	444	*39.9*	25.6	*12.0*
	Total	**9867**		**90.0**		**1112**		**212.4**	

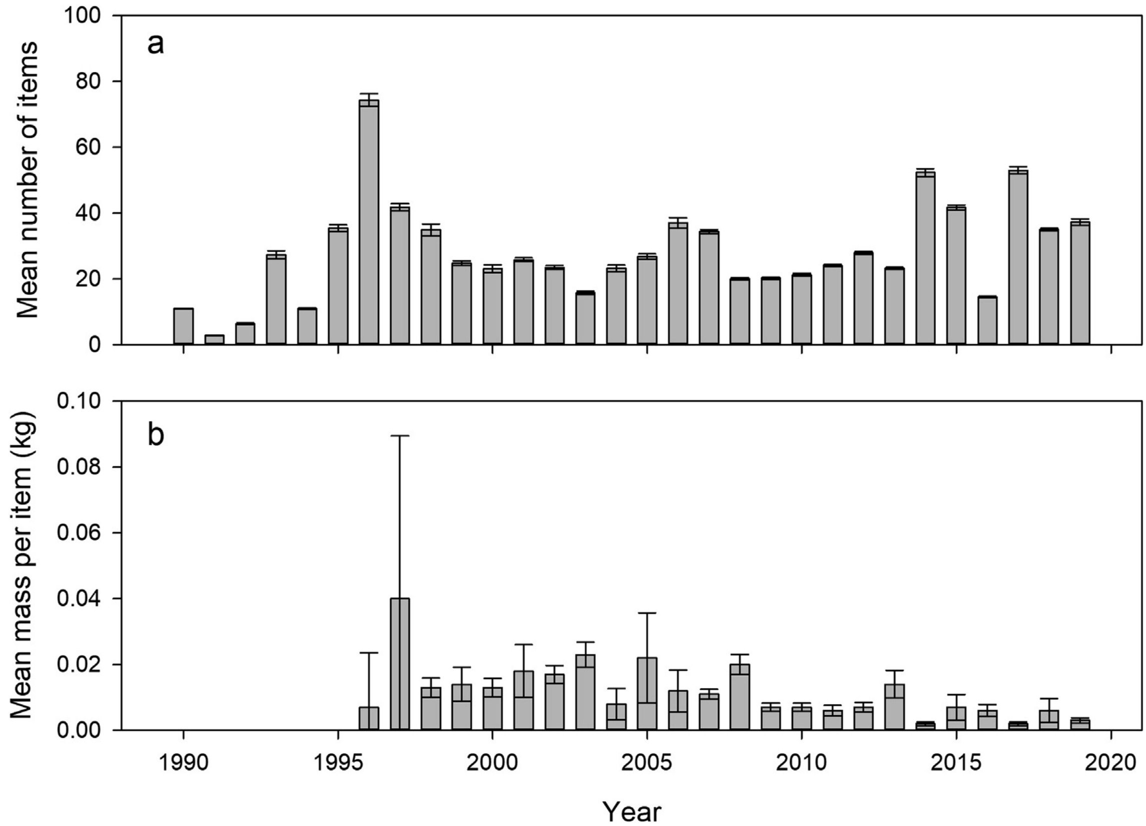

Fig. 2. (a) mean number and (b) mean mass per item of beached debris items recovered per year from Main Bay, Bird Island, 1989–2019. Error bars show ± 2SE.

significant negative relationship with year dropping on average 174 g per year (Fig. 7c), although this only explained ~10.5% of the deviance. The total mass of items at Signy Island showed no significant trend. Overall the results for the total number of plastic items collected were similar to those for all items (Fig. 7b). At Bird Island there was a tendency for the number of plastic items to increase over time ($p = 0.058$), but the mass of plastic items showed a significant negative relationship over time (Fig. 7d). The number of plastic items at Signy Island showed a slight but non-significant decrease over time (Fig. 7b) and there was no trend in the mass of plastic items. At Bird Island the relationship between number of items and their mass was reflected in the decline in mean mass per item over time for all items and plastic items (Fig. 8). However, at Signy Island, the mean mass per item, for all debris and for only plastic debris showed a non-linear relationship with time with an overall tendency for slightly heavier items in later years.

Fig. 3. Examples of plastic debris recovered from Main Bay, Bird Island, October 2018–March 2019.

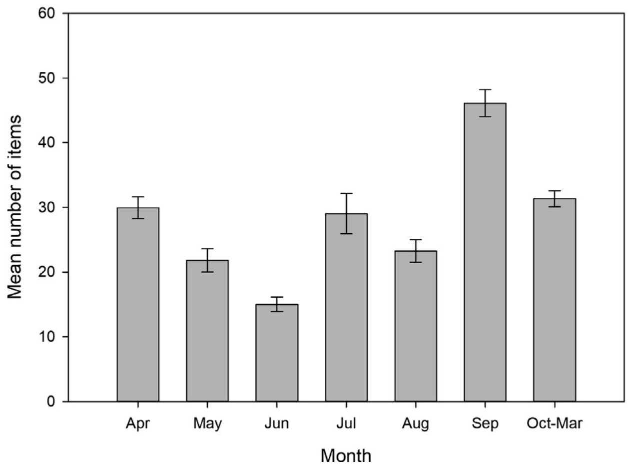

Fig. 4. Mean number of items recovered by monthly sampling at Bird Island 1991–2019. Data for October to March (total debris averaged over six months) are included for comparison. Error bars show ± 2SE.

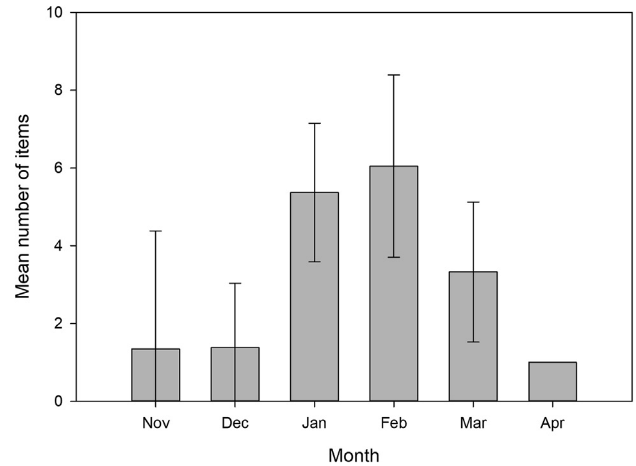

Fig. 6. Mean number of items recovered at Signy Island by monthly sampling unit, 1991 to 2019. Error bars show ± 2SE.

4. Discussion

We report here on 30 years of beached debris sampling from the Southern Ocean. These data represent one of the longest and most comprehensive time series of beached marine debris available globally. Plastic was the dominant material found in our study, as is the case elsewhere in the South Atlantic (Ryan, 1987; Convey et al., 2002; Barnes et al., 2018; Monteiro et al., 2018) and globally (Derraik, 2002; Barnes et al., 2009; Ryan et al., 2009; Cózar et al., 2014; Avio et al., 2016; Li et al., 2016).

4.1. Origin and nature of beached marine debris

Both Bird Island and Signy Island support a very small human presence and are far removed from population centres, so the majority of items recovered will be from distant sources, from local shipping or possibly from the research stations themselves (albeit strict waste management practices are employed at both research stations in accordance with the Environmental Protcol or GSGSSI legislation). Ryan et al. (2019) found that ships were responsible for most of the bottles stranding at Innacessible Island in the central South Atlantic, with the majority of items originating from South America and Asia. In our study

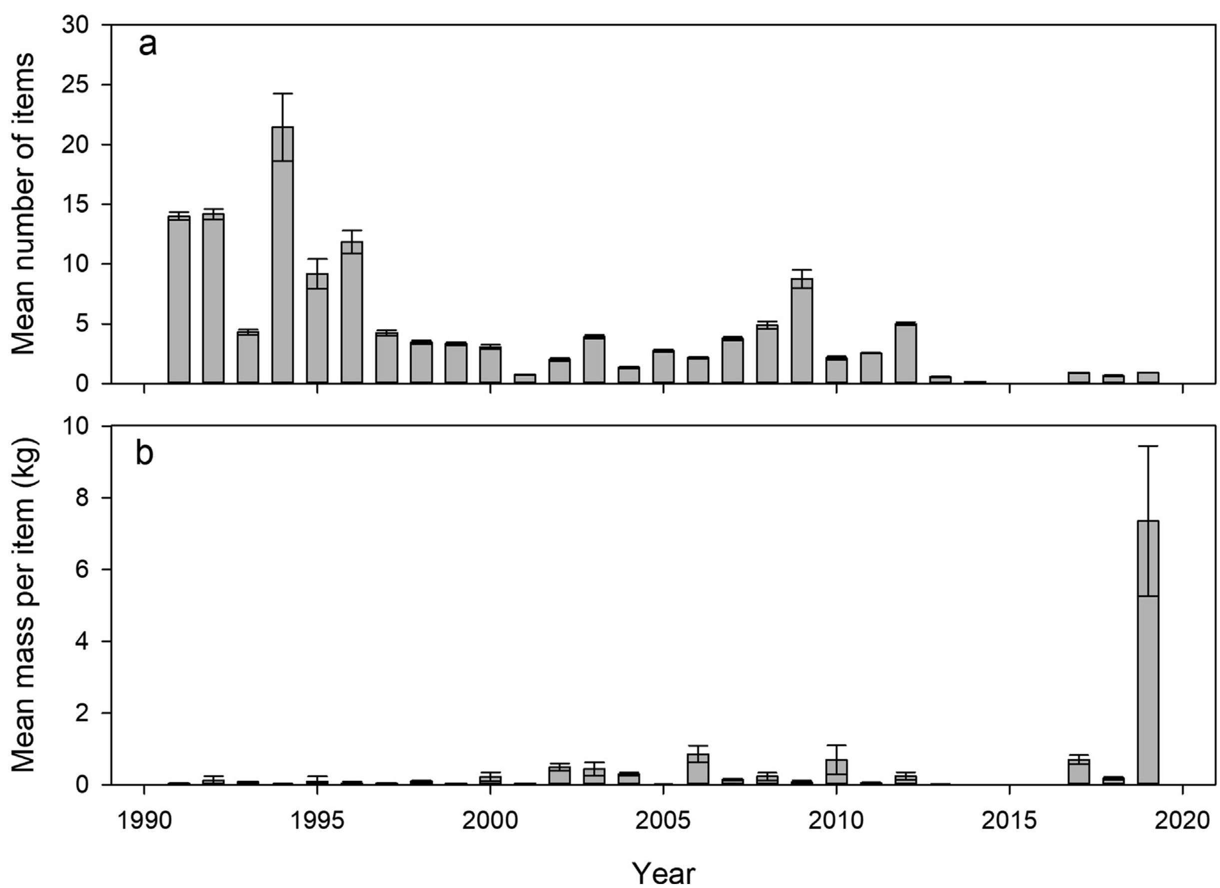

Fig. 5. (a) mean number and (b) mean mass per item of beached debris items recovered per summer season at Signy Island 1991 to 2019. Error bars show ± 2SE.

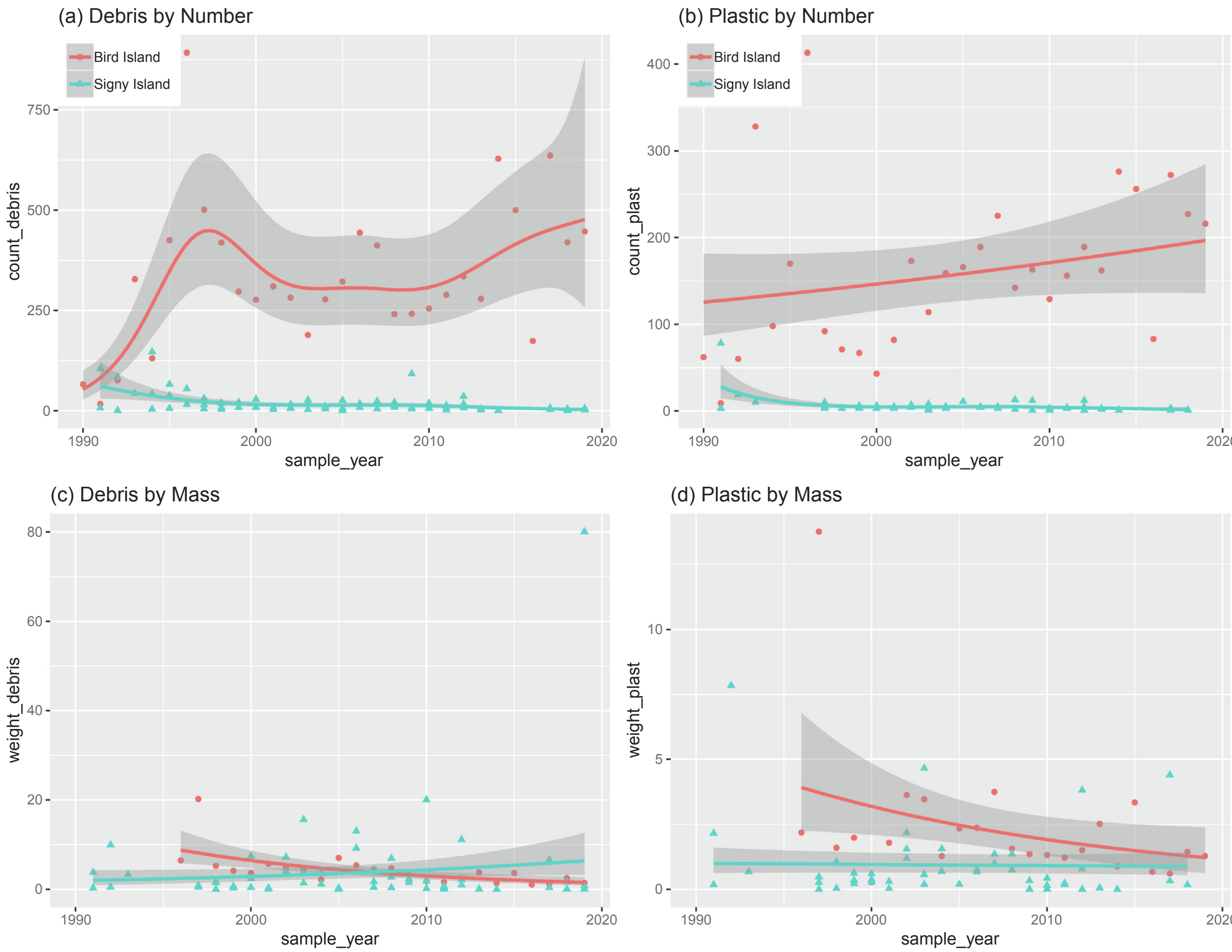

Fig. 7. Total number of (a) all debris items (b) plastic debris items, and summed mass of (c) all debris items (d) plastic debris items for each year (April to March) against year with collection location (Island) as a factor. Lines represent modelled output from GAMs. Bird Island shown in red and Signy Island in blue. Grey shading indicates standard error. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

we found that some of the items recovered from the two sites had labels originating from various locations including Europe, South America and Asia, though it is unclear as to where they may have entered the marine environment. Due to its buoyancy, plastic debris may be transported large distances by ocean currents. In the Scotia Sea near-surface flow is dominated by the northeastward-flowing Antarctic Circumpolar Current (ACC) that connects the Antarctic Peninsula region to South Georgia (e.g. Orsi et al., 1995). At the South Orkney Islands, the Weddell Front flows around the southern side of the South Orkney Plateau before retroflecting to the northwest of the plateau (Heywood et al., 2004). In addition to the large-scale flows, smaller-scale and higher frequency processes, including cross-shelf transfer and retention and tides, will be important for deposition of debris at the Bird Island and Signy Island sampling locations. Trajectories of near-surface drifters and observations of rafted biological material demonstrate that items can be transferred southwards from lower latitudes to polar regions (Fraser et al., 2018; Waller et al., 2017), suggesting the possibility of plastic transfer from South America and beyond. It is possible that some of the debris accumulating at Bird Island and Signy Island may have originated from local shipping (cf. Ryan et al., 2019), although legislative measures are in place to avoid the input of plastic into the environment (local or otherwise).

Fishing gear contributed the largest proportion of debris by mass at both Bird Island (53%) and at Signy Island (69%), despite contributing only 39% of items by number at Bird Island and 10% at Signy Island. This is likely to be due to a small number of very large fishing items recovered (e.g. nets and buoys). Fishing gear often comprises a disproportionally large amount of litter, for example in the central Pacific (Lebreton et al., 2018). While both Bird and Signy Island samples contained large numbers of miscellaneous plastic items, there were variations in types of debris found; more fishing line/net was collected at Bird Island, while plastic packaging bands were the most common type of identified plastic at Signy Island. In terms of consumer plastics, similar proportions of bottles/cups and packaging bags/sheets were found at the two sites but polystyrene was proportionally more prevelant at Bird Island. These findings might reflect differences in fishing/shipping activities in the two regions or differing retention of the different debris items. It is possible that many items (particularly packaging bands which were prohibited from use in the CCAMLR Convention area in 1996) have been floating around in the marine environment for many years before making landfall. Timescales and pathways of transport depend on the timing of the release of material and its position in the water column (whether at or beneath the surface; Wichmann et al., 2019), which could, in part, account for differential deposition of e.g. packaging bands and fishing nets. Modelling studies using the data here, alongside local and regional oceanographic models will be used in future studies to understand the mechanisms of debris transport in the Scotia Sea (cf. van Sebille et al., 2015; Fraser et al., 2018; Lacerda et al.,

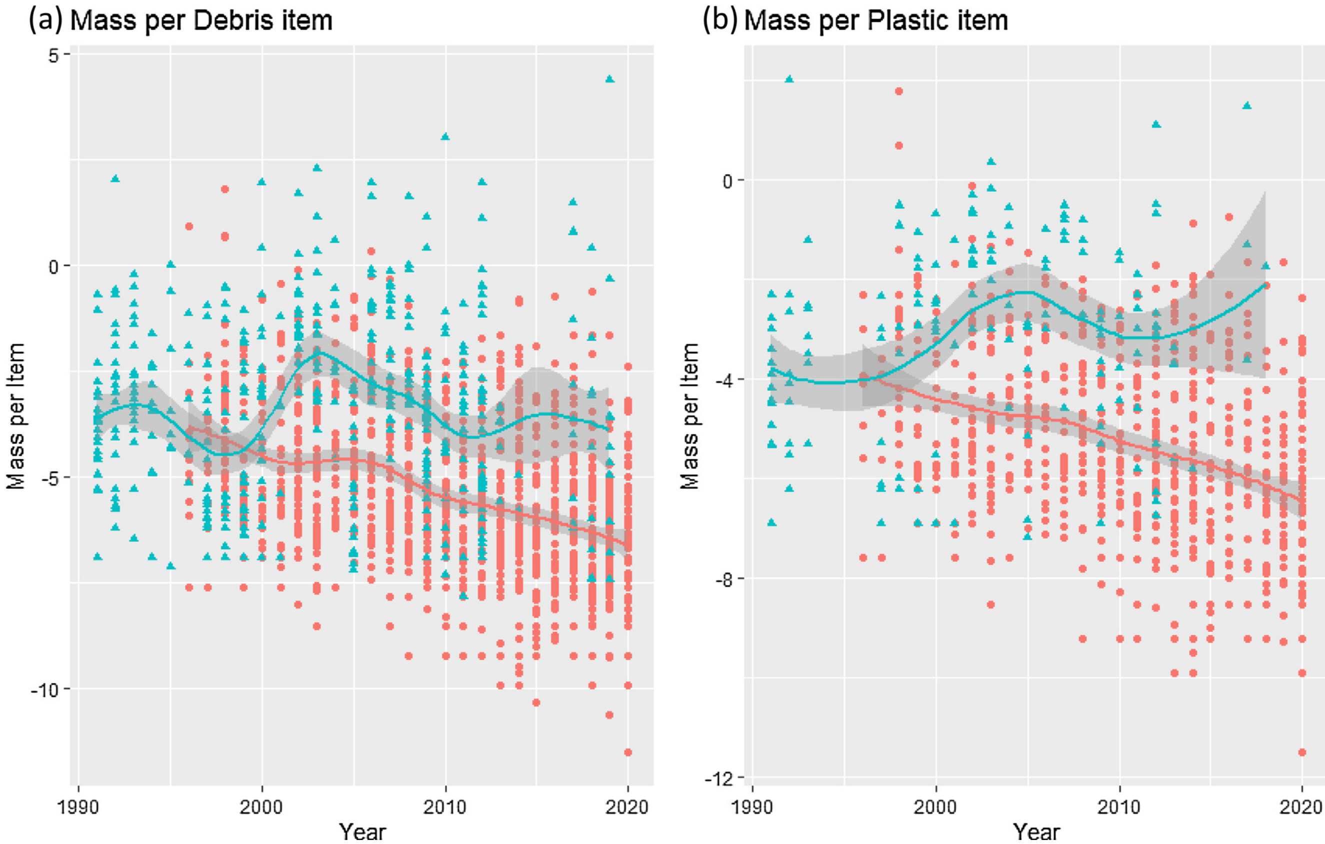

Fig. 8. Log mean mass of (a) all debris items (b) plastic debris items against year of collection (April to March) at Bird Island (in red) and Signy Island (in blue). Lines represent modelled output from GAMs. Grey shading indicates standard error. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2019).

Many of the miscellaneous plastic items were fragments which makes it impossible to establish their type or origin. However, the use of Fourier-Transform Infrared (FTIR) spectroscopy and Raman spectroscopy techniques have enabled the assessment of plastic fragments in order to identify their composition and likely origins (Thompson et al., 2004; Lenz et al., 2015; Lacerda et al., 2019). Recent studies in Antarctic waters found polymers comprising polyurethane (insulation and sealants from ships/bases) and polyamide (characteristic of fishing net and ropes) which were likely to be of local origin (Lacerda et al., 2019). Future studies will use these techniques to further understand the composition of debris from Bird Island and Signy Island.

Metal (e.g. tins, nails, wires, fur seal flipper bands) and rubber items (e.g. tubing, gloves, a meteorological balloon) were present at both sites but were proportionally more prevalent at Signy Island than at Bird Island. A small proportion of these items may have originated from the research station itself from a time before the implementation of the Protocol on Environmental Protection to the Antarctic Treaty, when waste management practices were less rigorous, or could have been historical artefacts from the whaling industry, particularly at Signy Island. Since the early 1990s stringent waste management practices have been enforced at both Bird Island and Signy Island Research Stations, so we would expect the vast majority of debris to be from marine sources.

It is possible that small amounts of debris, including fishing floats and hooks, found in our surveys may have originated from seabirds, but this debris is generally found in the vicinity of bird colonies rather than on beaches (Huin and Croxall, 1996; Nel and Nel, 1999; Phillips and Waluda, this volume). Seabirds can mistake floating marine debris as food and return it to their chicks on nests. Such debris has been recorded at Bird Island, particularly in association with wandering, black-browed and grey-headed albatrosses, as well as in giant petrel nests (Huin & Croxall, 1996; Phillips and Waluda, this volume) but has been less common at Signy island where there are no breeding populations of albatrosses; however long-line hooks have occasionally been found in giant petrel nests (M Dunn; pers obs.).

4.2. Trends and patterns in debris accumulation

We found little evidence of a trend in plastic accumulation over the last 30 years, consistent with other studies, for example in the North Atlantic subtropical gyre (Law et al., 2010) and the Baltic Sea (Beer et al., 2018). Ryan (2008) found no changes in the ingestion of plastics by seabirds in the Atlantic and the southwest Indian Ocean between the 1980s and 1999–2006, and van Franeker and Law (2015) found a decrease in plastic ingested by fulmars in the Southern North Sea between 1979 and 2012. This suggests that much of the plastic in our oceans may be “lost” from the ocean surface to sinks such as the deep sea (Woodall et al., 2014), rather than reaching oceanic shores.

Levels of debris accumulation reported here are consistent with other islands in the South Atlantic Ocean (see review in Monteiro et al., 2018), with marine-based activities the primary source of beached debris. There is some suggestion of declining debris accumulation with increasing latitude in our survey data, with accumulation of debris much lower at Signy Island than Bird Island. This could indicate the effectiveness of legislation to reduce debris in the Antarctic Treaty region or may relate to local conditions, with seasonal sea ice potentially a barrier to the accumulation of oceanic marine debris at Signy Island. The mean mass of debris items was generally higher at Signy Island, suggesting that only larger items are able to travel this far. Alternatively, the beach substrate at Signy Island is much coarser than at Bird Island such that smaller items of debris may be caught up between larger rocks and boulders and not recovered in the surveys. It is possible that smaller items may sink due to oceanographic processes or biofouling (Fazey and Ryan, 2016), or be abraded by sea ice at these higher latitudes. We did not record biofouling in the present study, but bryozoans and polychaetes have been recorded on plastic items recovered at Bird Island (Barnes, 2014) and on the Antarctic Peninsula (Barnes and Fraser, 2003), but there are no equivalent data from Signy Island. Local conditions can also affect the deposition of debris on beaches, with wind, topography and local currents and tides all having an effect, even at very small scales. Wind direction was shown to be an important factor at Signy Island (but not measured at Bird Island) with debris accumulation much higher on windward compared to lee shores. Similar patterns of increased debris on windward shores are observed elsewhere, for example the Caribbean (Debrot et al., 2013), Henderson Island in the South Pacific (Lavers & Bond, 2017) and various island shores in the Atlantic Ocean (Monteiro et al., 2018).

Analyses of both sites suggested highest deposition in the 1990s, which may, in some cases, include sampling of items which had accumulated in the period before any surveys took place. This is particularly evident at Cummings and Foca Cove, Signy Island, at which the highest rate of deposition was seen in the earliest years of surveys (1991 at Foca Cove and 1994 at Cummings Cove). The highest level of debris occurred in 1996 at Bird Island, which is a similar pattern to that seen in seals entangled at the same location (Waluda and Staniland, 2013). At Bird Island the rate of deposition was highest in September, possibly driven in part by winter storms. In contrast, at Signy Island, deposition was highest in January and February potentially due to debris accumulating once sea ice has cleared from around the island.

During the period of the surveys, particularly at Bird Island, a trend was observed towards more, smaller plastic items. This finding might indicate the breakdown of larger pieces of plastic as opposed to an increased input into the system of smaller items. During the spring and early austral summer (late September to early December) ultra-violet (UV) light levels are raised due to seasonally thinned stratospheric ozone over Antarctica (Farman et al., 1985). High UV and reduced temperatures mean that plastic items tend to become brittle, break down into small pieces, and eventually degrade further (Moore, 2008). Since the early 2010s there has been very little debris recovered at Signy Island with no debris at all in 2015 or 2016, despite no reduction in survey effort. Further work is required to understand why this might have occurred.

Early analyses of these same data (1991–1995) from Bird Island found debris to be dominated by synthetic line (76%), packaging bands (6%) and polythene bags (6%) (Walker et al., 1997). Whilst these items are still present, the diversity of items appears to have increased (Table 3). The same study found debris accumulation to be higher during the winter in all years (Walker et al., 1997), whereas we found winter debris to be higher in 10 out of 27 years (for which data from both seasons are available), suggesting debris accumulation is highly variable across the year.

4.3. Recent policy and practical developments within the Southern Ocean

This study highlights the prevalence of anthropogenic marine debris (particularly plastic) in the Southern Ocean. CCAMLR has been at the forefront of plastic monitoring in the Southern Ocean, and has recently proposed a review of their programme to formalise methodologies to bring it into line with global measures (CCAMLR Secretariat, 2019). Similarly, the Scientific Committee on Antarctic Research has established a Plastic in Polar Regions Action Group with the aim of estimating current levels of pollution, understanding the risk to ecosystem health and establishing measures to limit plastic pollution in polar environments (https://www.scar.org/science/plastic/home/). Furthermore, the Antarctic Treaty Consultative Meeting (ATCM), agreed Resolution 1 (2019) '*Reducing Plastic Pollution in Antarctica and the Southern Ocean*' at ATCM XLII in July 2019. The Treaty Parties agreed to support greater monitoring of plastic pollution in Antarctica using developing standards and comparative methodologies.

Further guidance on minimising plastic pollution has been produced by both National Operators working in Antarctica and elements of the Antarctic tourism industry. The Council of Managers of National Antarctic Programs (COMNAP) Environmental Protection Group proposed key recommendations for National Operators to reduce macro- and micro-plastic pollution in Antarctica (see: https://www.comnap.aq/Groups/Environment/SitePages/Home.aspx). These include working with suppliers to reduce plastics being transported to Antarctica and the removal/clean-up of plastic pollution, including recording levels of plastic pollution discovered. The industry body for Antarctic tourism, IAATO, has also taken steps to reduce plastic pollution in the Southern Ocean through its Plastic Reduction Programme (including formal participation in the CCAMLR Marine Debris Programme) and by developing new guidelines for visitors to the polar regions that aim to reduce single-use plastics (IAATO, 2019).

Monitoring the marine environment for the last three decades has provided us with unprecedented insights into the composition and deposition of marine debris in this part of the Scotia Sea. Despite its remoteness, thirty years of monitoring in the Southern Ocean has shown a prevelance of anthroprogenic debris washed up on Antarctic and sub-Antarctic beaches, with plastic items dominating this pollution. These data, together with oceanographic models should allow us to further understand the sources and transport pathways in the Southern Ocean. Our analyses suggest that measures to restrict debris input into the Southern Ocean have been successful in part but there is a clear need for a wider understanding of the extent of marine debris across the Southern Ocean as a whole.

CRediT authorship contribution statement

Claire M. Waluda: Conceptualization, Formal analysis, Methodology, Visualization, Writing - original draft. **Iain J. Staniland:** Formal analysis, Methodology, Investigation, Writing - review & editing. **Michael J Dunn:** Investigation, Writing - review & editing. **Sally E Thorpe:** Writing - review & editing. **Emily Grilly:** Writing - review & editing, Data curation. **Mari Whitelaw:** Data curation. **Kevin A Hughes:** Writing - review & editing.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105460.

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