OCCURRENCE OF PLASTIC MICRO-DEBRIS IN THE SOUTHERN CALIFORNIA CURRENT SYSTEM

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ABSTRACT

We analyzed the spatial distribution, concentration, and characteristics of plastic micro-debris in neuston samples from the CalCOFI region off the southern Californian coast from winter cruises in 1984, 1994, and 2007. By sorting archived CalCOFI zooplankton samples we were able to separate micro-debris particles and characterize particle size, circularity, and surface area using digital image analysis by ZooScan. Our results suggest that plastic micro-debris is widespread in the California Current system off the southern California coast. Fifty-six to 68% of the CalCOFI stations had detectable plastic micro-debris. The average concentrations and masses of the particles were not significantly different over the three decades. Median concentrations of plastic micro-debris ranged from 0.011–0.033 particles/m^3 in different years, with a maximum of 3.141 particles/m^3. Our results also suggest that not only is plastic micro-debris widely distributed, it has been present in the northeast Pacific Ocean water column for at least 25 years.

INTRODUCTION

Marine debris is becoming a global issue, affecting diverse ocean regions, both in the neuston and below the water's surface (Sheavly and Register 2007; Arthur et al. 2009). The geographic distribution of marine debris, and its effects on ocean ecosystems, have only recently begun to be investigated (Moore 2008). Marine debris originates from either terrestrial sources (e.g., beach and other coastal accumulations, or through rivers) or from oceanic sources (e.g., ships or from offshore installations; Williams et al. 2005). Regardless of origin, marine debris could have impacts on marine organisms, habitats, and human economies (e.g., Smith et al. 1997; Derraik 2002; Lattin et al. 2004; McDermid and McMullen 2004; Sheavly and Register 2007; Moore 2008; Hinojosa and Thiel 2009; Santos et al. 2009).

Gregory and Ryan (1997) reported that plastics comprise 60%–80% of marine debris. These plastics are a rapidly growing segment of the U.S. municipal solid waste (MSW) stream. Plastics constituted less than 1% of MSW generation in 1960, increasing to 12% in 2007 (EPA 2008). Marine plastic debris has been divided into two size classes for ease of description: macro (>5 mm) and micro debris (<5mm; Arthur et al. 2009). Plastic micro-debris is composed of fragments of manufactured plastic products and pre-production plastic pellets from which plastic objects are manufactured (McDermid and McMullen 2004). Little is known about the occurrence, abundance, and effect of these plastic micro-particles in the pelagic zone of the ocean. In addition, there is little quantitative information on changes of plastic particles in the ocean over time (cf. Thompson et al. 2004). Without such information, it is difficult to assess whether plastic micro-debris is a recent addition to the ocean or has existed for an extended period of time.

Here we sought to determine whether there has been a change in the presence of plastic micro-particles in the California Current system over a multi-decadal time scale. To address this question we analyzed winter CalCOFI (California Cooperative Oceanic Fisheries Investigations) manta tow samples over three decades, from selected winter cruises in 1984, 1994, and 2007, the latter originating from Doyle et al.[1]

METHODS

Zooplankton samples for this study were collected on three CalCOFI cruises (RV *David Starr Jordan* cruise 8401 during 4–16 January 1984, RV *David Starr Jordan* cruise 9401 during 20 January–5 February 1994, and RV *David Starr Jordan* cruise 0701 during 12–29 January 2007) using the manta net neuston sampler (Brown and Cheng 1981) towed off the side of the research vessel in water undisturbed by the ship's wake. These years were selected to represent one year from the 1980s, 1990s, and 2000s, avoiding El Niño years; time and resources did not permit additional analyses. Samples were archived in the Pelagic Invertebrates Collection of the Scripps Institution of Oceanography. Only samples from the southern sec-

[1]Doyle, M. J., W. Watson, N. M. Bowlin, and S. B. Sheavly. In Review. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. Contact M. Doyle at: Miriam.Doyle@noaa.gov

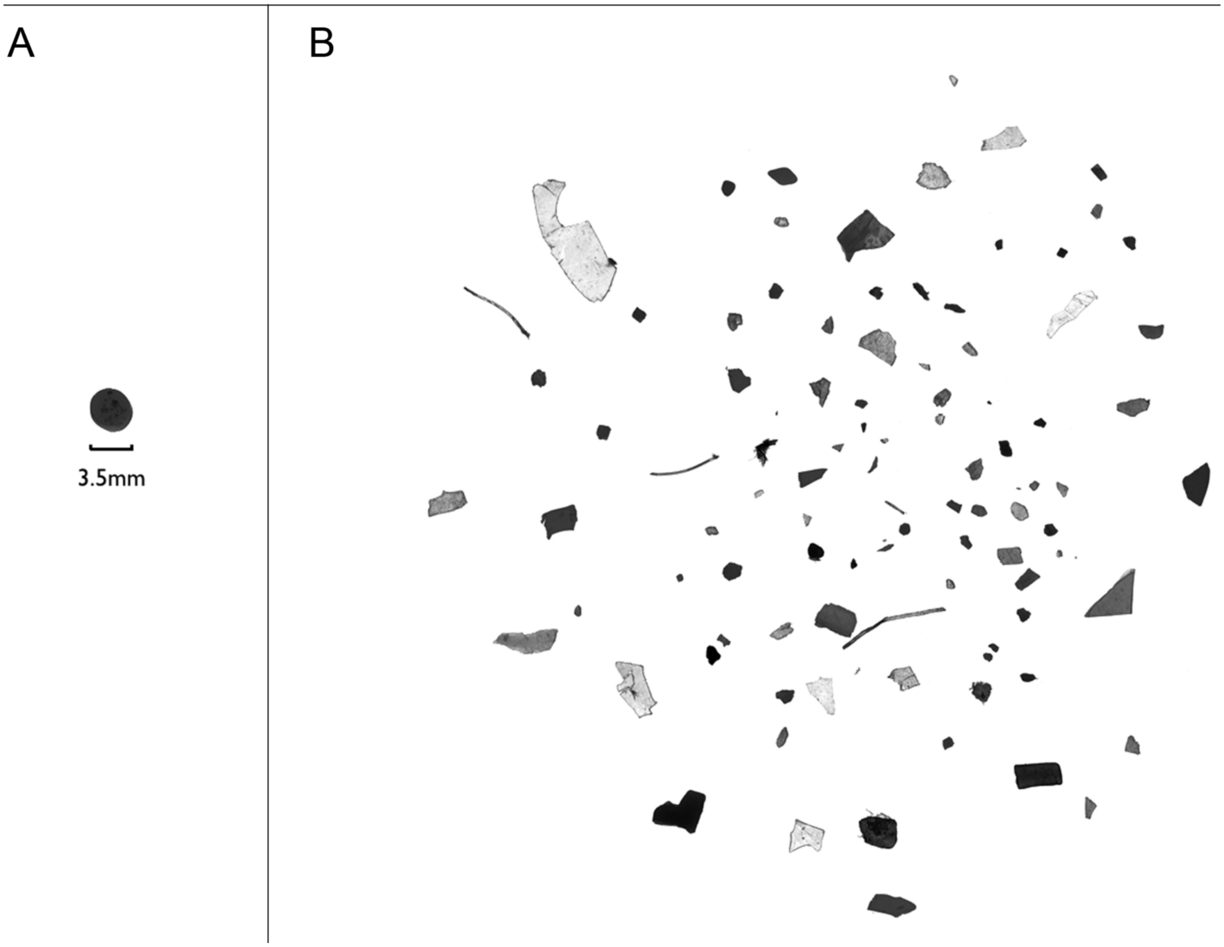

Figure 1. ZooScan images of plastic micro-debris particles from two CalCOFI stations off southern California on cruise 9401: (A) Line 83.3, station 40.6, and (B) Line 86.7, station 60. Scale bar (3.5 mm) applies to both panels.

tor of the California Current system, in the region currently occupied by CalCOFI, were considered. Specific tow times and dates for each station may be obtained from: http://collections.ucsd.edu/pi/index.cfm. Winter cruises were selected because previous analyses suggested that plastic debris is relatively widespread in the CalCOFI region at that time of year (Doyle et al.[1]). Most of the samples from 2007 had already been analyzed by Doyle et al.[1], but we were able to increase the number of samples analyzed from that cruise to 66 samples. Tow duration for the manta net was approximately fifteen minutes at a speed of 0.5–0.75 m/s, with a net mesh of 0.505 mm. After retrieval of the neuston sample, all collected material was carefully washed into the cod end and preserved in a glass sample jar in a 1.8% solution of sodium tetraborate-buffered formaldehyde in seawater. A calibrated flowmeter was fitted in the mouth of each net and the flowmeter readings were converted to cubic meters of water filtered.

We utilized the sample sorting protocol described by Doyle et al.[1] Briefly, each sample was sorted at 6X magnification using a Wild M-5 binocular dissecting scope. All inorganic marine debris (plastic, metal, glass, paint, etc.) was removed from each sample and placed in a labeled vial. The debris items were then sorted a second time to separate the plastic particles from remaining debris. All our analyses herein refer exclusively to plastic debris particles. These plastic particles were rinsed with de-ionized water and oven dried at 55°C for 8–12 hours. Dry mass was determined to the nearest 0.00001 gm using an analytical balance. The dry mass of plastic micro-debris particles for each sample was standardized according to the volume of water filtered by the sampling gear, and recorded as dry mass in mg/m^3 of seawater.

After recording dry mass, plastic micro-debris particles from cruises 8401 and 9401 were digitally imaged with a ZooScan digital scanner (Grosjean et al. 2004; Gorsky et al., in press). Particles from 0701 were not available for these analyses. Linear dimensions, surface area, and circularity of individual particles were measured using ImageJ-based tools in Zooprocess software, calibrated against manual measurements (Gorsky et al., in press). Feret diameter is the longest distance between any two points along the boundary of an object, and is

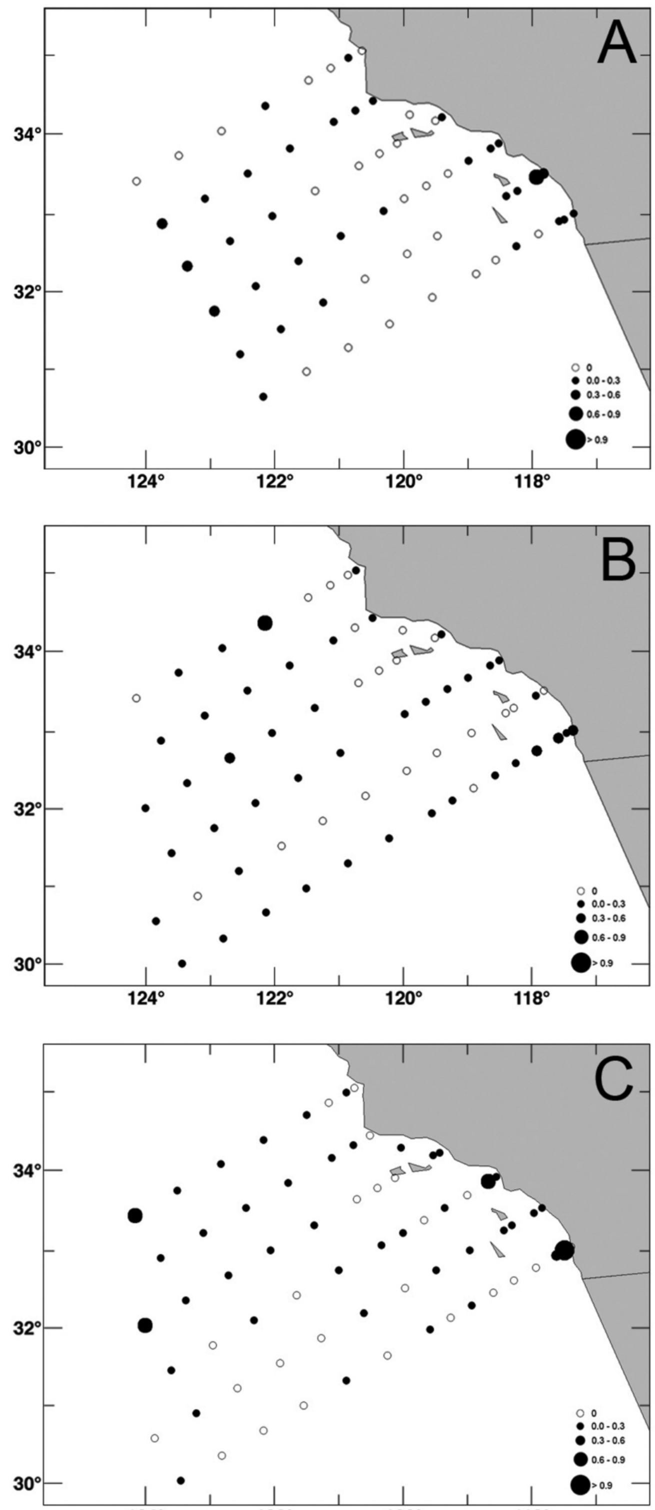

Figure 2. Spatial distribution of plastic micro-debris particles in the winter CalCOFI Manta net samples from cruises (A) 8401, (B) 9401, and (C) 0701. Open circles indicate no plastic debris detected and filled circle diameters are proportional to particle concentrations (No./m³).

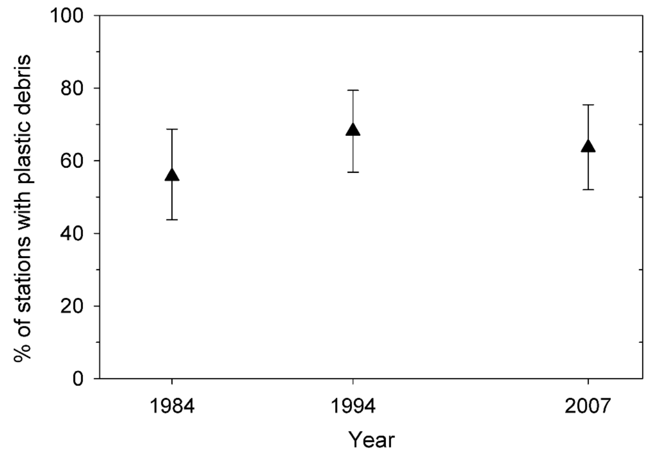

Figure 3. Temporal variation in percentage of stations from winter CalCOFI cruises with plastic micro-debris (mean ± 95% C.L. based on binomial distribution).

closely related to total length (Gorsky et al., in press). Circularity is defined as 4π (area)/perimeter^2, which ranges from 0 to 1, with 1.0 indicating a perfectly circular object. Figure 1 illustrates examples of ZooScan images of plastic micro-debris from two of our samples. The circularity of the pre-production plastic pellet in Figure 1A is 0.711, while circularity of the elongate rectangular piece of plastic bearing a notch, toward the upper left of Figure 1B is 0.124.

RESULTS

Plastic micro-debris was found in neuston samples at the majority of stations sampled on all CalCOFI cruises (fig. 2). Debris was detected in the inshore, transitional, and offshore regions of the sampling pattern. There was no relationship between the numerical concentration of particles and distance of collection locations from shore, or between the mass concentration of particles and distance from shore, for each cruise considered separately ($p > 0.20$) or for all cruises combined ($p > 0.20$, Spearman rank correlation). The original data are tabulated in Appendix 1.

The number of stations with plastic micro-debris particles was 34 out of 61 stations (55.7%) in 1984, 45 out of 66 stations (68.2%) in 1994, and 42 out of 66 stations (63.6%) in 2007 (fig. 3). None of the years differed in percentage of stations with plastic debris ($p > 0.05$, based on binomial confidence limits).

Concentrations of plastic micro-debris particles were highly variable across the sampling region (figs. 2, 4). The highest particle concentration (3.141 debris particles/m^3) was found in 2007 at the southeastern-most point of the CalCOFI station grid near San Diego (fig. 2C). Relatively high concentrations of particles were found near San Diego, or just north of San Diego, on each cruise. Frequency distributions of particle concentrations were

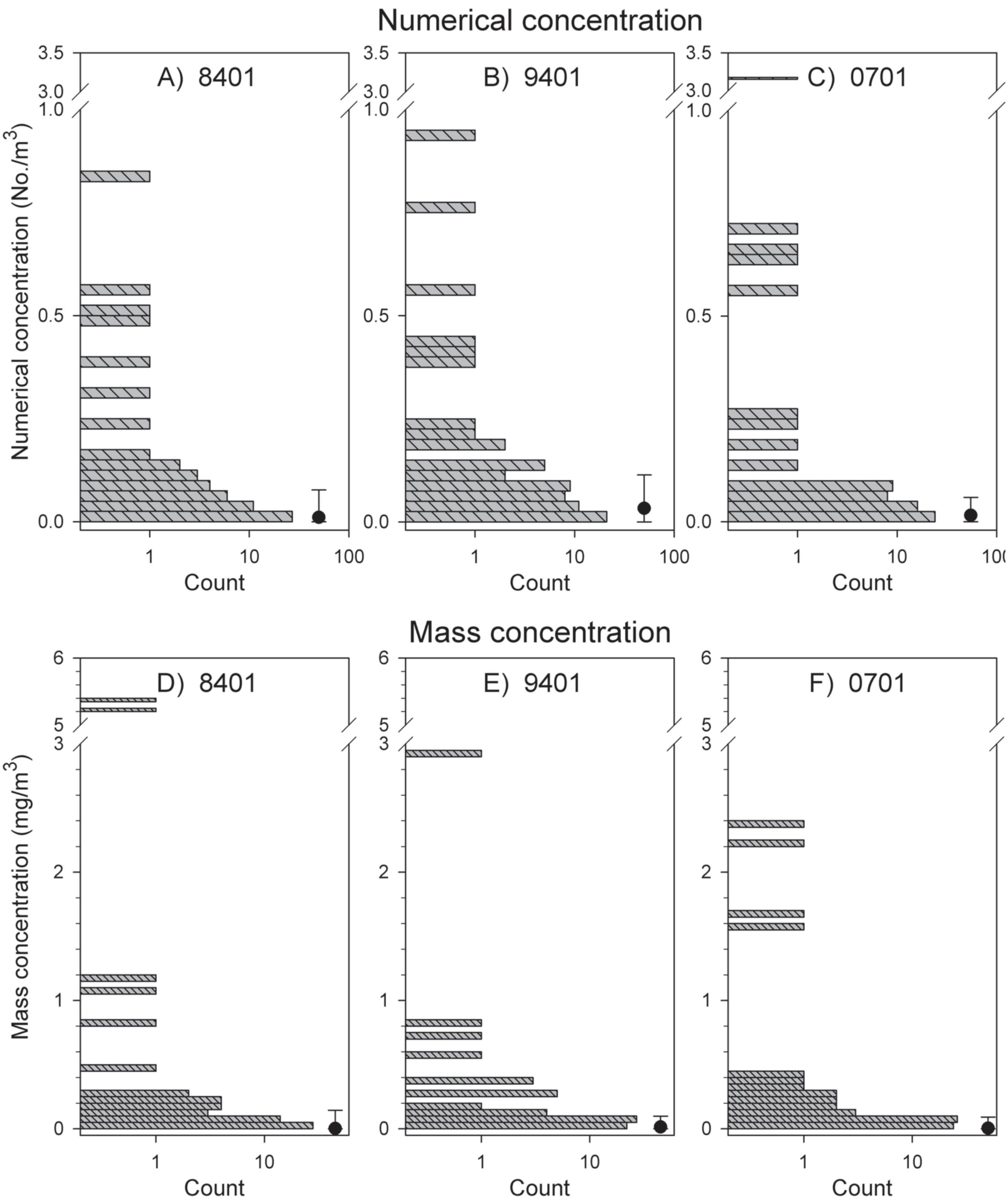

Figure 4. Frequency distributions of numerical concentrations of plastic particles (No./m³, panels A, B, C) and dry mass concentrations of plastic particles (mg/m³, panels D, E, F) over CalCOFI cruises spanning three decades (8401, 9401, and 0701). Symbols in the lower right corner of each plot indicate the median and 20th–80th percentile distributions.

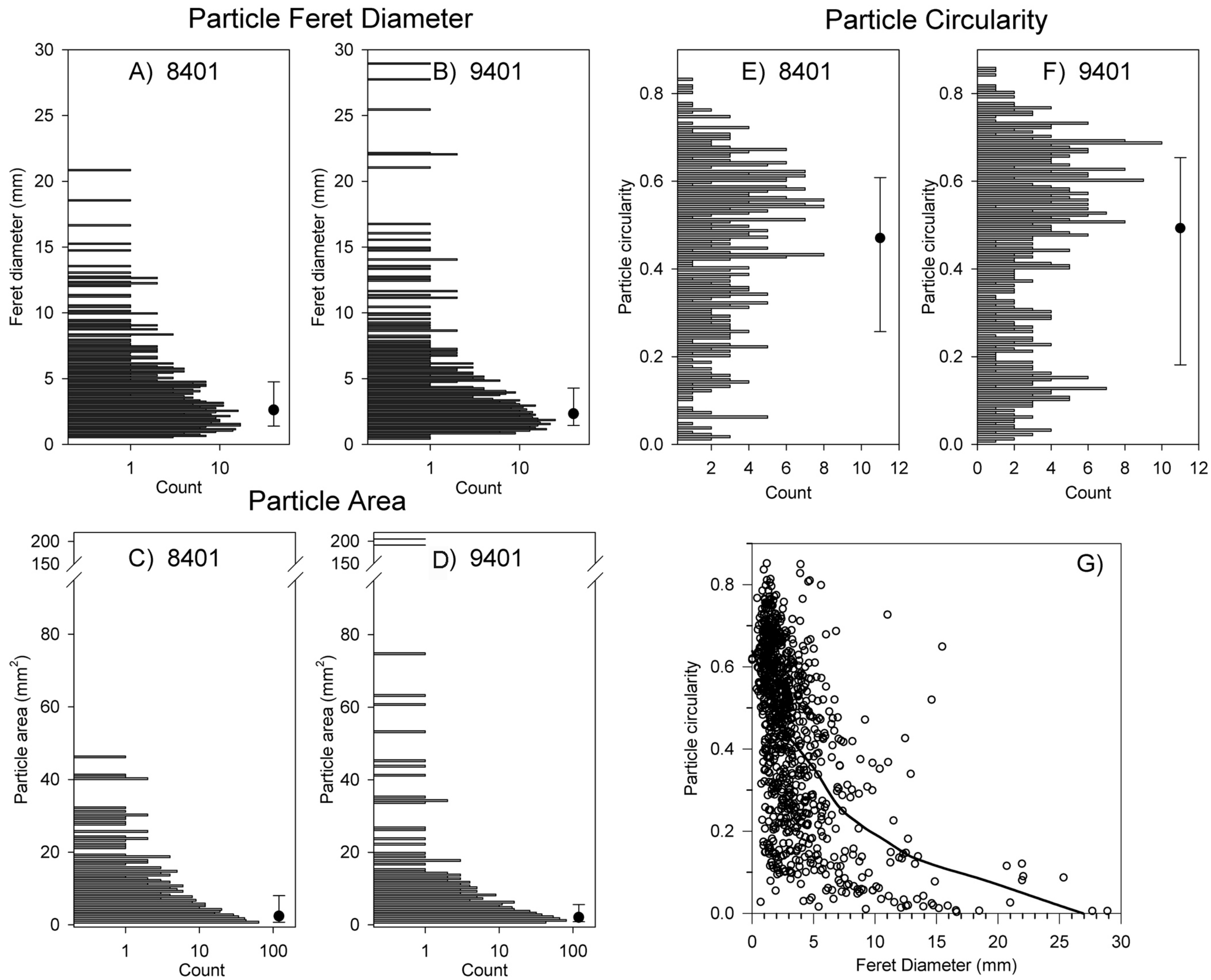

Figure 5. Frequency distributions of (A, B) particle Feret diameter (mm), (C, D) particle surface area (mm²), and (E, F) particle circularity for the two cruises (8401 and 9401) when plastic particles could be analyzed by ZooScan. Symbols on the right side of each plot indicate the median and 20th–80th percentile distributions. (G) Relationship between particle circularity and particle Feret diameter (mm), for all particles from 8401 and 9401. The solid line describes a fit with a non-parametric Loess smoother (Cleveland and Devlin 1988), with sampling proportion = 0.5.

highly skewed, with most stations showing a small number of particles and a few locations showing appreciably higher concentrations (fig. 4A–C). Median particle concentrations (and 20th and 80th percentile limits of the median; followed by maximum value) in 1984, 1994, and 2007 were 0.011 (0.000–0.077; 0.822), 0.033 (0.000–0.114; 0.909), and 0.016 (0.000–0.059; 3.141) particles/m³ (fig. 4), respectively. There was no significant difference in particle numerical concentration among cruises (Kruskal-Wallis 1-way ANOVA, $p > 0.20$). The dry mass concentrations were similarly very patchy with medians (20th and 80th percentile limits; maximum): 0.003 (0.000–0.144; 5.337), 0.014 (0.000–0.099; 2.876), and 0.005 (0.000–0.092; 2.305) mg dry mass/m³ for 1984, 1994, and 2007, respectively (fig. 4D–F). There was no significant difference in particle mass concentration among cruises (Kruskal-Wallis 1-way ANOVA, $p > 0.60$). The highest dry mass concentration was 5.337 mg/m³ in winter 1984.

ZooScan optical analysis of individual particles revealed that the median particle Feret diameter (approximately equivalent to particle length) was 2.62 mm on cruise 8401 and 2.33 mm on cruise 9401, with a broad range of sizes in both years (fig. 5A, B). The plastic micro-debris particles also showed a skewed frequency distribution of particle surface area (fig. 5C, D), with a broad tail of particles much larger than the medians (2.42 mm² in 8401 and 2.06 mm² in 9401). The circularity of the particles was similar on both cruise 8401 (median = 0.470) and cruise 9401 (median = 0.493), with numerous more irregularly shaped particles (fig. 5E, F). None of the measured characteristics (Feret diameter, surface area, and circularity) varied significantly between cruises (Mann-Whitney U test, $p > 0.10$ in all cases). Circularity varied inversely with particle size (Spearman rank correlation = -0.534, $p < 0.00001$), indicating that larger micro-debris particles had more elongate shapes and/or irregular surfaces while progressively smaller particles were consistently more circular (fig. 5G).

DISCUSSION

Results from this study indicate that plastic micro-debris particles are widespread in the surface layer of the ocean in the southern region of the California Current system in winter, and have been present in the area for at least 25 years. Although plastic micro-debris is patchily distributed, 56% to 68% of the stations from throughout the approximately 200,000 km^2 of the sampling domain had detectable plastic debris, including all subregions analyzed.

We detected no significant differences among years in the percentage of stations with plastic micro-debris particles. However, analysis of intervening years would be required to fully assess the magnitude of interannual variability and its relationship to variations in terrestrial sources of plastics, as well as variations in ocean circulation. Thompson et al. (2004) suggested there was an increase in plastic debris particles in plankton samples from waters north of the United Kingdom between the 1960–70s and the 1980–90s.

We detected no trends in particle concentration or particle dry mass distribution over the three decades represented in our study, or in characteristics of the particles analyzed for the two time periods when these could be compared in detail. However, the patchy distribution of these particles in the ocean led to highly skewed frequency distributions. These distributions highlight the importance of a few locations with much higher concentrations, or heavier particles, than the median. Consequently, if there were true underlying trends over time, extensive sampling would be required to resolve them statistically.

It is noteworthy that there was no relationship between the numerical concentration or the dry mass concentration of particles and distance from shore, the presumed source of the majority of debris. We found concentrations of micro-debris in the inshore, intermediate, and offshore regions of the sampling domain. This widespread pattern of occurrence is consistent with the inverse relationship between particle circularity and particle length, as well as declining particle numbers with particle length. Increasing particle circularity with smaller particle size suggests that larger marine debris items with irregular edges become progressively smaller and rounded through time via mechanical breakdown. The dominance of smaller particles in the size spectrum also suggests that the dominant pathway of formation is particle fragmentation (apart from the very small number of intact pre-production plastic pellets detected), and could imply a relatively long residence time in the ocean as small particles accumulate over time. Protracted residence times would lead to greater dispersal by ocean circulation, and thus more geographically widespread micro-debris, as we have observed. Our interpretation of protracted residence time of plastic particles is consistent with Doyle et al.[1]

The average micro-particle size was 2.3–2.6 mm, which is somewhat smaller than the typical diameter of pre-production plastic pellets (3.5 mm). Although a few intact pellets were found, most particles were smaller. In light of passage of smaller particles through the 505 µm mesh sampling net we utilized, it is likely that the true underlying size distribution of micro-debris is skewed even further toward abundant small particles. Although some of the samples we analyzed had been archived for 25 years, the similarity of particle concentrations, length, circularity, and mass distributions in different years of our study suggest there was no particle loss or degradation with time of preservation.

Doyle et al.[1], investigating the distribution and abundance of plastic particles in the southeastern Bering Sea, the CalCOFI region, and further north off the U.S. West Coast from spring 2006 to winter 2007, concluded that a small amount of plastic micro-debris was widely distributed throughout the survey regions. In the Bering Sea, 25% of the spring and 40% of the fall samples contained plastic micro-debris. In the CalCOFI region, the respective percentages were 8.8% in April, 81.2% in July, and 66.7% in October 2006. For all these surface samples, the arithmetic mean of plastic micro-debris mass was less than 0.2 mg/m^3, and the arithmetic mean particle concentration ranged from 0.004 to 0.19/m^3. Subsurface (bongo net) sampling to 210 m depth from spring, summer, and fall 2006 CalCOFI cruises did not yield any plastic micro-debris particles. However, 28% of the subsurface bongo samples collected during January 2007 yielded low mean concentrations and masses of plastic particles.

Doyle et al.[1] compared the mass of plastic micro-debris with zooplankton dry mass and found, on average, the plastic micro-debris mass was 2–3 orders of magnitude lower than zooplankton biomass in the California Current system. We were not able to make such comparisons because displacement volumes or other measures of zooplankton biomass were not available for our samples. It remains to be determined in a quantitative and rigorous manner how California Current system marine micro-debris loads compare with those of the open ocean ecosystem of the North Pacific Central Gyre.

Previous research on plastic debris in the ocean has focused mainly on macro debris, recorded from the poles to the equator (Thompson et al. 2004). Smaller particles have been reported, but they have received far less attention. Carpenter and Smith (1972) reported mean concentrations of 3500 pieces and 290 g/km^2 and concluded that plastic particles were widespread in the western Sargasso Sea. On a multi-ship plankton survey of coastal and oceanic waters from Cape Cod to the Caribbean, Colton et al. (1974) observed a high occurrence of widely distributed plastic particles. The first ship reported a mean concentration of 10.5 g/km^2 for all stations sampled, the second ship 18.1 g/km^2, and the third 77.7 g/km^2.

According to Day and Shaw (1987), the occurrence and abundance of pelagic plastic has been studied less in the North Pacific Ocean and Bering Sea than in the North Atlantic Ocean, Mediterranean Sea, and Caribbean Sea. Day and Shaw (1987) determined the distribution and abundance of pelagic plastics in subtropical and subarctic North Pacific Ocean and Bering Sea waters in 1985 and compared their results with similar observations made in the same areas from 1976 and 1984. They reported great variation, but the mean concentration of small plastics in subtropical waters was around 26 times that in sub-arctic waters and around 400 times that in the Bering Sea. Moore et al. (2001) measured plastics in the North Pacific Central Gyre, recording 27,698 small pieces of plastic with a weight of 424 g from 11 stations. The mean concentration of particles was 334,271 pieces/km^2. Moore et al. (2002) investigated five stations that ran parallel to the southern California coast, collecting during a dry period and also following a rain event. Prior to the storm, the concentration was approximately three pieces/m^3, which is comparable to the maximum value we measured in the present study, while after the rain event, concentrations more than doubled at all stations tested.

Further investigation is needed of the occurrence, distribution, and fate of plastic micro-particles in the California Current system. We suggest that additional analyses be conducted from intervening years, other seasons, and at subsurface depths. We chose to analyze El Niño-neutral years, in order to make the years analyzed from each decade more comparable. However, the relationship between particle distributions and changes in ocean circulation during El Niño-Southern Oscillation are of interest. Also, because manta nets were introduced to CalCOFI only in the late 1970s, it would be informative to analyze subsurface tows that date back to 1949. By using these archived CalCOFI plankton samples, combined with analyses of the chemical characteristics of marine debris and experiments evaluating their effects on planktonic organisms (Arthur et al. 2009), it will be possible to advance our understanding of the history of occurrence and present consequences of marine debris in a major coastal ecosystem.

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APPENDIX TABLE 1

Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
8401	76.7	48	16-Jan-1984	96	0.0000	0.0000			
8401	76.7	51	16-Jan-1984	72	0.1653	0.0138	0.413	10.51	3.97
8401	76.7	55	16-Jan-1984	67	0.0000	0.0000			
8401	76.7	60	16-Jan-1984	107	0.0000	0.0000			
8401	76.7	70	15-Jan-1984	92	1.0012	0.0761	0.255	11.86	5.73
8401	76.7	80	15-Jan-1984	95	0.0000	0.0000			
8401	76.7	90	15-Jan-1984	96	0.0000	0.0000			
8401	76.7	100	15-Jan-1984	85	0.0000	0.0000			
8401	80	51	11-Jan-1984	101	0.0344	0.2970	0.356	9.21	4.84
8401	80	55	12-Jan-1984	81	0.0032	0.0123	0.341	4.56	3.25
8401	80	60	12-Jan-1984	94	0.1114	0.0106	0.331	11.53	4.41
8401	80	60	12-Jan-1984	101	0.0000	0.0792	0.668	0.22	0.66
8401	80	70	13-Jan-1984	91	0.0000	0.0000			
8401	80	70	13-Jan-1984	93	0.0000	0.0000			
8401	80	80	14-Jan-1984	85	0.0019	0.0118	0.330	2.09	2.49
8401	80	90	14-Jan-1984	100	0.0057	0.0200	0.472	5.17	3.48
8401	80	100	14-Jan-1984	86	0.1902	0.3721	0.498	4.56	3.17
8401	82	46	10-Jan-1984	82	0.0000	0.0000			
8401	83.3	40.6	10-Jan-1984	96	0.0248	0.0417	0.411	21.16	3.58
8401	83.3	42	10-Jan-1984	87	0.0000	0.0000			
8401	83.3	51	10-Jan-1984	85	0.0000	0.0000			
8401	83.3	55	10-Jan-1984	84	0.0000	0.0000			
8401	83.3	60	10-Jan-1984	80	0.0000	0.0000			
8401	83.3	70	9-Jan-1984	99	0.0000	0.0000			
8401	83.3	80	9-Jan-1984	91	0.2371	0.0549	0.505	6.55	3.66
8401	83.3	90	9-Jan-1984	94	0.0348	0.0106	0.441	4.49	3.09
8401	83.3	100	8-Jan-1984	79	0.2158	0.4810	0.417	2.62	3.60
8401	83.3	100	8-Jan-1984	93	0.4454	0.1290	0.476	2.58	3.49
8401	86.7	33	5-Jan-1984	116	0.1303	0.1207	0.439	10.25	4.81
8401	86.7	35	5-Jan-1984	122	5.3366	0.0410	0.032	4.93	13.38
8401	86.7	40	5-Jan-1984	90	0.0027	0.0222	0.384	0.86	1.94
8401	86.7	45	5-Jan-1984	80	0.0000	0.0000			
8401	86.7	50	6-Jan-1984	89	0.0000	0.0000			
8401	86.7	55	6-Jan-1984	104	0.0000	0.0000			
8401	86.7	60	6-Jan-1984	92	0.0027	0.0217	0.412	1.27	1.85
8401	86.7	70	7-Jan-1984	90	0.0150	0.0333	0.303	3.66	3.82
8401	86.7	80	7-Jan-1984	94	0.0291	0.0745	0.410	2.45	3.50
8401	86.7	90	7-Jan-1984	96	0.0077	0.0208	0.321	5.54	4.66
8401	86.7	100	7-Jan-1984	85	0.1768	0.4706	0.462	2.77	2.13
8401	90	28	5-Jan-1984	90	0.1592	0.5333	0.507	1.45	1.82
8401	90	30	5-Jan-1984	101	1.1132	0.8218	0.379	7.04	3.99
8401	90	35	4-Jan-1984	109	0.0347	0.0275	0.242	16.99	5.15
8401	90	37	5-Jan-1984	107	0.7887	0.2243	0.460	6.35	3.47
8401	90	53	5-Jan-1984	104	0.0000	0.0000			
8401	90	60	7-Jan-1984	78	0.0000	0.0000			
8401	90	70	7-Jan-1984	96	0.0000	0.0000			
8401	90	80	8-Jan-1984	85	5.1880	0.1059	0.475	25.01	7.23
8401	90	90	8-Jan-1984	92	0.0199	0.0652	0.570	2.26	2.16
8401	90	100	8-Jan-1984	98	0.0973	0.0918	0.335	4.05	3.25
8401	93.3	26.7	12-Jan-1984	96	0.0015	0.0104	0.057	2.43	9.06
8401	93.3	29	12-Jan-1984	82	0.0565	0.0366	0.529	2.50	2.11
8401	93.3	30	11-Jan-1984	59	0.1276	0.0678	0.350	6.30	5.18
8401	93.3	35	10-Jan-1984	90	0.0000	0.0000			

APPENDIX TABLE 1 (continued)
Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
8401	93.3	40	10-Jan-1984	129	0.1382	0.0078	0.308	23.05	9.38
8401	93.3	45	10-Jan-1984	109	0.0000	0.0000			
8401	93.3	50	10-Jan-1984	119	0.0000	0.0000			
8401	93.3	60	10-Jan-1984	119	0.0000	0.0000			
8401	93.3	70	9-Jan-1984	122	0.0000	0.0000			
8401	93.3	80	9-Jan-1984	70	0.0000	0.0000			
8401	93.3	90	9-Jan-1984	84	0.0000	0.0000			
8401	93.3	100	9-Jan-1984	107	0.0556	0.0374	0.373	5.65	4.70
9401	76.7	49	5-Feb-1994	104	0.0072	0.0577	0.341	4.30	3.35
9401	76.7	51	5-Feb-1994	97	0.0000	0.0000			
9401	76.7	55	5-Feb-1994	88	0.0000	0.0000			
9401	76.7	60	5-Feb-1994	87	0.0000	0.0000			
9401	76.7	70	5-Feb-1994	96	0.6702	0.7396	0.468	3.70	2.98
9401	76.7	80	4-Feb-1994	103	0.0241	0.0485	0.330	3.41	2.70
9401	76.7	90	4-Feb-1994	81	0.0021	0.0617	0.511	0.57	1.08
9401	76.7	100	4-Feb-1994	91	0.0000	0.0000			
9401	80	51	2-Feb-1994	92	0.5308	0.0543	0.362	4.21	2.72
9401	80	55	2-Feb-1994	92	0.0000	0.0000			
9401	80	60	3-Feb-1994	101	0.0138	0.0198	0.265	2.45	8.45
9401	80	70	3-Feb-1994	89	0.0147	0.0337	0.294	3.13	6.39
9401	80	80	3-Feb-1994	99	0.0196	0.0505	0.330	3.29	3.74
9401	80	90	3-Feb-1994	81	0.3064	0.0741	0.306	3.85	5.08
9401	80	100	4-Feb-1994	82	0.0013	0.0122	0.004	5.88	16.64
9401	81.8	46.9	2-Feb-1994	102	0.0000	0.0000			
9401	83.3	40.6	2-Feb-1994	94	0.2306	0.0106	0.711	10.69	3.92
9401	83.3	42	2-Feb-1994	95	0.0000	0.0000			
9401	83.3	51	1-Feb-1994	88	0.0000	0.0000			
9401	83.3	55	1-Feb-1994	94	0.0000	0.0000			
9401	83.3	60	1-Feb-1994	86	0.0000	0.0000			
9401	83.3	70	1-Feb-1994	97	0.0455	0.0412	0.491	2.91	2.26
9401	83.3	80	31-Jan-1994	89	0.2011	0.2247	0.407	6.10	5.27
9401	83.3	90	31-Jan-1994	102	0.3133	0.3922	0.519	2.69	3.16
9401	83.3	100	31-Jan-1994	89	0.0109	0.0225	0.314	5.67	14.91
9401	83.3	110	30-Jan-1994	86	0.0000	0.0116	0.027	4.05	11.57
9401	86.7	33	27-Jan-1994	89	0.3157	0.1573	0.476	35.10	7.33
9401	86.7	35	28-Jan-1994	106	0.2028	0.0849	0.314	5.67	14.91
9401	86.7	40	28-Jan-1994	97	0.0466	0.0515	0.597	2.13	1.98
9401	86.7	45	28-Jan-1994	99	0.2104	0.0404	0.219	7.06	4.12
9401	86.7	50	28-Jan-1994	87	0.0077	0.0230	0.619	0.02	0.02
9401	86.7	55	28-Jan-1994	99	0.0046	0.0202	0.631	0.68	1.19
9401	86.7	60	29-Jan-1994	99	0.7794	0.9090	0.335	3.14	2.57
9401	86.7	70	29-Jan-1994	86	0.0422	0.1860	0.474	2.54	2.46
9401	86.7	80	29-Jan-1994	91	0.0491	0.0989	0.505	4.35	2.64
9401	86.7	90	30-Jan-1994	94	0.0537	0.0319	0.355	0.93	2.07
9401	86.7	100	30-Jan-1994	88	0.0300	0.0454	0.423	2.39	3.13
9401	86.7	110	30-Jan-1994	90	0.0841	0.1111	0.449	2.38	3.26
9401	90	28	27-Jan-1994	87	0.0000	0.0000			
9401	90	30	27-Jan-1994	91	0.0312	0.0110	0.477	8.27	4.93
9401	90	35	27-Jan-1994	88	0.0000	0.0000			
9401	90	37	27-Jan-1994	87	0.0000	0.0000			
9401	90	45	26-Jan-1994	92	0.0000	0.0000			
9401	90	53	26-Jan-1994	88	0.0000	0.0000			
9401	90	60	26-Jan-1994	82	0.0000	0.0000			
9401	90	70	26-Jan-1994	91	0.0000	0.0000			
9401	90	80	25-Jan-1994	77	0.0000	0.0000			
9401	90	90	25-Jan-1994	84	0.0000	0.0000			
9401	90	100	25-Jan-1994	93	0.0088	0.0175	0.465	1.88	2.38
9401	90	110	24-Jan-1994	79	0.0000	0.0000			
9401	90	120	24-Jan-1994	94	0.0182	0.0106	0.019	12.01	15.91
9401	93.3	26.7	20-Jan-1994	99	2.8765	0.3636	0.504	14.27	5.26
9401	93.3	28	20-Jan-1994	93	0.0891	0.0645	0.408	8.83	4.03
9401	93.3	30	20-Jan-1994	91	0.2387	0.4066	0.492	2.58	2.24
9401	93.3	35	21-Jan-1994	93	0.1229	0.5380	0.518	2.51	5.46

APPENDIX TABLE 1 (continued)
Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
9401	93.3	40	21-Jan-1994	85	0.0061	0.0353	0.380	12.51	6.03
9401	93.3	45	21-Jan-1994	91	0.0490	0.0549	0.418	3.25	2.43
9401	93.3	50	21-Jan-1994	86	0.0000	0.0000			
9401	93.3	55	21-Jan-1994	88	0.0094	0.0341	0.125	3.25	7.22
9401	93.3	60	22-Jan-1994	93	0.0223	0.0538	0.542	4.12	2.84
9401	93.3	70	22-Jan-1994	90	0.0456	0.1222	0.560	2.30	2.25
9401	93.3	80	22-Jan-1994	100	0.0297	0.1200	0.479	1.61	2.34
9401	93.3	90	23-Jan-1994	99	0.0397	0.1212	0.533	1.65	2.13
9401	93.3	100	23-Jan-1994	89	0.0279	0.1011	0.435	1.73	2.34
9401	93.3	110	23-Jan-1994	91	0.0651	0.1648	0.430	3.55	3.11
9401	93.3	120	24-Jan-1994	98	0.0088	0.0204	0.542	1.00	1.73
0701	76.7	49	28-Jan-2007	79	0.0000	0.0000			
0701	76.7	51	28-Jan-2007	73	0.0550	0.0550			
0701	76.7	55	28-Jan-2007	57	0.0000	0.0000			
0701	76.7	60	29-Jan-2007	69	0.3444	0.1592			
0701	76.7	70	29-Jan-2007	72	2.3049	0.2083			
0701	76.7	80	29-Jan-2007	78	0.0205	0.0513			
0701	76.7	90	29-Jan-2007	71	0.0865	0.0141			
0701	76.7	100	29-Jan-2007	75	0.2019	0.6818			
0701	80	51	28-Jan-2007	76	0.0000	0.0000			
0701	80	55	28-Jan-2007	70	0.0313	0.0284			
0701	80	60	27-Jan-2007	56	0.0063	0.0179			
0701	80	70	27-Jan-2007	69	0.0491	0.0723			
0701	80	80	27-Jan-2007	65	0.0011	0.0154			
0701	80	90	27-Jan-2007	67	0.0404	0.0299			
0701	80	100	26-Jan-2007	65	0.1972	0.0308			
0701	81.8	46.9	24-Jan-2007	90	0.1573	0.0332			
0701	83.3	40.6	24-Jan-2007	82	0.2866	0.0366			
0701	83.3	42	24-Jan-2007	80	0.0038	0.0125			
0701	83.3	51	24-Jan-2007	66	0.0000	0.0000			
0701	83.3	55	25-Jan-2007	68	0.0000	0.0000			
0701	83.3	60	25-Jan-2007	46	0.0000	0.0000			
0701	83.3	70	25-Jan-2007	67	0.1040	0.0594			
0701	83.3	80	25-Jan-2007	57	0.0005	0.0175			
0701	83.3	90	26-Jan-2007	70	0.0459	0.0717			
0701	83.3	100	26-Jan-2007	64	0.0027	0.0156			
0701	83.3	110	26-Jan-2007	75	0.3720	0.6133			
0701	86.7	33	23-Jan-2007	69	0.0193	0.0290			
0701	86.7	35	23-Jan-2007	66	1.5129	0.6393			
0701	86.7	40	23-Jan-2007	65	0.0000	0.0000			
0701	86.7	45	23-Jan-2007	68	0.1467	0.0593			
0701	86.7	50	23-Jan-2007	64	0.0000	0.0000			
0701	86.7	55	23-Jan-2007	66	0.0198	0.0152			
0701	86.7	60	22-Jan-2007	65	0.0048	0.0154			
0701	86.7	70	22-Jan-2007	61	0.0048	0.0659			
0701	86.7	80	22-Jan-2007	69	0.0000	0.0000			
0701	86.7	90	22-Jan-2007	62	0.0048	0.0160			
0701	86.7	100	21-Jan-2007	59	0.0000	0.0000			
0701	86.7	110	21-Jan-2007	70	0.0742	0.2282			
0701	90	28	18-Jan-2007	64	0.0055	0.0156			
0701	90	30	18-Jan-2007	64	0.0406	0.1250			
0701	90	35	18-Jan-2007	60	0.0103	0.0167			
0701	90	37	18-Jan-2007	66	0.0008	0.0152			
0701	90	45	18-Jan-2007	64	0.0125	0.0156			
0701	90	53	19-Jan-2007	58	0.0009	0.0174			
0701	90	60	19-Jan-2007	59	0.0000	0.0000			
0701	90	70	19-Jan-2007	59	0.0118	0.0508			
0701	90	80	20-Jan-2007	60	0.0000	0.0000			
0701	90	90	20-Jan-2007	70	0.0000	0.0000			
0701	90	100	20-Jan-2007	54	0.0000	0.0000			
0701	90	110	21-Jan-2007	70	0.0007	0.0143			
0701	90	120	16-Jan-2007	66	0.0000	0.0000			
0701	93.3	26.7	12-Jan-2007	58	0.0000	0.0000			

APPENDIX TABLE 1 (continued)

Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
0701	93.3	28	13-Jan-2007	59	1.6112	3.1409			
0701	93.3	30	13-Jan-2007	71	2.1591	0.5390			
0701	93.3	35	13-Jan-2007	60	0.0000	0.0000			
0701	93.3	40	13-Jan-2007	60	0.0000	0.0000			
0701	93.3	45	13-Jan-2007	61	0.0000	0.0000			
0701	93.3	50	14-Jan-2007	58	0.2363	0.0342			
0701	93.3	55	14-Jan-2007	66	0.0000	0.0000			
0701	93.3	60	14-Jan-2007	62	0.0421	0.0324			
0701	93.3	70	14-Jan-2007	63	0.0000	0.0000			
0701	93.3	80	14-Jan-2007	56	0.0018	0.0540			
0701	93.3	90	15-Jan-2007	57	0.0000	0.0000			
0701	93.3	100	15-Jan-2007	62	0.0000	0.0000			
0701	93.3	110	15-Jan-2007	70	0.0000	0.0000			
0701	93.3	120	16-Jan-2007	56	0.0323	0.0179			