2010 ICM Problem

The Great Pacific Ocean Garbage Patch

Recently, there has been considerable news coverage of the "Great Pacific Ocean Garbage Patch."

See the following:

http://www.nytimes.com/2009/11/10/science/10patch.html?em

http://www.sciencefriday.com/program/archives/200907314

http://www.reuters.com/article/idUSTRE57R05E20090828

Based on recent scientific expeditions into the Pacific Ocean Gyre (a convergence zone where debris is accumulating), a wide variety of technical and scientific problems associated with this debris mass are coming to light. While dumping waste into the ocean is not a new activity, the scientific community's realization that much of the debris (plastics, in particular) are accumulating in high densities over a large area of the Pacific Ocean is new. The scientific community also is learning that this debris creates many potential threats to marine ecology, and, therefore, to human well-being. Those who study this accumulation often describe it as plastic soup or confetti.

See: http://news.nationalgeographic.com/news/2009/09/photogalleries/pacific-garbage-patch-pictures/

This year's ICM problem uses interdisciplinary modeling to addresses the complex issues stemming from the presence and accumulation of ocean debris, in order to help researchers and ultimately government policy makers to understand the severity, range, and potential global impact of the situation.

As modeling advisors to the expedition, your job is to focus on ***one*** element of this debris problem, model and analyze its behavior, and determine its potential effect on marine ecology and the government policies and practices that should be implemented to ameliorate its negative effects. Be sure to consider needs for future scientific research and the economic aspects of the problem, and then write a report to your expedition leader summarizing your findings and proposals for solutions and needed policies and practices. Some of the possible issues/questions you could investigate with your model include:

1. What are the potential short- and long-term effects of the plastic on the ocean environment? What kind of monitoring is required to track the impact on the marine ecosystem? Be sure to account for temporal and spatial variability. What are the associated resourcing requirements?
2. How can the extent, density and distribution of the plastic in the gyre be best understood and described? What kind of monitoring plan is required to track the growth/decay/movement of the plastics, and what kind of resourcing is required to implement that plan?
3. What is the nature or mechanism of the photodegradation of the plastic and its composition as it enters the ocean and accumulates in the gyre? (For example, we are amazed to find that the particles of degraded plastic tend to reach a similar size.)
4. Where does the plastic come from and what steps can be taken to control or reduce the risks associated with this situation? What are the economic costs and the economic benefits of controlling or ending the situation, and how do they compare? How much plastic is manufactured, discarded, and recycled? How much of that is likely to go into the ocean? How much of that is likely to float?

5. Could similar situations develop in other places in the oceans? What should we monitor and how? What is happening in the North Atlantic Gyre and the Alaskan Gyre? Use your model to estimate the plastic density in the future in the southern gyres (South Atlantic, South Pacific)?

6. What is the immediate impact of banning polystyrene takeout containers? (See: http://www.publicceo.com/2009/12/more-cities-ban-polystyrene-takeout-food-containers/) What is the impact over 10–50 years?

7. Any other scientific/technological issue associated with this situation is also acceptable, as long as modeling is an important component of your investigation and analysis.

To clarify your task, focus on ***one*** critical aspect of this problem and model the behavior of the important matters or phenomena. Specify the quantities that are of greatest present or future interest to the ***one*** aspect you choose to model and analyze. Your ICM report should be in the form of a ***ten-page*** team report to an expedition leader who has asked you to help her identify the relevant behaviors of the matters and phenomena under consideration, provide the analysis for impact of the behavior of those matters or phenomena, and advise her on the government's potential to act on the problem to improve this situation before it worsens.

The following files contain some helpful data:

CountDensity1999-2009.pdf; Moore 2001.pdf; Yamashita 2007.pdf

Here are some suggested papers you can use to inform your model formulation and obtain more data:

Note: As a reminder, it is best to stick to the scientific literature, not the media coverage, for your facts. The mainstream media coverage of this issue has been misleading in many cases. For further explanation, see: http://seaplexscience.com/2009/11/13/millions-billions-trillions-of-scientific-errors-in-the-nyt/

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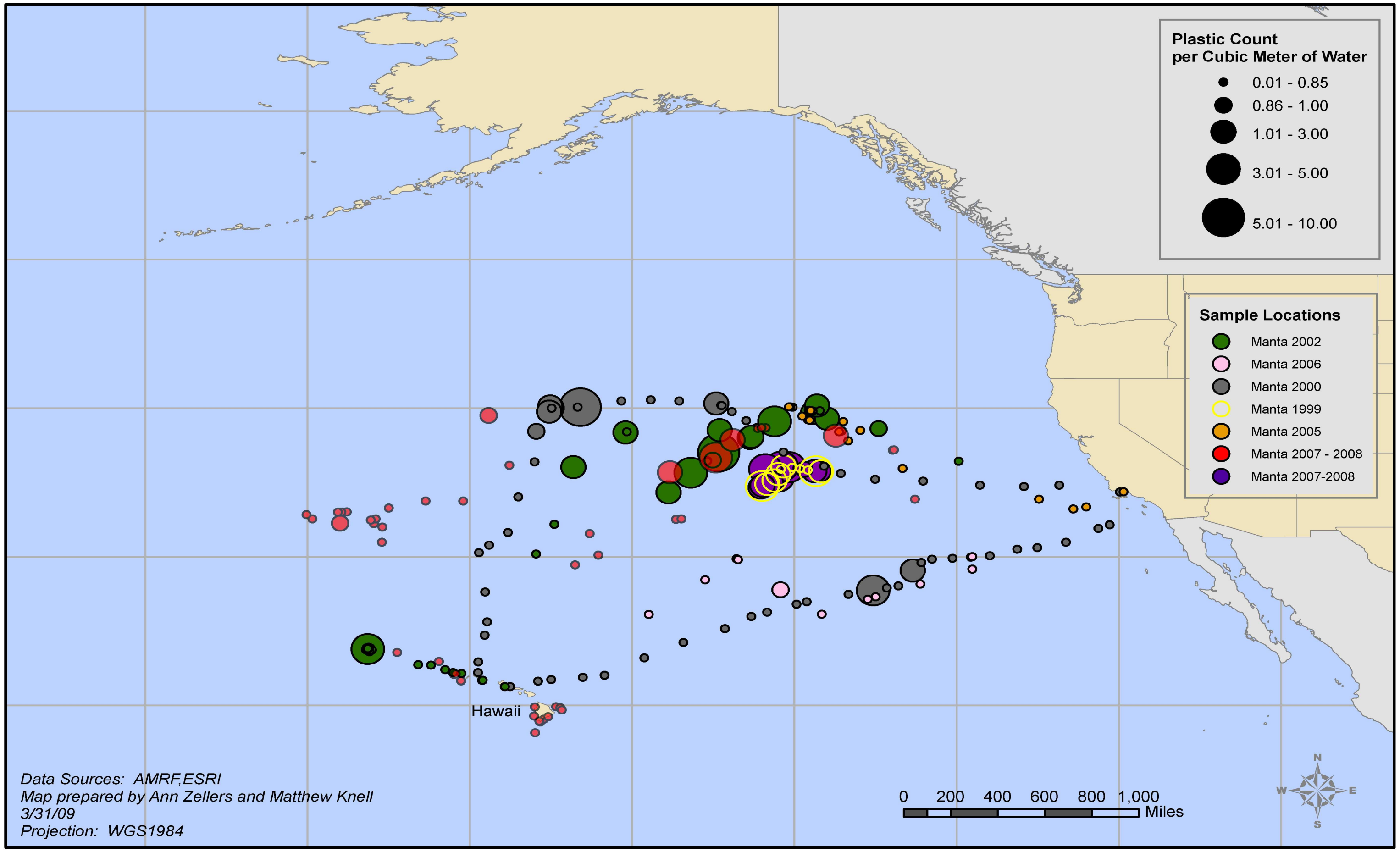

Count Densities of Plastic Debris from Ocean Surface Samples
North Pacific Gyre 1999 - 2008

Pergamon

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A Comparison of Plastic and Plankton in the North Pacific Central Gyre

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The potential for ingestion of plastic particles by open ocean filter feeders was assessed by measuring the relative abundance and mass of neustonic plastic and zooplankton in surface waters under the central atmospheric high-pressure cells of the North Pacific Ocean. Neuston samples were collected at 11 random sites, using a manta trawl lined with 333 u mesh. The abundance and mass of neustonic plastic was the largest recorded anywhere in the Pacific Ocean at 334 271 pieces km^2 and 5114 g km^2, respectively. Plankton abundance was approximately five times higher than that of plastic, but the mass of plastic was approximately six times that of plankton. The most frequently sampled types of identifiable plastic were thin films, polypropylene/monofilament line and unidentified plastic, most of which were miscellaneous fragments. Cumulatively, these three types accounted for 98% of the total number of plastic pieces. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: North Pacific central gyre; neuston; plastics; zooplankton; debris; pollution monitoring.

Marine debris is more than an aesthetic problem, posing a danger to marine organisms through ingestion and entanglement (Day, 1980; Balazs, 1985; Fowler, 1987; Ryan, 1987; Robards, 1993; Bjorndal *et al.*, 1994; Laist, 1997). The number of marine mammals that die each year due to ingestion and entanglement approaches 100 000 in the North Pacific Ocean alone (Wallace, 1985). Worldwide, 82 of 144 bird species examined contained small debris in their stomachs, and in many species the incidence of ingestion exceeds 80% of the individuals (Ryan, 1990). In addition, a recent study has determined that plastic resin pellets accumulate toxic chemicals, such as PCBs, DDE, and nonylphenols, and may serve as a transport medium and source of toxins to marine organisms that ingest them (Mato *et al.*, 2001).

Many studies have focused on the ingestion of small debris by birds because their stomach contents can be regurgitated by researchers in the field without causing harm to the animal. Less well studied are the effects of ingestible debris on fish, and no studies have been conducted on filter-feeding organisms, whose feeding mechanisms do not permit them to distinguish between debris and plankton. Moreover, no studies have compared the amount of neustonic debris to that of plankton to assess the potential effects on filter feeders.

Concerns about the effects of neustonic debris in the marine environment are greatest in oceanographic convergences and eddies, where debris fragments naturally accumulate (Shaw and Mapes, 1979; Day, 1986; Day and Shaw, 1987). The North Pacific central gyre, an area of high atmospheric pressure with a clockwise ocean current, is one such area of convergence that forces debris into a central area where winds and currents diminish. This study compares the abundance and mass of neustonic debris with the amount of zooplankton in this area.

Materials and Methods

Eleven neuston samples were collected between August 23 and 26, 1999, from an area near the central pressure cell of the North Pacific sub tropical high (Fig. 1). Sampling sites were located along two transects: a westerly transect from 35°45.8′N, 138°30.7′W to 36°04.9′N, 142°04.6′W; and a southerly transect from 36°04.9′N, 142°04.6′W to 34°40.0′N. Location along the transect and trawl duration were selected randomly. Samples were collected using a manta trawl with a rectangular opening of 0.9×0.15 m^2, and a 3.5 m long, 333 u net with a 30×10 cm^2 collecting bag. The net was towed at the surface outside of the effects of port wake (from the stern of the vessel) at a nominal speed of 1 m s^{-1}; actual speed varied between 0.5 and 1.5 m s^{-1}, as measured with a B&G paddlewheel sensor. Each trawl was conducted for a random distance, ranging from 5 to 19 km. Sampling was conducted as the ship moved along the transect with an approximately even split of sampling between daylight and night-time hours. Estimates of plastic and plankton per square kilometer were obtained by using the width of the trawl net opening times the length of the trawl.

Samples were fixed in 5% formalin, then soaked in fresh water and transferred to 50% isopropyl alcohol.

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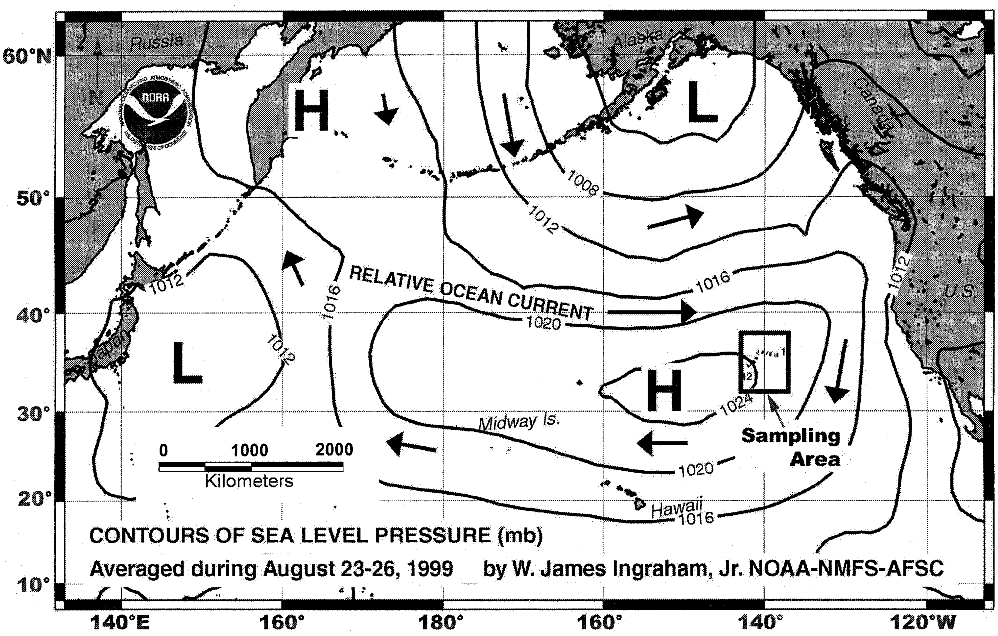

Fig. 1 Location of sampling area in the North Pacific gyre.

To separate the plastic particles from living tissue, the samples were drained and put in seawater, which floated most of the plastic to the surface, leaving the living tissue at the bottom. Top and bottom portions were inspected under a dissecting microscope. Intermixed plastic was removed from the tissue fraction and tissue was removed from the plastic fraction and placed in the appropriate containers. Plankton were counted and identified to class.

Plastic was sorted by rinsing through Tyler sieves of 4.76, 2.80, 1.00, 0.71, 0.50, and 0.35 mm. Plastic and plankton were oven dried at 65°C for 24 h and weighed. Individual pieces of plastic were categorized into standardized categories by type (fragment, Styrofoam fragment, pellet, polypropylene/monofilament line fragment, thin plastic films), and one nonplastic category (tar); then they were counted.

Results

A total of 27 698 small pieces of plastic weighing 424 g were collected from the surface water at stations in the gyre, yielding a mean abundance of 3 34 271 pieces km^2 and a mean mass of 5114 g/km^2. Abundance ranged from 31 982 pieces km^2 to 969 777 pieces/km^2, and mass ranged from 64 to 30 169 g km^2.

A total of 152 244 planktonic organisms weighing approximately 70 g were collected from the surface water, with a mean abundance of 18 37 342 organisms km^2 and mean mass of 841 g/km^2 (dry weight). Abundances ranged from 54 003 organisms km^2 to 50 76 403 organisms km^2, and weights ranged from 74 to 1618 g/km^2.

Plastic fragments accounted for the majority of the material collected in the smaller size categories (Table 1). Thin plastic films, such as those used in sandwich bags, accounted for half of the abundance in the second largest size category, and pieces of line (polypropylene and monofilament) comprised the greatest fraction of the material collected in the largest size category.

Plankton abundance was higher than plastic abundance in 8 out of 11 samples, with the difference being higher at night (Fig. 2). In contrast, the mass of plastic was higher than the plankton mass in 6 out of 11 samples. The ratio of plastic-to-plankton mass was higher

TABLE 1

Abundance (pieces km^2) by type and size of plastic pieces and tar found in the North Pacific gyre.

Mesh-size (mm)	Fragments	Styrofoam pieces	Pellets	Polypropylene/ monofilament	Thin plastic films	Miscellaneous		
						Tar	Unidentified	Total
> 4.760	1931	84	36	16 811	5322	217	350	24 764
4.759–2.800	4502	121	471	4839	9631	97	36	19 696
2.799–1.000	61 187	1593	12	9969	40 622	833	72	114 288
0.999–0.710	55 780	591	0	2933	26 273	278	48	85 903
0.709–0.500	45 196	567	12	1460	10 572	121	0	57 928
0.499–0.355	26 888	338	0	845	3222	169	229	31 692
Total	195 484	3295	531	36 857	95 642	1714	736	334 270

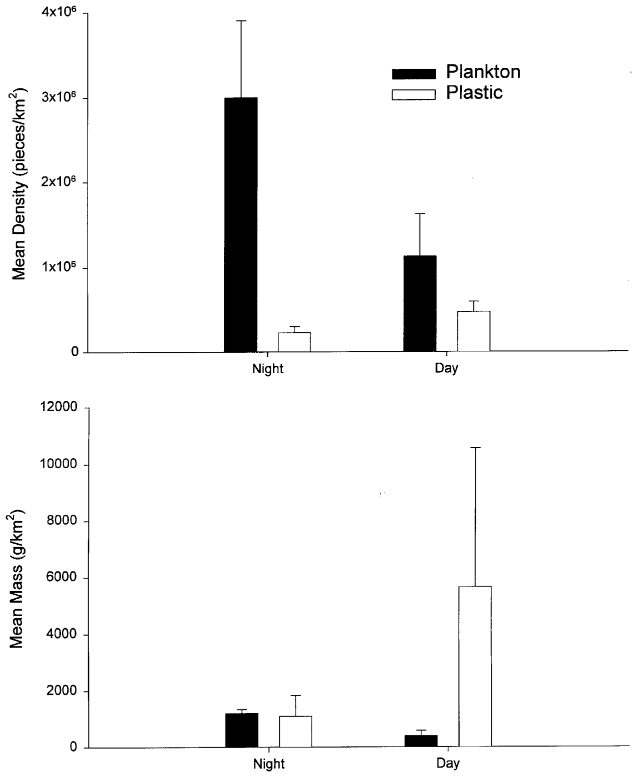

Fig. 2 Abundance and mass of plankton and plastic in night versus day samples.

during the day than at night, although much of the difference during the day was due to a plastic bottle being caught in one daylight sample and 1 m of polypropylene line being caught in the other.

Discussion

The mean abundance and weight of plastic pieces calculated for this study are the largest observed in the North Pacific Ocean. Previous studies have estimated mean abundances of plastic pieces ranging from 3370 to 96 100 pieces km^2 and mean weights ranging from 46 to 1210 g km^2 (Day and Shaw, 1987). The highest previous single sample abundance and weight recorded for the North Pacific Ocean was taken from an area about 500 miles east of Japan. At 316 800 pieces km^2 and 3492 g km^2 (Day *et al.*, 1990), the abundance and weight are three and seven times less than the highest sample recorded in this study, respectively.

Several possible reasons are suggested for the high abundance found in this study. The first is the location of our study area, which was near the central of the North Pacific subtropical high pressure cell. Previous studies in the North Pacific Ocean were conducted without reference to the central pressure cell (Day *et al.*, 1990), which should serve as a natural eddy system to concentrate neustonic material including plastic. However, while previous studies did not focus on the subtropical high, many studies were conducted as transects that passed through the gyre (Day *et al.*, 1986, 1988, 1990). Thus, it is unlikely that location alone was the reason for the higher densities we observed, as Day *et al.* (1990) collected samples from the western part of this same area.

An alternate hypothesis is that the amount of plastic material in the ocean is increasing over time, which Day and Shaw (1987) have previously suggested based upon a review of historical studies. Plastic degrades slowly in the ocean (Andrady, 1990; US EPA, 1992). While some of the larger pieces may accumulate enough fouling organisms to sink them, the smaller pieces are usually free of fouling organisms and remain afloat. Thus, new plastics added to the ocean may not exit the system once introduced unless they are washed ashore. Although numerous studies have shown that islands are repositories of marine debris (Lucas, 1992; Corbin and Singh, 1993; Walker *et al.*, 1997), the North Pacific Ocean has few islands except near coastal boundaries. The dominant clockwise gyral currents also serve as a retention mechanism that inhibits plastics from moving toward mainland coasts. A recent surface current modeling study simulated that most of the particles from our sampling area should be retained there for at least 12 years (Ingraham *et al.*, in press).

The large ratio of plastic to plankton found in this study has the potential to affect many types of biota. Most susceptible are the birds and filter feeders that focus their feeding activities on the photic portion of the water column. Many birds have been examined and found to contain small debris in their stomachs, a result of their mistaking plastic for food (Day *et al.*, 1985; Fry *et al.*, 1987; Ainley *et al.*, 1990; Ogi, 1990; Ryan, 1990; Laist, 1997). While no record was kept of the presence or absence of fouling organisms on plastic particles during sorting, a subsequent random sampling of each size class found 91.5% of the particles to be free of fouling organisms. As the size class decreased, there were fewer particles that showed evidence of fouling. Hence ingestion of plastic for its attached food seems unlikely, especially for organisms feeding on the surface. However, organisms such as the two filter-feeding salps (*Thetys vagina*) collected in this study which were found to have plastic fragments and polypropylene/monofilament line firmly embedded in their tissues, may have ingested the line at depth and utilized fouling organisms for food.

Although our study focused on the neuston, samples also were collected from two oblique tows to a depth of 10 m. We found that the density of plastic in these areas was less than half of that in the surface waters and was primarily limited to monofilament line that had been fouled by diatoms and microalgae, thereby reducing its buoyancy. The smaller particles that have the greatest potential to affect filter feeders were even more reduced with depth, as should be expected because of their positive buoyancy and lack of fouling organisms, noted above.

Several limitations restrict our ability to extrapolate our findings of high plastic-to-plankton ratios in the

North Pacific central gyre to other areas of the ocean. The North Pacific Ocean is an area of low biological standing stock; plankton populations are many times higher in nearshore areas of the eastern Pacific, where upwelling fuels productivity (McGowan *et al.*, 1996). Moreover, the gyre beneath the subtropic high probably serves to retain plastics, whereas plastics may wash up on shore in greater numbers in other areas. Conversely, areas closer to the shore are more likely to receive inputs from land-based runoff and ship loading and unloading activities, whereas a large fraction of the materials observed in this study appear to be remnants of offshore fishing-related activity and shipping traffic.

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Floating plastic in the Kuroshio Current area, western North Pacific Ocean

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Floating marine debris, particularly plastic, is widely distributed in the world's oceans (e.g. Carpenter and Smith, 1972; Day and Shaw, 1987; Ryan, 1988; Day et al., 1990; Moore et al., 2001; Thiel et al., 2003). The plastic is ingested by various marine organisms (e.g. Colton et al., 1974; Day, 1980; Thompson et al., 2004), and its biological effects due to physical blocking of digestive functions is of great concern (Ryan and Jackson, 1987). Moreover, Mato et al. (2001) recently found that plastic resin pellets contain toxic chemicals such as PCBs and nonylphenol. They suggested

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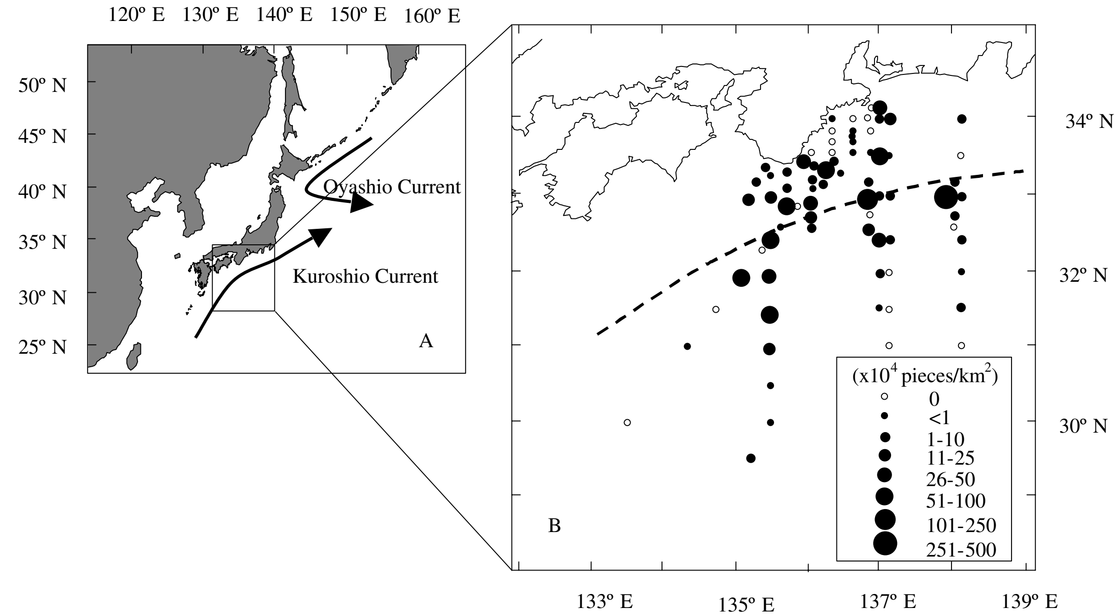

Fig. 1. Locations of stations sampled for plastic in 2000–2001 (A). Distribution and abundance (pieces/km^2) of total plastics in the Kuroshio Current area (B). Broken line in (B) denotes the Kuroshio flow path during the study period (Quick Bulletin of Ocean Conditions by Japan Coast Guard (2000, 2001)).

that plastic resin pellets could be an exposure route for toxic chemicals, potentially affecting marine organisms. Thus, plastic pollution is now recognized as a serious problem in marine ecosystems (Derraik, 2002).

The abundance of floating plastic was reported to be high in subtropical and transitional waters in the North Pacific Ocean (Day and Shaw, 1987). The Kuroshio Current is hypothesized to aid in the transport of these plastics all over the North Pacific Ocean (Day and Shaw, 1987). However, no information is available on the distribution of plastic in the Kuroshio Current area. Here, we report on the distribution, abundance, mass, type and size of plastics in the Kuroshio Current area for the first time and compare the present results with those reported from elsewhere in the North Pacific Ocean.

Investigations were carried out during seven cruises of T/V *Seisui Maru*; 4–10 April 2000, 5–9 June 2000, 13–21 June 2000, 29 September–5 October 2000, 5–9 March 2001, 12–16 March 2001, 18–26 April 2001. Samples were collected by a surface tow using a neuston net (mouth opening 50×50 cm; side length 3 m; mesh size 330 μm) at 76 stations (Fig. 1A). Each sample was collected for 10 min at a ship's speed of 2 kt. The area per sample, on average, was 2.33×10^{-4} km^2.

In the laboratory, plastics were sorted and were dried at room temperature. Each dried sample was weighed on an electronic balance. Plastics were categorized into eight types: plastic resin pellets, plastic products, fragments of plastic products, rubber, fiber, Styrofoam, plastic sheets (less than 2 mm thick), and sponge, following Ogi and Fukumoto (2000). The longest length of all pieces of plastic was measured to the nearest millimetre with a vernier caliper. Then, the plastics were categorized into 11 size categories (from 1 mm to >11 mm).

Plastics were detected at 55 (72%) of 76 stations. Abundance (0–3,520,000 pieces/km^2; Fig. 1B) and mass (0–

Table 1
Mean abundance (pieces/km^2) by the and size of plastics found in the sampling area during 2000–2001

Size (mm)	Plastic resin pellets	Plastic products	Fragments of plastic	Rubber	Fiber	Styrofoam	Plastic sheets	Sponge
1	49	0	13,100	177	64	5960	2300	0
2	331	0	24,000	44	229	4450	4340	0
3	269	0	36,900	44	1980	9770	3660	0
4	849	0	10,700	0	977	8170	2960	0
5	682	0	3280	0	829	2900	1560	51
6	89	0	3000	60	938	1820	1710	0
7	0	0	1760	0	932	719	1130	0
8	0	0	1320	0	384	604	1160	0
9	0	0	1140	59	404	268	869	64
10	0	0	368	183	539	393	562	0
>11	0	103	2570	263	5280	749	4290	0
Total	2269	103	98,138	830	12,556	35,803	24,541	115

Table 2
Abundance (pieces/km^2) and mass (g/km^2) of floating plastics in the North Pacific Ocean during 1972–2001

Location	Year	Number of samples	Frequency of occurrence (%)	Abundance (pieces/km^2)		Mass (g/km^2)		Literature
				Mean ± SD	Maximum	Mean ± SD	Maximum	
Subtropical North Pacific Ocean along 35°N	1972	33	63.6	–	34,000	300	3500	Wong et al. (1974)
Bering sea	1974–1975	20	10.0	68	–	–	–	Shaw (1977)
Gulf of Alaska	1974–1975	51	23.5	132	–	–	–	Shaw (1977)
Subtropical North Pacific Ocean along 158°N	1976	14	92.9	–	–	–	1250	Shaw and Mapes (1979)
Bering sea	1985–1988	66	7.6	100 ± 600	–	1.0 ± 4.2	–	Day et al. (1990)
Subarctic North Pacific Ocean	1985–1988	64	71.9	12,800 ± 22,300	–	61.4 ± 225.5	–	Day et al. (1990)
Transional water	1985–1988	60	93.3	57,000 ± 72,800	316,800	291.6 ± 714.4	3940	Day et al. (1990)
Subtropical North Pacific Ocean	1985–1988	2	100	61,000 ± 74,000	–	535.1 ± 726.1	1050	Day et al. (1990)
Japan Sea and nearshore Japan	1985–1988	11	100	74,700 ± 73,800	221,000	128.2 ± 172.2	–	Day et al. (1990)
North Pacific Central Gyre[a]	1999	11	100	3,32,000	–	–	–	Moore et al. (2001)
Kuroshio Current area	2000–2001	76	72.4	174,000 ± 467,000	3,520,000	3600 ± 18,100	153,000	This study

[a] The sum of fragments, styrofoam pieces, pellets, fiber and thin plastic films.

153,000 g/km^2; Table 2) varied greatly among stations. The highest abundance was found at 32°58′N, 138°00′E near the Kuroshio flow path. Densities of plastic were low in coastal regions and in areas south of 31°30′N (Fig. 1B). Both surface currents and winds could be responsible for the dispersal of plastics away from the source area on land (Ryan, 1988). Although Ryan (1988) observed a decrease in the abundance of plastics with distance from shore off southwestern South Africa, our results showed the opposite pattern, with plastic densities being an order of magnitude higher ~150 km offshore ($\sim 1 \times 10^5$ pieces/km^2) than they were near the coast ($\sim 1 \times 10^4$ pieces/km^2). Plastics were especially abundant around 32–33°N, where the Kuroshio Current flows (Fig. 1A). Hence, our results give solid evidence for the hypothesis of Day and Shaw (1987) that the Kuroshio Current plays a role in transporting and distributing plastics all over the North Pacific Ocean.

Fragments of plastic products and plastic sheets were recorded at 55% (42 of 76 stations) and 54% (41 of 76 stations), respectively, of the stations. Plastic resin pellets were found at 20% of the stations. Fragments of plastic products were dominant numerically, consisting 56% of all plastic pieces that were collected (Table 1). Styrofoam was the second most abundant material (21% of all plastic pieces). In contrast, resin pellets constituted a minor component of the plastic collected (1% of all plastic pieces). These proportions of fragments of plastic products and plastic resin pellets were similar to those observed in the North Pacific Central Gyre (Moore et al., 2001). However, the proportion of styrofoam was higher in the Kuroshio Current area (21% of all plastic pieces) than in the North Pacific Central Gyre (1%; Moore et al., 2001). This difference is probably related to the fact that styrofoam absorbs water, loses buoyancy, and sinks during the long time it takes to drift into the North Pacific Central Gyre.

The size of plastic pieces ranged from 1 mm to 280 mm. The dominant size-class was 3 mm (30% of all plastic pieces; Table 1). In contrast, pieces of plastic >11 mm represented only 8% of all plastic. Surprisingly, smaller plastics of size-class 1–3 mm formed a numerically dominant component (62%) of all marine plastic debris. Although there is little information on the size of plastics in the ocean (Shaw and Day, 1994; Moore et al., 2002), Moore et al. (2001) also found that small plastic (<2.8 mm) was the most common size (87% of all plastic pieces) in the North Pacific Central Gyre. In earlier studies, plastic debris sampling was sometimes conducted by visual observation from ships (e.g. Matsumura and Nasu, 1997). However, such an observation cannot provide accurate information on the size and weight of the plastics. Therefore, monitoring the distribution and abundance of plastic debris, especially small plastic, with neuston nets must play an important role in future studies.

Published data on the abundance and mass of floating plastic in the North Pacific Ocean is summarized for comparison with the present results (Table 2). Obviously, the abundances of plastics in Moore et al. (2001) and the present study are approximately one to two orders of magnitude greater than those reported in 1970s and 1980s, respectively. In addition, the mean mass of plastics in this study was greater than has been reported in the subtropical North Pacific Ocean in 1970s (300 g/km^2) and 1980s (535 g/km^2). As concluded by Day and Shaw (1987), the abundance of floating plastic debris has continued to increase in the North Pacific Ocean since the 1970s.

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