Title
Occurrence of Plastic Micro-Debris in the California Current System

Author
Gilfillan, Lisa

Publication Date
2009-04-01

Occurrence of plastic micro-debris in the California Current System

Lisa R. Gilfillan[1], Mark D. Ohman[1], Miriam J. Doyle[2], William Watson[3]

[1]Scripps Institution of Oceanography, University of CA, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA

[2] Joint Institute for the Study of the Atmosphere and Oceans, P.O. Box 355672, University of Washington, Seattle, WA 98195, USA

[3] NOAA National Marine Fisheries Service, Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037, USA

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 85 % of the CalCOFI stations had detectable plastic micro-debris present, with an increasing trend in occurrence over time. Although the average concentration, length, and mass of the particles was not significantly different over the three decades, 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 & 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 (Derraik 2002, Hinojosa & Thiel 2009, Lattin et al. 2004, McDermid & McMullen 2004, Moore 2008, Santos et. al. 2009, Sheavly & Register 2007, Smith et al. 1997).

According to Derraik (2002), plastics make up most of the marine litter worldwide. Between 1970 and 2003, plastics became the fastest growing segment of the US municipal waste stream, and marine litter is now 60-80% plastic by volume, reaching 90-95% in some places (Moore 2008). Marine plastic debris can be divided into two categories: macro (>5 mm) and micro (<5mm; Moore 2008). Plastic micro-debris is composed of fragments of manufactured plastic products and pre-production plastic pellets (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 winter cruises in 1984, 1994, and 2007, the latter originating from Doyle et al. (in review).

Methods

Zooplankton samples for this study were collected on three CalCOFI cruises (8401: 4 -16 January 1984, 9401: 20 January- 5 February 1994, and 0701: 12- 29 January 2007) using the Manta net neuston sampler (Brown & Cheng 1981). Samples were archived in the Pelagic Invertebrates Collection of the Scripps Institution of Oceanography. Only samples from the southern sector 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. in review). The samples from 2007 had already been analyzed by Doyle et al. (in review), but of the 66 samples from that cruise in our study region only 34 had plastic debris differentiated from other particles, and therefore our sample size for that cruise is 34. Tow duration for the Manta is approximately fifteen minutes and the net mesh is 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 borate-buffered formaldehyde in seawater. A calibrated flowmeter was fitted in the mouth of each net and the flowmeter readings were converted to m^3 of water filtered.

We utilized the sample sorting protocol described by Doyle et al. (in review). 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, oven dried at 55°C for eight hours and dry mass 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. ms.). 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. ms.). Figure 1 illustrates examples of ZooScan images of plastic micro-debris from two samples.

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 all subregions sampled, including the inshore, transitional, and offshore regions. There was no relationship between distance from shore and either numerical concentration of particles or mass concentration of particles, for each cruise considered separately ($p > 0.20$) or for all cruises combined ($p > 0.20$, Spearman rank correlation).

There was a temporal increase in percentage of stations with plastic particles: 34 out of 61 stations (55.7 %) in 1984, 45 out of 66 stations (68.2 %) in 1994, and 31 out of 34 stations (85.3 %) in 2007 (Fig. 3). The years 1984 and 2007 differed in percentage of stations with plastic debris ($p < 0.05$, based on binomial distribution), but 1994 did not differ from the preceding or following time period ($p > 0.05$).

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 southeasternmost point of the CalCOFI station grid near San Diego (Fig. 3c). Frequency distributions of particle concentrations were 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) in 1984, 1994 and 2007 were 0.012 (0.000-0.077), 0.033 (0.000-0.114), and 0.000 (0.000-0.056) particles m^{-3} (Fig. 4), respectively, indicating no significant differences among cruises. The dry mass concentrations were similarly very patchy with no significant difference among medians: 0.003 (0.000-0.144), 0.014 (0.000-0.099), and 0.000 (0.000-0.047) mg dry mass m^{-3} for 1984, 1994, and 2007, respectively (Fig. 4d-f). The highest dry mass concentration was 5.337 mg m^{-3} in winter 1984.

ZooScan optical analysis of individual particles revealed that the median particle feret diameter (approximately equivalent to particle length) was 2.59 mm on cruise 8401 and 2.26 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 (2.40 mm^2 in 8401 and 1.92 mm^2 in 9401). The circularity of the particles was similar on both cruise 8401 (median= 0.448) and cruise 9401 (median = 0.494), with numerous more irregularly shaped particles (Fig. 5e,f). Circularity varied inversely with particle size (Spearman rank correlation = -0.624, $p < 0.00001$), 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 85 % 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 a significant difference among years in the percentage of stations with plastic debris particles suggestive of a temporal increase between 1984 and 2007. However analysis of intervening years would be required to confirm this as a temporal trend. 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's-1970's and the 1980's-1990's. In contrast to the percentage of positive stations, we did not detect 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 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, transitional, 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 small number of intact pre-production plastic pellets detected), and could imply a relatively long residence time in the ocean. Protracted residence times may result in greater dispersal by ocean currents, 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. (in review).

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 escapement of smaller particles through the 505μm 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 is no particle loss or degradation with time of preservation.

Doyle et.al (in review), 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 mass of plastic particles.

Doyle et. al (in review) compared mass of plastic micro-debris with zooplankton dry mass and found, on average, the plastic micro-debris mass was 2-3 orders 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.

Further investigation is needed regarding 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 ENSO are of interest. Also, because Manta nets were only introduced to CalCOFI 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.

Acknowledgements

We wish to thank the Scripps Institution of Oceanography and the Center for Marine Biodiveristy and Conservation for hosting this research project. Also, thanks to many people who made this work possible, including: Todd Cannatelli, Alison Cawood, Anna Simeon and Annie Townsend. A contribution from the SIO Pelagic Invertebrates Collection and the CCE Long Term Ecological Research site, supported by NSF.

References

Arthur, C., Baker, J., Bamford, H., [eds.] 2009. Proceedings of the international research workshop on the occurrence, effects, and fate of microplastic marine debris, September 9-11 2008. NOAA Technical Memorandum NOS-OR&R-30.

Brown, D. M., Cheng, L., 1981. New net for sampling the ocean surface. Mar. Ecol. Prog. Ser. 5:225-227.

Derraik, Jose, G. B., 2002. The pollution of the marine environment by plastic debris: a review.

Marine Pollution Bulletin 44:842-852.

Doyle, M. J., Watson, W., Bowlin, N. M., Sheavly, S. B., 2009. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. (manuscript in review)

Gorsky, G., M. D. Ohman, M. Picheral, S. Gasparini, L. Stemmann, J.-B. Romagna, A. Cawood, Prejger, F., 2009. Digital zooplankton image analysis using the ZooScan integrated system. (manuscript)

Grosjean, P., M. Picheral, C. Warembourg, Gorsky, G. 2004. Enumeration, measurement, and identification of net zooplankton samples using the ZOOSCAN digital imaging system. ICES J. Mar. Sci. **61**: 518-525.

Hinojosa, I. A., Thiel, M., 2009. Floating marine debris in fjords, gulfs and channels of southern Chile. Marine Pollution Bulletin 58: 341-350.

Lattin, G. L., Moore, C.J., Zellers, A.F., Moore, S.L., Weisberg, S.B., 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Marine Pollution Bulletin 49: 291-294.

McDermid, K. J., McMullen, T. L., 2004. Quantitative analysis of small-plastic debris on beaches in the Hawaiian archipelago. Marine Pollution Bulletin 48: 790-794.

Moore, C. J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environmental Research 108:131-139.

Santos, I. R., Friedrich, A. C., Ivar do Sul, J. A., 2009. Marine debris contamination along undeveloped tropical beaches from northeast Brazil. Environ. Mont. Assess. 148: 455-462.

Sheavly, S. B., Register, K. M., 2007. Marine debris & plastics: Environmental concerns, sources, impacts and solutions. J. Polym Environ., 15:301-305.

Smith, K. V., Zhang, X. P., Raymond, B., 1997. Marine debris, beach quality, and non-market values. Environmental and Resource Economics, 10: 233-247.

Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, Russell, A.E. 2004. Lost at sea: where is all the plastic? Science 304: 838.

Williams, A.T., Tudor, D.T., Gregory, M.R., 2005. Marine debris-inshore, offshore, seafloor litter. In: Encyclopedia of Coastal Science. Springer, The Netherlands, pp. 623-628.

Figure Captions

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.

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. m^{-3}).

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

Figure 4. Frequency distributions of numerical concentrations of plastic particles (No. m^{-3}, panels a, b, c) and dry mass concentrations of plastic particles (mg m^{-3}, 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 20^{th}-80^{th} percentile distributions.

Figure 5. Frequency distributions of (a,b) particle feret diameter (mm), (c, d) particle surface area (mm^2), 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 20^{th}-80^{th} percentile distributions. (g) Relationship between particle circularity and particle feret diameter (mm), for all particles from 8401 and 9401. The solid line describes a nonparametric Loess fit to the data.

Fig. 1

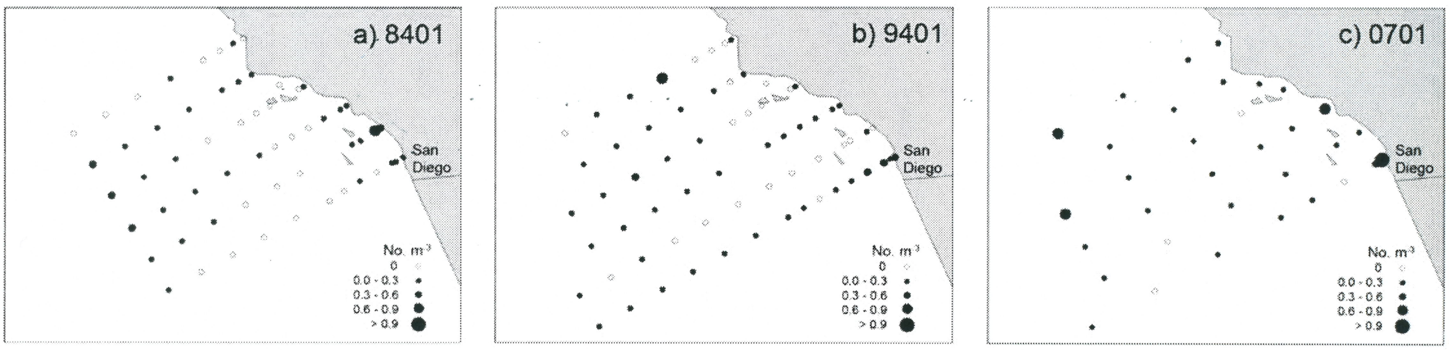
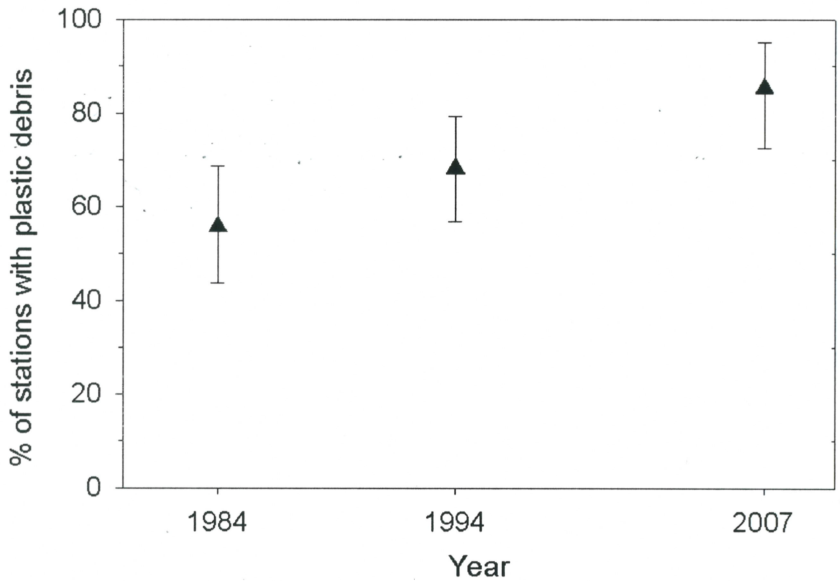
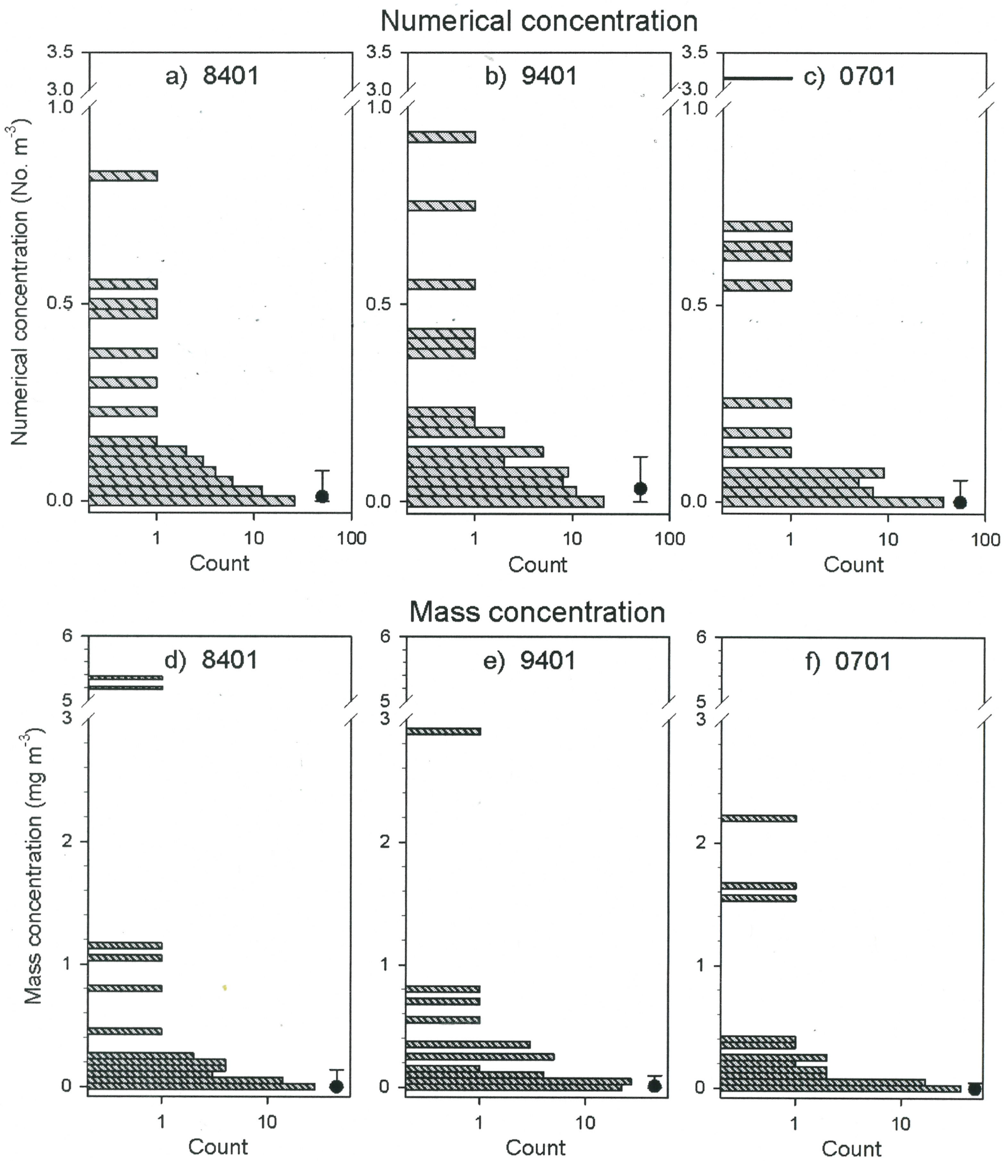

a) 8401
San Diego
No. m-3
0
0.0 - 0.3
0.3 - 0.6
0.6 - 0.9
> 0.9
b) 9401
San Diego
No. m-3
0
0.0 - 0.3
0.3 - 0.6
0.6 - 0.9
> 0.9
c) 0701
San Diego
No. m-3
0
0.0 - 0.3
0.3 - 0.6
0.6 - 0.9
> 0.9

Fig. 2



100
80
60
40
20
0
% of stations with plastic debris
1984
1994
2007
Year

Fig. 3



Numerical concentration
a) 8401
b) 9401
c) 0701
Numerical concentration (No. m^{-3})
3.5
3.0
1.0
0.5
0.0
1
10
100
Count
Mass concentration
d) 8401
e) 9401
f) 0701
Mass concentration (mg m^{-3})
6
5
3
2
1
0
Count

Fig. 4

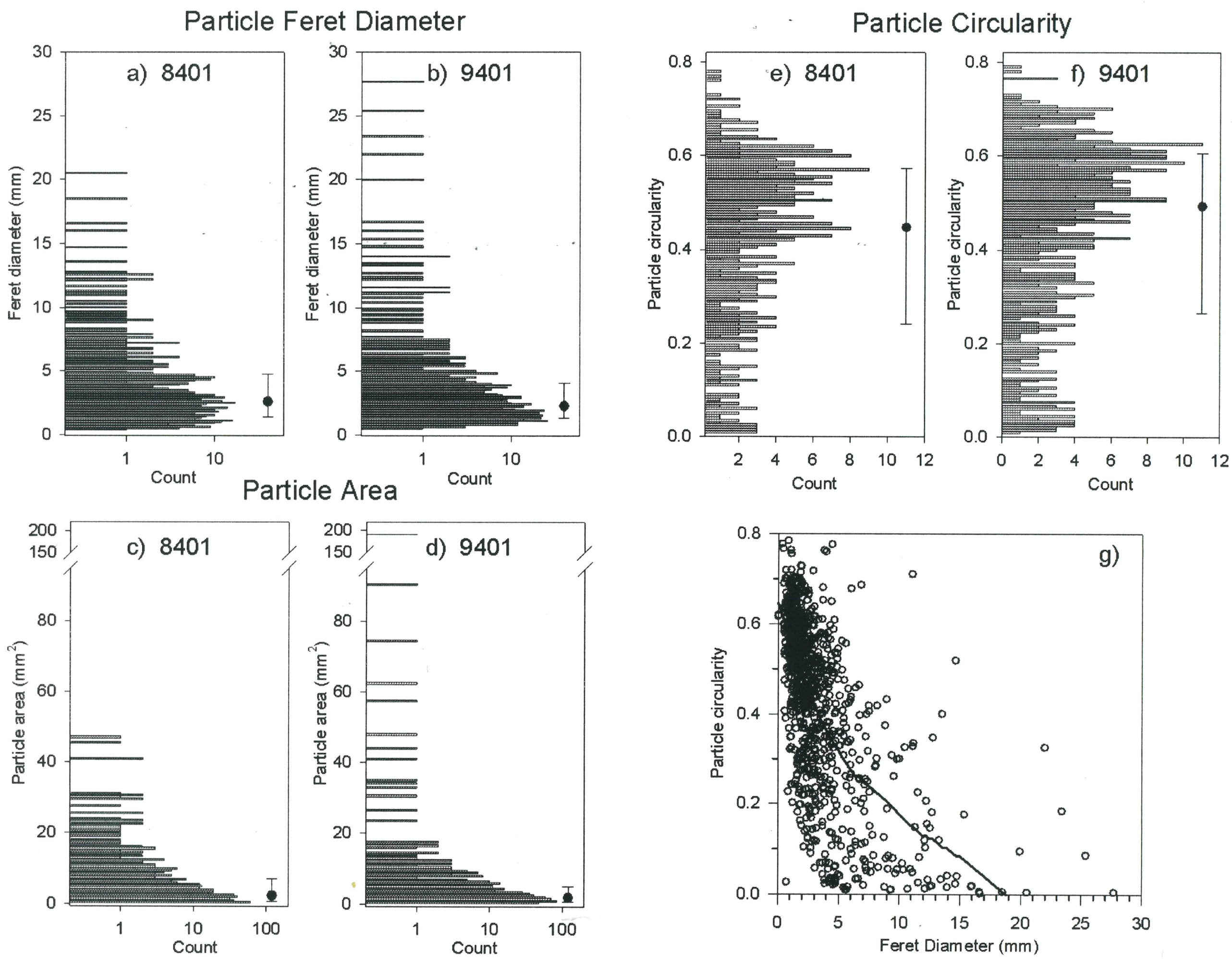

Particle Feret Diameter
a) 8401
b) 9401
Feret diameter (mm)
Count
Particle Circularity
e) 8401
f) 9401
Particle circularity
Count
Particle Area
c) 8401
d) 9401
Particle area (mm^2)
Count
g)
Particle circularity
Feret Diameter (mm)

Fig. 5