J-STAGE Advance published date: December 8, 2021

SPATIAL AND TEMPORAL DISTRIBUTION OF FLOATING MARINE MACRO DEBRIS IN THE INDO-PACIFIC REGION OF THE ANTARCTIC

Tatsuya ISODA[1]*, Koji MATSUOKA[1], Tsutomu TAMURA[1] and Luis A. PASTENE[1, 2]

[1] *Institute of Cetacean Research, 4–5 Toyomi-cho, Chuo-ku, Tokyo 104–0055, Japan*
[2] *Project Microbiomes as Bioindicators of the Aquatic Ecosystem Health in Chilean Patagonia, Centro de Estudios del Cuaternario de Fuego-Patagonia y Antártica (CEQUA), Punta Arenas, Chile*
**Corresponding author: isoda@cetacean.jp*

Abstract

Marine debris can affect marine species including whales through ingestion and entanglements. Surveys of marine debris in the Antarctic waters are very limited. This study investigated the floating marine macro debris occurring in the Indo-Pacific sector of the Antarctic (35°E–145°W), south of 60°S, based on Japanese sighting surveys conducted between the austral summer seasons 1991/92 and 2018/19. In order to examine the spatial differences in distribution and density, the marine macro debris data were divided into IWC management Areas IIIE, IV, V and VIW as well as into CCAMLR Convention Areas. Furthermore, to investigate temporal differences, the data were divided into two periods: 1991/92–2004/05 and 2005/06–2018/19. A total of 175 objects were found, consisting mainly of metal and polymer products. Buoys/floats constituted the most frequent sightings, representing 67% of all marine macro debris found. The density indices (number of marine macro debris observed by 100 n.miles) increased from the first to the second period in all Areas. The increase in the number of marine macro debris between the first and second periods was statistically significant in Areas IV and V. The larger number of marine macro debris in the second period (represented predominantly by buoys/floats) coincides with an increase in fishing activities in the surveyed area. However, the overall number of floating marine macro debris in the Indo-Pacific sector of the Antarctic is low and much lower than that reported for the North Pacific and North Atlantic, and this result is consistent with the low incidence of marine macro debris found in the stomach of Antarctic minke whales reported for the same sector. Continued monitoring of floating marine macro debris is recommended given the increasing trend in the number of fisheries and tourist activities in the Antarctic.

Key words: Antarctic, Japanese sighting survey, marine macro debris, fishing buoy.

Introduction

Marine pollution is defined as the introduction by man, directly or indirectly, of substance or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of sea water and reduction of amenities (GESAMP, 1991). Marine debris, also known as marine litter, is a kind of pollutant including, among many others, man-made objects such as polymer bags, buoys, rope, lost fishing lines and nets. Once in the sea, such debris becomes mobile and their movement, distribution and accumulation pattern depend on oceanic currents and gyres. A workshop of the International Whaling Commission Scientific Committee (IWC/SC) agreed that

marine debris, and its contributions to entanglements, exposures including ingestions, and associated impacts, including toxicity, is both a welfare and a conservation issue for cetaceans on a global scale (IWC, 2014). Naturally, marine debris can affect other pelagic species as well.

The problem of pollution by marine debris is more frequent and critical in populated areas. Evidence from remote oceanic islands suggests a southward-decreasing, strong latitudinal gradient in litter densities from subtropical and temperate waters through the subtropical convergence to the Antarctic Polar Front and beyond. That is, there is a clear decreasing trend in marine debris accumulation with latitude (Gregory and Ryan, 1997; Barnes, 2005). However, in recent years, marine debris has been recorded in remote places such as sub-Antarctic and Antarctic regions (Barnes *et al.*, 2010; Ivar do Sul *et al.*, 2011). The sources of this pollutant in the Antarctic could be global oceanic debris drifting across the Antarctic Polar Front or debris from tourism and fisheries activities, which have been increasing in sub-Antarctic and Antarctic areas (Lamers *et al.*, 2008; CCAMLR, 2012).

As indicated above, floating marine debris could be a threat affecting the welfare and conservation of large whales migrating to the Antarctic each austral summer for feeding. Such threats could be through entanglements, ingestions, and associated impacts, including toxicity (IWC, 2014; Baulch and Perry, 2014). For this reason, it is important to monitor the type, number and distribution of floating marine debris in the Antarctic feeding grounds. Unfortunately, previous studies of this kind are very scarce in the Antarctic. Suaria *et al.* (2020) investigated the abundance of floating plastics around the Southern Ocean from a survey conducted during the Antarctic Circumnavigation Expedition in 2016/17, and the authors confirmed the Southern Ocean as the region with the lowest concentration of plastic globally. The IWC International Decade for Cetacean Research-Southern Ocean Whale and Ecosystem Research (IDCR-SOWER) conducted observations on floating macro debris in 1987/88 (Matsuoka *et al.*, 2003) and up to 2009/10 when the survey was completed (Murase *et al.*, 2020). Although a brief summary was presented in Murase *et al.* (2020), analyses of the data collected are yet to be conducted. The authors found low occurrence of marine macro debris in the Antarctic.

The main objective of this study was the investigation of the spatial and temporal distribution of floating marine macro debris in the Indo-Pacific sector of the Antarctic. The study is based on observations conducted from systematic vessel-based sighting surveys of the former research programs JARPA/JARPAII (Japanese Whale Research Program under Special Permit in the Antarctic, Phases I and II) (Government of Japan, 1987, 1989, 2005) and NEWREP-A (New Scientific Whale Research Program in the Antarctic Ocean) (Government of Japan, 2015), over a period of 28 years. Outputs from this study could provide valuable information for the development of conservation policies of whales and the Antarctic ecosystem.

Materials and methods

Research area

The marine macro debris observations were conducted along the surveys of the JARPA, JARPAII and NEWREP-A, which had as the main objective the systematic collection of sighting and biological data of whales in IWC Antarctic management Areas III (0°–70°E), IV (70°–130°E), V (130°E–170°W) and VI (170°–120°W). The marine macro debris data analyzed in this study were from the eastern part of Area III (IIIE) (35°–70°E), Area IV, Area V and the western part of Area VI (VIW) (170°–145°W), from 60°S to the ice edge, from where data for a longer period were available (Figs. 1A and 1B). The marine macro debris data were also summarized according to the Convention Areas of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Figs. 1A and 1B show the geographical boundaries of the IWC and CCAMLR management areas used for the analyses in this study. IWC Area IIIE overlaps partially with CCAMLR Divisions 58.4.2–4; Area IV with Divisions 58.4.1–3; Area V with Division 58.4.1 and Sub-area 88.1; and Area VIW with Sub-area 88.2. In

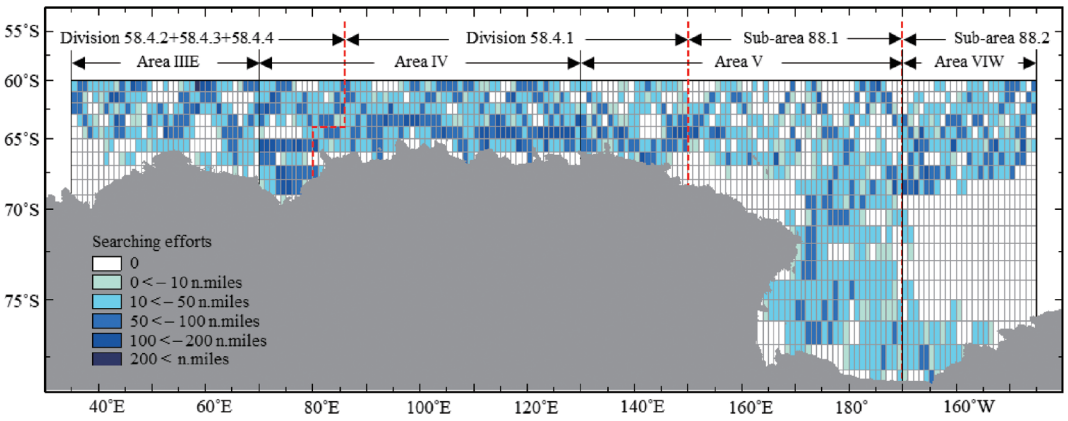

Fig. 1A. The sighting effort (n.miles surveyed by Lat. 1°×Long. 1° square) of the JARPA survey in the Indo-Pacific sector of the Antarctic during the austral summer seasons 1995/96 to 2004/05 (first period, a total of 50,476 n.miles surveyed). The figure also shows the geographical boundaries of the IWC and CCAMLR management areas used for the analyses in this study.

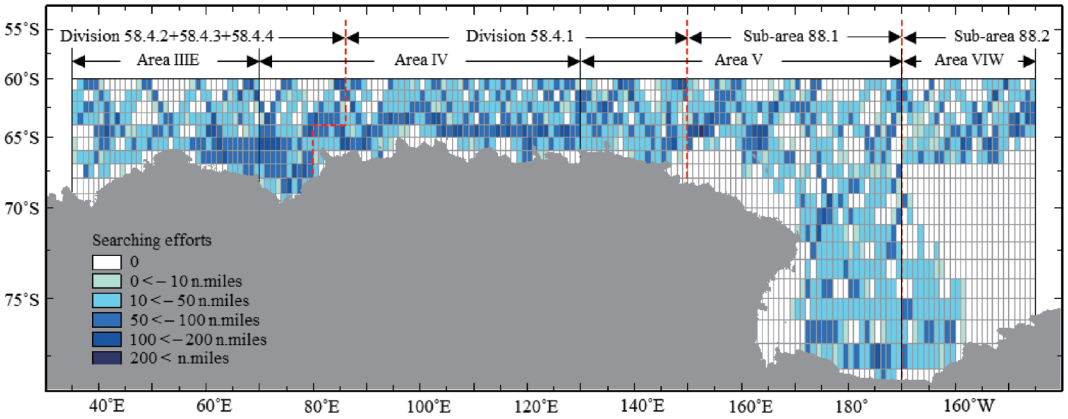

Fig. 1B. The sighting effort (n.miles surveyed by Lat. 1°×Long. 1° square) of the JARPAII and NEWREP-A surveys in the Indo-Pacific sector of the Antarctic during the austral summer seasons 2005/06 to 2018/19 (second period, a total of 52,328 n.miles surveyed). The figure also shows the geographical boundaries of the IWC and CCAMLR management areas used for the analyses in this study.

this regard, the data of marine macro debris collected in the Indo-Pacific sector of the Antarctic can be useful for these two international organizations. CCAMLR management areas involve the terminology 'Areas,' 'Divisions' and 'Sub-areas.' For practical purposes, in this study these are referred simply as CCAMLR 'Areas.'

As the surveys were limited to waters south of 60°S, i.e., south of the Antarctic Polar Front, which acts as a barrier of debris movement from lower latitude waters to the Antarctic (see above), the emphasis of this study was on longitudinal differences in the distribution of marine macro debris, given the wide longitudinal span of the surveys in the Indo-Pacific sector.

Research period

Marine macro debris surveys were conducted mainly during January–February, in the austral summer seasons between 1991/92 and 2018/19.

Survey procedure

Observation of marine macro debris was carried out from the platform of sighting vessels participating in JARPA, JARPAII and NEWREP-A. The main objective of the sighting vessels was the

collection of sighting data of whales for abundance estimation purposes. Although the protocol of the surveys included the observation of floating marine macro debris along the track-lines, they could not be considered as dedicated marine macro debris surveys. Details of the general sighting survey procedures can be found in Nishiwaki *et al.* (2006) and Nishiwaki *et al.* (2014). Basically, the sighting vessels followed a pre-determined zig-zag track-line at a speed of 11.5 knots. The sighting surveys involved two observers on the top platform (19 m high from the sea level) and five observers on the upper bridge platform (11 m high from the sea level). Sighting surveys, including the observations of marine macro debris on the sea surface, were carried out from the platforms using a scaled binocular developed by the Institute of Cetacean Research and FUJINON (FUJINON 7×50 FMT-SX; 7×50 mm, ICR model). The vessel did not deviate from the track-line when an item of marine macro debris was sighted.

Marine macro debris data were recorded separately for sighting surveys conducted 'on effort' (primary observers were present at the relevant observation platforms) and 'off effort' (marine macro debris recorded during drifting, transit and experiments). For each observation, the type of marine macro debris, the sighting date and the geographical position were recorded. When feasible, pictures were taken.

The surveys focused on marine macro debris objects of sizes approximately 300 mm or larger (estimated visually by experienced observers). It should be noted that the sighting probability of small objects decreases with distance from the vessels. As a consequence, some small objects occurring at long distances could have been missed. However, the survey procedures were exactly the same for each annual survey in the 28-year period, so the comparison of density indices (see below) between temporal strata is still a valid approach in relative terms.

Data analysis

To examine geographical differences in distribution, marine macro debris data were grouped by IWC management Area and CCAMLR Convention Areas. To investigate temporal trends in the Areas, marine macro debris data were grouped into two periods: 1991/92–2004/05 (first period) and 2005/06–2018/19 (second period). This temporal division was made so that the sighting effort (searching nautical miles) was evenly distributed between the two periods. In making this temporal division it was also considered that fishery and tourist activities in the Antarctic had increased from the 2000's (see Fig. 1 in Lamers *et al.*, 2008 and Figs. 6 and 7 in CCAMLR, 2012), and therefore an increase in the number of marine macro debris was expected for the second period.

No sighting survey was conducted in the seasons 2010/11, 2011/12 and 2013/14. Observations of marine macro debris between the seasons 1991/92 and 1994/95 were made under both 'on effort' and 'off effort,' however, the type of effort was not recorded. Therefore data in this period were not used when the density indices (see below) were calculated.

The density index (the number of marine macro debris observed per 100 n.miles) was calculated for each management Area in each of the two periods, based on the marine macro debris data collected under 'on effort' mode. The number of marine macro debris per unit area is an alternative method to assess its geographical and temporal distribution. Given the number and complexity of each IWC and CCAMLR area examined, the density index was selected for practical purposes.

A chi-square test was used to assess the differences in the number of marine macro debris between periods based on the expected frequency of 50 : 50.

Results

Sighting effort

Figs. 1A and 1B show the sighting effort expressed in nautical miles, surveyed in the first and

second periods, respectively. The searching effort was similar in both periods, 50,476 n.miles and 52,328 n.miles in the first and second periods, respectively.

Floating marine macro debris

Tables 1A–1C show the number of marine macro debris in the whole (A), first (B) and second (C) periods, respectively, grouped by the IWC Areas. A total of 175 observations of marine macro debris were recorded between 1991/92 and 2018/19 (15 metallic objects, 159 polymer products and one object of unknown material). Buoys/floats made of polymer (Fig. 2) accounted for 67% of all marine macro debris. Most buoys/floats observed were single objects. The total numbers of marine macro

Table 1A. Summary of floating marine macro debris recorded during systematic sighting surveys in the Indo-Pacific sector of the Antarctic by JARPA, JARPAII and NEWREP-A between the austral summer seasons 1991/92 and 2018/19, by IWC Area and effort (on and off).

Type of marine macro debris	Metal (Total number=15)				Polymer products (Total number=159)														Other (Total number=1)		Sub total		Total
	Can		Drum (≦200L)		buoy /float*		Bottle		Container		Fender		Net		Other polymer products **		Styrofoam products		Other products ***				
IWC Area / effort	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	
Area IIIE	0	0	1	0	5	2	1	2	0	0	0	0	0	0	0	0	1	0	0	0	8	4	12
Area IV	0	0	2	4	30	11	0	1	1	0	0	1	1	0	1	3	8	2	1	0	44	22	66
Area V	2	0	2	3	45	12	3	0	2	0	5	1	2	0	1	0	2	0	0	0	64	16	80
Area VIW	0	0	1	0	8	5	0	0	0	0	0	0	0	0	3	0	0	0	0	0	12	5	17
Total	2	0	6	7	88	30	4	3	3	0	5	2	3	0	5	3	11	2	1	0	128	47	175

*Observed on the surface as single objects, however, at least in eight cases, several objects were observed; those cases were counted as a single observation. Material of buoys/floats was considered to be polymer, in addition to Styrofoam and rubber.
**Two ropes, two tanks, one ball, one sheet, and two unknown products.
***A squared box of unknown material.

Table 1B. Summary of floating marine macro debris recorded during systematic sighting surveys in the Indo-Pacific sector of the Antarctic by JARPA, between the austral summer seasons 1991/92 and 2004/05 (first period), by IWC Area and effort (on and off).

Type of marine macro debris	Metal (Total number=9)				Polymer products (Total number=39)														Other (Total number=0)		Sub total		Total
	Can		Drum (≦200L)		buoy /float		Bottle		Container		Fender		Net		Other polymer products		Styrofoam products		Other products				
IWC Area / effort	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	
Area IIIE	0	0	1	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	1	4
Area IV	0	0	1	2	5	1	0	0	1	0	0	0	0	0	0	1	6	1	0	0	13	5	18
Area V	2	0	1	1	7	3	3	0	0	0	1	0	0	0	0	0	0	0	0	0	14	4	18
Area VIW	0	0	1	0	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3	8
Total	2	0	4	3	18	7	3	1	1	0	1	0	0	0	0	1	6	1	0	0	35	13	48

Table 1C. Summary of floating marine macro debris recorded during systematic sighting surveys in the Indo-Pacific sector of the Antarctic by JARPAII and NEWREP-A, between the austral summer seasons 2005/06 and 2018/19 (second period), by IWC Area and effort (on and off).

Type of marine macro debris	Metal (Total number=6)				Polymer products (Total number=120)														Other (Total number=1)		Sub total		Total
	Can		Drum (≦200L)		buoy /float		Bottle		Container		Fender		Net		Other polymer products		Styrofoam products		Other products				
IWC Area / effort	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	
Area IIIE	0	0	0	0	3	2	1	1	0	0	0	0	0	0	0	0	1	0	0	0	5	3	8
Area IV	0	0	1	2	25	10	0	1	0	0	0	1	1	0	1	2	2	1	1	0	31	17	48
Area V	0	0	1	2	38	9	0	0	2	0	4	1	2	0	1	0	2	0	0	0	50	12	62
Area VIW	0	0	0	0	4	2	0	0	0	0	0	0	0	0	3	0	0	0	0	0	7	2	9
Total	0	0	2	4	70	23	1	2	2	0	4	2	3	0	5	2	5	1	1	0	93	34	127

Fig. 2. Example of a single floating marine macro debris observed at two distances from the vessel at position 67°S, 179°W (IWC Area V; CCAMLR Sub-area 88.1) during the 2013/14 austral summer season. Picture by one of the authors (KM).

Table 2A. Summary of floating marine macro debris recorded during systematic sighting surveys in the Indo-Pacific sector of the Antarctic by JARPA, JARPAII and NEWREP-A between the austral summer seasons 1991/92 and 2018/19, by CCAMLR Area and effort (on and off).

Type of marine macro debris	Metal (Total number=15)				Polymer products (Total number=159)														Other (Total number=1)		Sub total		Total
	Can		Drum (≦200L)		buoy /float		Bottle		Container		Fender		Net		Other polymer products		Styrofoam products		Other products				
CCAMLR Area / effort	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	
58.4.2+58.4.3+58.4.4	0	0	1	0	15	4	1	2	1	0	0	0	0	0	0	1	1	1	0	0	19	8	27
58.4.1	0	0	3	7	34	15	1	1	1	0	5	2	2	0	2	2	9	1	1	0	58	28	86
88.1	2	0	1	0	31	6	2	0	1	0	0	0	1	0	0	0	1	0	0	0	39	6	45
88.2	0	0	1	0	8	5	0	0	0	0	0	0	0	0	3	0	0	0	0	0	12	5	17
Total	2	0	6	7	88	30	4	3	3	0	5	2	3	0	5	3	11	2	1	0	128	47	175

Table 2B. Summary of floating marine macro debris recorded during systematic sighting surveys in the Indo-Pacific sector of the Antarctic by JARPA, between the austral summer seasons 1991/92 and 2004/05 (first period), by CCAMLR Area and effort (on and off).

Type of marine macro debris	Metal (Total number=9)				Polymer products (Total number=39)														Other (Total number=0)		Sub total		Total
	Can		Drum (≦200L)		buoy /float		Bottle		Container		Fender		Net		Other polymer products		Styrofoam products		Other products				
CCAMLR Area / effort	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	
58.4.2+58.4.3+58.4.4	0	0	1	0	6	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	8	1	9
58.4.1	0	0	1	3	3	2	1	0	0	0	1	0	0	0	0	1	6	1	0	0	12	7	19
88.1	2	0	1	0	5	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	10	2	12
88.2	0	0	1	0	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3	8
Total	2	0	4	3	18	7	3	1	1	0	1	0	0	0	0	1	6	1	0	0	35	13	48

Table 2C. Summary of floating marine macro debris recorded during systematic sighting surveys in the Indo-Pacific sector of the Antarctic by JARPAII and NEWREP-A, between the austral summer seasons 2005/06 and 2018/19 (second period), by CCAMLR Area and effort (on and off).

Type of marine macro debris	Metal (Total number=6)				Polymer products (Total number=120)														Other (Total number=1)		Sub total		Total
	Can		Drum (≦200L)		buoy /float		Bottle		Container		Fender		Net		Other polymer products		Styrofoam products		Other products				
CCAMLR Area / effort	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	on	off	
58.4.2+58.4.3+58.4.4	0	0	0	0	9	4	1	1	0	0	0	0	0	0	0	1	1	1	0	0	11	7	18
58.4.1	0	0	2	4	31	13	0	1	1	0	4	2	2	0	2	1	3	0	1	0	46	21	67
88.1	0	0	0	0	26	4	0	0	1	0	0	0	1	0	0	0	1	0	0	0	29	4	33
88.2	0	0	0	0	4	2	0	0	0	0	0	0	0	0	3	0	0	0	0	0	7	2	9
Total	0	0	2	4	70	23	1	2	2	0	4	2	3	0	5	2	5	1	1	0	93	34	127

debris were 48 and 127 in the first and second periods, respectively. The buoys/floats were the main marine macro debris in both periods but its percentage was higher in the second period (52% and 73% in the first and second period, respectively).

A similar pattern was observed when the data were grouped by CCAMLR Areas (Tables 2A–2C).

Geographical distribution of marine macro debris

Figs. 3A and 3B show the geographical distribution of marine macro debris in the first and second periods, respectively, in both IWC and CCAMLR Areas. In the first period, the marine macro debris (mainly buoys/floats) were concentrated near the borders between IWC Areas but they were more widely distributed through the CCAMLR Areas. In the second period, the distribution of marine macro debris (mainly buoys/floats) was notably wider in both IWC and CCAMLR Areas, and they were concentrated mainly in Areas IV (CCAMLR Areas 58.4.1–3) and V (CCAMLR Areas 58.4.1 and 88.1), reflecting perhaps the larger searching effort spent in those Areas.

The most southerly marine macro debris sighting was a buoy in the Ross Sea, at position 76°S, 171°W (IWC Area V, CCAMLR Area 88.1).

Density index

Tables 3A–3C show the density indices in the whole (A), first (B) and second (C) periods, respec-

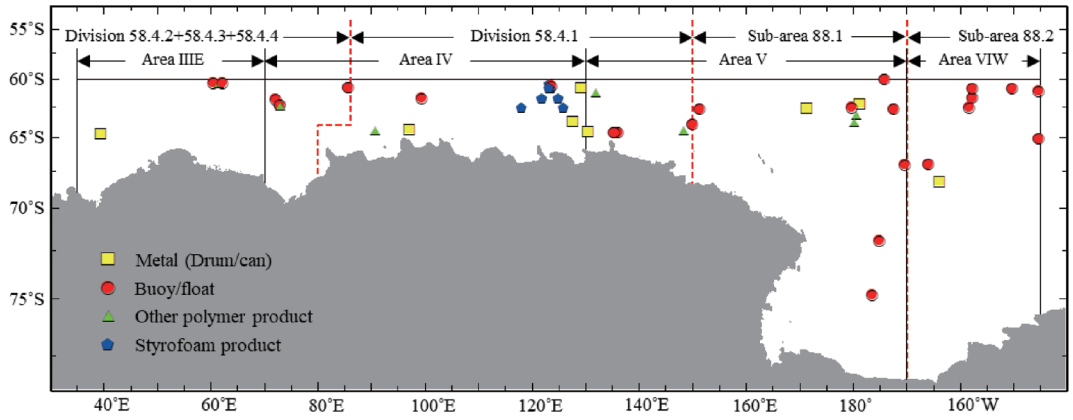

Fig. 3A. Distribution of marine macro debris sighted by JARPA survey in the Indo-Pacific sector of the Antarctic during the austral summer seasons 1991/92 to 2004/05 (first period) (on and off effort), by IWC and CCAMLR management areas.

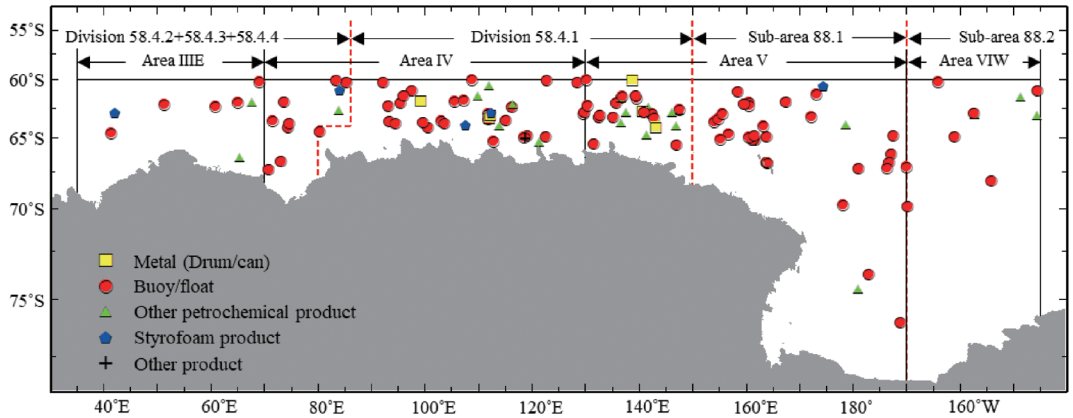

Fig. 3B. Distribution of marine macro debris sighted by JARPAII and NEWREP-A surveys in the Indo-Pacific sector of the Antarctic during the austral summer seasons 2005/06 to 2018/19 (second period) (on and off effort), by IWC and CCAMLR management areas.

tively, grouped by the IWC Areas. The index for all Areas and period was 0.12. The largest index was in Area V and the smallest in Area IIIE. The density indices increased between the first and second period in all Areas. A chi-square test resulted in significant temporal differences in the number of marine macro debris in Areas IV (chi-square=7.36, df=1, p=0.007) and V (chi-square=20.25, df=1, p<0.001). However no significant differences were found between periods when the density indices were used. It is likely that the values of density are too low to detect any difference. No significant differences were found in the number of marine macro debris between the first and second periods in Areas IIIE (chi-square=0.50, df=1, p=0.480) and VIW (chi-square=0.33, df=1, p=0.564).

Tables 4A–4C show the density indices in the whole (A), first (B) and second (C) periods, respectively, grouped by the CCAMLR Areas. The pattern found is very similar to the analysis of IWC Areas. The largest index was in Area 58.4.1 and the smallest in Area 58.4.2–4. The density indices increased between the first and second periods in all Areas. A chi-square test resulted in significant temporal differences in the number of marine macro debris in Area 58.4.1 (chi-square=19.93, df=1, p<0.001) and 88.1 (chi-square=9.26, df=1, P=0.002). However no significant differences were found between the two periods when the density indices were used. No significant differences in the

Table 3A. The searching distance (n.miles), number of marine macro debris and density indices (number of marine macro debris observed per 100 n.miles) during JARPA, JARPAII and NEWREP-A surveys in the Indo-Pacific sector of the Antarctic during the austral summer seasons 1995/96 to 2018/19, by IWC Area (data for the period 1991/92–1994/95 were not used for the reasons explained in the 'Data analysis' section).

IWC Area	Searching distance	Number of marine macro debris	Density index
Area IIIE	15,576	8	0.05
Area IV	36,408	44	0.12
Area V	38,488	64	0.17
Area VIW	12,331	12	0.10
Total	102,804	128	0.12

Table 3B. The searching distance (n.miles), number of marine macro debris and density indices (number of marine macro debris observed per 100 n.miles) during JARPA survey in the Indo-Pacific sector of the Antarctic during the austral summer seasons 1995/96 to 2004/05 (first period), by IWC Area (data for the period 1991/92–1994/95 were not used for the reasons explained in the 'Data analysis' section).

IWC Area	Searching distance	Number of marine macro debris	Density index
Area IIIE	7,300	3	0.04
Area IV	18,912	13	0.07
Area V	17,684	14	0.08
Area VIW	6,579	5	0.08
Total	50,476	35	0.07

Table 3C. The searching distance (n.miles), number of marine macro debris and density indices (number of marine macro debris observed per 100 n.miles) during JARPAII and NEWREP-A surveys in the Indo-Pacific sector of the Antarctic during the austral summer seasons 2005/06 to 2018/19 (second period), by IWC Area.

IWC Area	Searching distance	Number of marine macro debris	Density index
Area IIIE	8,276	5	0.06
Area IV	17,496	31	0.18
Area V	20,804	50	0.24
Area VIW	5,752	7	0.12
Total	52,328	93	0.18

Table 4A. The searching distance (n.miles), number of marine macro debris and density indices (number of marine macro debris observed per 100 n.miles) during JARPA, JARPAII and NEWREP-A surveys in the Indo-Pacific sector of the Antarctic during the austral summer seasons 1995/96 to 2018/19, by CCAMLR Area (data for the period 1991/92–1994/95 were not used for the reasons explained in the 'Data analysis' section).

CCAMLR Area	Searching distance	Number of marine macro debris	Density index
58.4.2+58.4.3+58.4.4	26,510	19	0.07
58.4.1	34,756	58	0.17
88.1	27,304	39	0.14
88.2	14,234	12	0.08
Total	102,804	128	0.12

Table 4B. The searching distance (n.miles), number of marine macro debris and density indices (number of marine macro debris observed per 100 n.miles) during JARPA survey in the Indo-Pacific sector of the Antarctic during the austral summer seasons 1995/96 to 2004/05 (first period), by CCAMLR Area (data for the period 1991/92–1994/95 were not used for the reasons explained in the 'Data analysis' section).

CCAMLR Area	Searching distance	Number of marine macro debris	Density index
58.4.2+58.4.3+58.4.4	12,720	8	0.06
58.4.1	17,773	12	0.07
88.1	12,637	10	0.08
88.2	7,347	5	0.07
Total	50,476	35	0.07

Table 4C. The searching distance (n.miles), number of marine macro debris and density indices (number of marine macro debris observed per 100 n.miles) during JARPAII and NEWREP-A surveys in the Indo-Pacific sector of the Antarctic during the austral summer seasons 2005/06 to 2018/19 (second period), by CCAMLR Area.

CCAMLR Area	Searching distance	Number of marine macro debris	Density index
58.4.2+58.4.3+58.4.4	13,790	11	0.08
58.4.1	16,984	46	0.27
88.1	14,667	29	0.20
88.2	6,887	7	0.10
Total	52,328	93	0.18

number of marine macro debris were found between the first and second periods in Areas 58.4.2–4 (chi-square=0.47, df=1, p=0.491) and 88.2 (chi-square=0.33, df=1, p=0.564).

Discussion

The present study summarized the spatial and temporal distribution of marine macro debris in the Indo-Pacific sector of the Antarctic based on data collected systematically over a period of 28 years. The data were organized based on the management areas of two international organizations in charge of the conservation and management of Antarctic marine living resources, the IWC and the CCAMLR. Although similar surveys have been conducted previously in the Antarctic (e.g., Matsuoka *et al.*, 2003; Suaria *et al.*, 2020), the present study is the first to report marine macro debris information which were collected along systematic sighting surveys in the same region (Indo-Pacific sector of the Antarctic) over a long period of time (28 years).

Marine debris has been increasing worldwide and one of the main concerns is the negative effect of this kind of pollutant on marine species through ingestion and entanglements (see reviews by Panti *et al.*, 2019; IWC, 2020). Emphasizing the importance of this subject, two international workshops were held recently to discuss the interaction between marine mammal and marine debris, and to define future research plans (Panti *et al.*, 2019; IWC, 2020).

The main results of the present study can be summarized as follows: i) the occurrence of floating marine macro debris in the Indo-Pacific sector of the Antarctic is low, and much lower in comparison with the occurrence in other oceans of the world; ii) buoys/floats made of polymer were the main marine macro debris found in this sector of the Antarctic, comprising 67% of all marine macro debris observed; iii) the largest density indices were found in IWC Areas IV and V (and CCAMLR Areas 58.4.1 and 88.1); and iv) there is an increasing temporal trend of marine macro debris (particularly buoys/floats) in all Areas, which was statistically significant in IWC Areas IV and V (and CCAMLR Areas 58.4.1 and 88.1).

Regarding i) above, the results of low occurrence of marine macro debris in the Antarctic are consistent with the results of Suaria *et al.*, (2020) and the preliminary results of IWC/IDCR-SOWER (Murase *et al.*, 2020). Matsumura and Nasu (1997) reported floating marine macro debris in the North Pacific Ocean and its adjacent waters for the period 1987–1991. Their surveys covered approximately 926,000 n.miles and recorded 136,338 pieces of marine macro debris (including natural objects). About 60% of marine macro debris were polymer products (e.g., fishing gear, Styrofoam products, and other polymer products). Total densities expressed in number of objects observed per 1 n.mile^2 were 20–40 in coastal waters, 0.2 in the north equatorial current area (5°–15°N, across the central Pacific), and 1–3 in the subarctic boundary area (35°–45°N). Barnes and Milner (2005) reported the results of floating marine macro debris across the entire latitudinal range from the Antarctic to the North Atlantic. Densities of marine macro debris ranged from 0 to 5 items/km^2 in sub-Antarctic and Antarctic waters. Marine macro debris density values have a peak of 10 to 100+ items/km^2 in the North Atlantic (English Channel). Clearly, the number of marine macro debris in the Indo-Pacific sector of the Antarctic is much lower than those observed in the North Pacific and North Atlantic oceans, although it should be noted that the density index used in the present study is not directly comparable with the densities reported in other studies.

Points ii), iii) and iv) above are related with the occurrence of buoys/floats, the main marine macro debris observed in the Indo-Pacific sector of the Antarctic. Buoys/floats accounted for about 67% of all sighted floating marine macro debris and its density indices increased between the first and second periods. It should be noted that Barnes *et al.* (2010) recorded three pieces of marine macro debris (a polymer cup and two fishing buoys) in the Dumont d'Urville and Davis Seas (i.e. Areas IV and V) during a survey conducted in the 2007/08 austral summer season. Figs. 4A and 4B show the annual trend of the density indices for buoys/floats in each of the management Areas of IWC and CCAMLR, respectively. An increasing trend is observed, particularly in IWC Area IV and V (Fig. 4A); and in CCAMLR Areas 58.4.1 and 88.1 (Fig. 4B), after the 2005/06 austral summer season. It is important to investigate the source of the buoys/floats observed and the reasons for the increasing trend in density after this season.

Oceanic fronts, such as the subtropical Convergence and Antarctic Polar Front, act as barriers for the movement of marine debris from low latitude waters to polar areas (Gregory and Ryan, 1997). Although these barriers are considered permeable by some authors (e.g. Gregory, 2009), the hypothesis that all buoys/floats observed in the Indo-Pacific sector of the Antarctic were transported from lower latitudes has a low plausibility. Since the season 2004/05, licensed longline vessels have conducted exploratory fishery for Antarctic toothfish (*Dissostichus mawsoni*) in CCAMLR Area 58.4.1, which overlaps partially with IWC management Areas IV and V. The number of licensed vessels in Area 58.4.1 was four to seven in 2004/05 to 2007/08 seasons, however it decreased to one to three in 2008/09 to 2014/15 seasons (SC-CAMLR, 2012a; CCAMLR, 2013, 2014, 2015). In Area 88.1, which

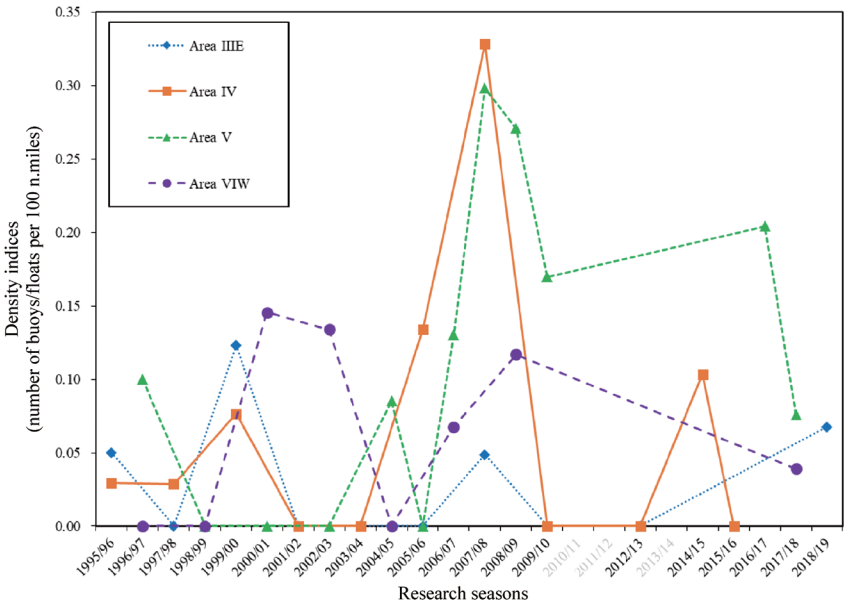

Fig. 4A. The trend of the density indices of sighted buoys/floats by austral summer season and IWC Area, between 1995/96 and 2018/19 (data for the period 1991/92–1994/95 were not used for the reasons explained in the 'Data analysis' section).

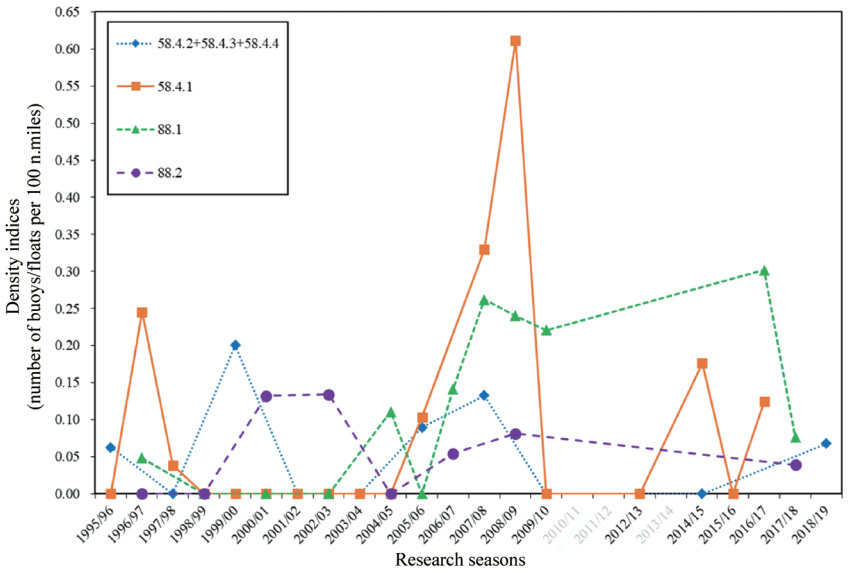

Fig. 4B. The trend of the density indices of sighted buoys/floats by austral summer season and CCAMLR Area, between 1995/96 and 2018/19 (data for the period 1991/92–1994/95 were not used for the reasons explained in the 'Data analysis' section).

overlaps partially with IWC management Areas V, one to three licensed longline vessels fished in the exploratory fishery for *Dissostichus* spp. from 1996/97 to 2001/02 (except 10 vessels in 2000/01). This number increased to more than 10 in 2002/03 to 2011/12 (SC-CAMLR, 2012b), 16 in 2016/17 and 25 in 2017/18 (CCAMLR, 2017, 2018). The number of sighted buoys/floats increased significantly in Areas IV and V after the 2005/06 season, peaked in the 2007/08 season, and then decreased. However, the decrease in Area V was less prominent than in Area IV (Fig. 4A). The pattern exhibited in Figs. 4A and 4B mimics the fluctuations of longline fishing operations in these Areas. In addition to this, operations by IUU (illegal, unreported and unregulated) vessels have been reported in these areas (SC-CAMLR, 2012a, 2012b). Therefore, it is likely that the buoys/floats debris observed in the

present study come from fishing vessels operating in Areas 58.4.1 and 88.1. Although not statistically significant, the density index increased between the first and second period in Area 88.2, where fishing activities were also reported (see Fig. 1 in Brooks *et al.*, 2020). It should be noted that a loss of fishing gears from bottom longline fisheries targeting Antarctic toothfish operating in Areas 88.1 and 88.2 was reported in Webber and Parker (2012).

Fishing operations are a source of marine macro debris in the Antarctic, contributing not only to direct fishing-related debris but also miscellaneous debris items (Ivar do Sul *et al.*, 2011). Webber and Parker (2012) recommended that fishing vessels and/or the CCAMLR observers should record detailed information on gear loss, in order to estimate unaccounted fishing mortality and to reduce the loss of fishing gear. Such information is also essential to understanding the interaction among whales, fisheries and marine debris.

Despite the increasing trend observed in some areas, the overall number of floating marine macro debris in the Indo-Pacific sector of the Antarctic is very low, and this result is consistent with the low incidence of marine macro debris and entanglements found in the stomach of Antarctic minke whales in the same sector of the Antarctic (see Isoda *et al.*, this issue).

Conclusions

This study provided the results of the first systematic and comprehensive surveys of floating marine macro debris in the Indo-Pacific sector of the Antarctic conducted for a period of 28 years. The occurrence of floating marine macro debris (metal and polymer products mainly) was generally low. The level of occurrence was substantially lower in comparison with the information reported for other oceanic basins, and this result is consistent with the low incidence of marine macro debris and entanglements found in the stomach of Antarctic minke whales in the same sector of the Antarctic. The main floating marine macro debris was fishing buoys/floats, which increased during the second half of the survey period. The probable source of the buoys/floats are fishing vessels operating in the Antarctic. Long-term surveys (e.g., JARPA, JARPAII and NEWREP-A) proved to be very useful for collecting information of marine debris in the Antarctic. This monitoring of marine macro debris is continuing in the same region under the Japanese Abundance and Stock-structure Surveys in the Antarctic (JASS-A) program (Government of Japan, 2019) since the 2019/20 season. It is recommended that periodical analyses of marine macro debris are conducted and reported in the future.

Acknowledgements

We would like to thank all of the captains, crew members, cruise leaders and researchers onboard the research vessels of JARPA, JARPAII and NEWREP-A surveys for their contributions in collecting the data used in this study. We also thank the anonymous reviewers for useful comments that improved the manuscript notably.

References

Barnes, D. K. A. 2005. Remote islands reveal rapid rise of Southern Hemisphere sea debris. *Sci. World J.* 5: 915–921. doi: 10.1100/tsw.2005.120.

Barnes, D. K. A. and Milner, P. 2005. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Mar. Biol.* 146: 815–825. doi: 10.1007/s00227-004-1474-8.

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

Baulch, S. and Perry, C. 2014. Evaluating the impacts of marine debris on cetaceans. *Mar. Pollut. Bull.* 80(1–2): 210–221. doi: 10.1016/j.marpolbul.2013.12.050.

Brooks, C. M., Crowder, L. B., Österblom, H. and Strong, A. L. 2020. Reaching consensus for conserving the global commons: The case of the Ross Sea, Antarctica. *Conserv. Lett.* 13(1), e12676. doi: 10.1111/conl.12676.

CCAMLR. 2012. Statistical Bulletin. Volume 24 (2002–2011). CCAMLR, Hobart, Australia. 269 pp.

CCAMLR. 2013. Fishery Report: Exploratory fishery for *Dissostichus* spp. in Division 58.4.1. CCAMLR, Hobart, Australia. 10 pp.
CCAMLR. 2014. Fishery Report: Exploratory fishery for *Dissostichus* spp. in Division 58.4.1. CCAMLR, Hobart, Australia. 12 pp.
CCAMLR. 2015. Fishery Report: Exploratory fishery for *Dissostichus* spp. in Division 58.4.1. CCAMLR, Hobart, Australia. 15 pp.
CCAMLR. 2017. Fishery Report 2017: Exploratory fishery for *Dissostichus mawsoni* in Subarea 88.1. CCAMLR, Hobart, Australia. 30 pp.
CCAMLR. 2018. Fishery Report 2018: Exploratory fishery for *Dissostichus mawsoni* in Subarea 88.1. CCAMLR, Hobart, Australia. 31 pp.
GESAMP (IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution). 1991. Reducing Environmental Impacts of Coastal Aquaculture. *Rep. Stu. GESAMP* (47): 35 pp.
Government of Japan. 1987. The program for research on the Southern Hemisphere minke whale and for preliminary research on the marine ecosystem in the Antarctic. Paper SC/39/O4 presented to the IWC Scientific Committee, June 1987 (unpublished). 60 pp. [Paper available from the Office of the IWC].
Government of Japan. 1989. The research plan in 1989/90 season in conjunction with note for 'The program for research on the Southern Hemisphere minke whale and for preliminary research on the marine ecosystem in the Antarctic (SC/39/O4).' Paper SC/41/SHMi13 presented to the IWC Scientific Committee, 1989 (unpublished). 21 pp. [Paper available from the Office of the IWC].
Government of Japan. 2005. Plan for the second phase of the Japanese whale research program under special permit in the Antarctic (JARPA II) - Monitoring of the Antarctic ecosystem and development of new management objectives for whale resources. Paper SC/57/O1 presented to the IWC Scientific Committee, May–June 2005 (unpublished). 99 pp. [Paper available from the Office of the IWC].
Government of Japan. 2015. Research Plan for New Scientific Whale Research Program in the Antarctic Ocean (NEWREP-A). IWC.ALL.238, November 2015 (unpublished). 110 pp. [Paper available from the Office of the IWC].
Government of Japan. 2019. Outline of a research program to investigate the abundance, abundance trends and stock structure of large whales in the Indo-Pacific region of the Antarctic, including a survey plan for the 2019/20 austral summer season (revised version of document SC/68a/ASI08 presented to the IWC SC 2019 meeting). Paper SC/26/NPR-JP presented to the 26th meeting of the NAMMCO Scientific Committee, October-November 2019 (unpublished). 16 pp.
Gregory, M. R. 2009. Environmental implications of plastic debris in marine settings-entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Phil. Trans. R. Soc. B* 364: 2013–2025. doi: 10.1098/rstb.2008.0265.
Gregory, M. R. and Ryan, P. G. 1997. Pelagic plastics and other seaborne persistent synthetic debris: a review of Southern Hemisphere perspectives. pp. 49–66. *In*: Coe J. M. and Rogers D. B. (eds.) *Marine Debris. Sources, Impacts, and Solutions.* Springer Series on Environmental Management. Springer-Verlag, New York. 432 pp. doi: 10.1007/978-1-4613-8486-1_6.
International Whaling Commission. 2014. Report of the IWC Scientific Committee Workshop on Marine Debris. *J. Cetacean Res. Manage. (Suppl.)* 15: 519–541.
International Whaling Commission. 2020. Report of the IWC Workshop on Marine Debris: The Way Forward, 3–5 December 2019, La Garriga, Catalonia, Spain. Paper SC/68B/REP/03 presented to the IWC Scientific Committee, May 2020 (unpublished). 38 pp. [Paper available from the Office of the IWC].
Ivar do Sul, J. A., Barnes, D. K., Costa, M. F., Convey, P., Costa, E. S. and Campos, L. 2011. Plastics in the Antarctic environment: Are we looking only at the tip of the iceberg? *Oecol. Aust.* 15(1): 150–170. doi: 10.4257/oeco.2011.1501.11.
Lamers, M., Haase, D. and Amelung, B. 2008. Facing the elements: analysing trends in Antarctic tourism. *Tour. Rev.* 63: 15–27. doi: 10.1108/16605370810861017.
Matsumura, S. and Nasu, K. 1997. Distribution of floating debris in the North Pacific Ocean: sighting surveys 1986–1991. pp. 15–24. *In*: Coe J.M. and Rogers D.B. (eds.). *Marine Debris. Sources, Impacts, and Solutions.* Springer Series on Environmental Management. Springer-Verlag, New York. 432 pp. doi: 10.1007/978-1-4613-8486-1_6.
Matsuoka, K., Ensor, P., Hakamada, T., Shimada, H., Nishiwaki, S., Kasamatsu, F. and Kato, H. 2003. Overview of minke whale sightings surveys conducted on IWC/IDCR and SOWER Antarctic cruises from 1978/79 to 2000/01. *J. Cetacean. Res. Manage.* 5(2): 173–201.
Murase, H., Palka, D., Punt, A. E., Pastene, L. A., Kitakado, T., Matsuoka, K., Hakamada, T., Okamura, H., Bando, T., Tamura, T., Konishi, K., Yasunaga, G., Isoda, T. and Kato, H. 2020. Review of the assessment of two stocks of Antarctic minke whales (eastern Indian Ocean and western South Pacific) conducted by the Scientific Committee of the International Whaling Commission. *J. Cetacean. Res. Manage.* 21(1): 95–122.
Nishiwaki, S., Ishikawa, H. and Fujise, Y. 2006. Review of general methodology and survey procedure under the JARPA. Paper SC/D06/J2 presented to the IWC JARPA review meeting, December 2006, (unpublished). 47 pp. [Paper available from the Office of the IWC].
Nishiwaki, S., Ishikawa, H., Goto, M., Matsuoka, K. and Tamura, T. 2014. Review of general methodology and survey procedure under the JARPAII. Paper SC/F14/J2 presented to the IWC JARPAII review meeting, February 2014, (unpublished). 34 pp. [Paper available from the Office of the IWC].
Panti, C., Baini, M., Lusher, A., Hernandez-Milan, G., Bravo Rebolledo, E. L., Unger, B., Syberg, K. and Simmonds, M. P. 2019. Marine litter: One of the major threats for marine mammals. Outcomes from the European Cetacean Society

workshop. *Environ. Pollut.* 247: 72–79. doi: 10.1016/j.envpol.2019.01.029.

SC-CAMLR. 2012a. Report of the Working Group on Fish Stock Assessment (Appendix Q: Fishery Report: Exploratory fishery for *Dissostichus* spp. (TOT) in Division 58.4.1). *In: Report of the thirty-first Meeting of the Scientific Committee (SC-CAMLR-XXXI)*, Annex 7. CCAMLR, Hobart, Australia. 12 pp.

SC-CAMLR. 2012b. Report of the Working Group on Fish Stock Assessment (Appendix N: Fishery Report: Exploratory fishery for *Dissostichus* spp. (TOT) in Subareas 88.1 and 88.2). *In: Report of the thirty-first Meeting of the Scientific Committee (SC-CAMLR-XXXI)*, Annex 7. CCAMLR, Hobart, Australia. 39 pp.

Suaria, G., Perold, V., Lee, J. R., Lebouard, F., Aliani, S. and Ryan, P. G. 2020. Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition. *Environ. Int.* 136: 105494. doi: 10.1016/j.envint.2020.105494.

Webber, D. N. and Parker, S. J. 2012. Estimating unaccounted fishing mortality in the Ross Sea region and Amundsen Sea (CCAMLR Subareas 88.1 and 88.2) bottom longline fisheries targeting Antarctic toothfish. *CCAMLR Science* 19: 17–30.

Received: December 12, 2020
Accepted: September 29, 2021
Published online: December 8, 2021