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Plastic pollution in the South Pacific subtropical gyre

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ABSTRACT

Plastic marine pollution in the open ocean of the southern hemisphere is largely undocumented. Here, we report the result of a (4489 km) 2424 nautical mile transect through the South Pacific subtropical gyre, carried out in March–April 2011. Neuston samples were collected at 48 sites, averaging 50 nautical miles apart, using a manta trawl lined with a 333 μm mesh. The transect bisected a predicted accumulation zone associated with the convergence of surface currents, driven by local winds. The results show an increase in surface abundance of plastic pollution as we neared the center and decrease as we moved away, verifying the presence of a garbage patch. The average abundance and mass was 26,898 particles km^{-2} and 70.96 g km^{-2}, respectively. 88.8% of the plastic pollution was found in the middle third of the samples with the highest value of 396,342 particles km^{-2} occurring near the center of the predicted accumulation zone.

1. Introduction

Plastic pollution is the dominant type of anthropogenic debris ubiquitous throughout the marine environment (Barnes et al., 2009; Derraik, 2002; Gregory and Ryan, 1997). Floating plastic fragments have been reported in the Northern Hemisphere subtropical gyres since the early 1970s in the North Atlantic (Carpenter and Smith, 1972; Colton et al., 1974; Law et al., 2010), and North Pacific (Day et al., 1990; Moore et al., 2001; Hidalgo-Ruz et al., 2012). Few data exist describing plastic pollution in the Southern Hemisphere subtropical gyres (Morris, 1980; Thiel et al., 2003), although 81% of the earth's surface south of the equator is seawater.

Plastic pollution, originating from sea- and land-based sources, migrates into subtropical gyres (Maximenko et al., 2012; Lebreton et al., 2012) where it forms accumulation zones of microplastic particles distinct from surrounding waters relatively free of plastic pollution. These gyres are formed by surface currents that are primarily a combination of Ekman currents driven by local wind and geostrophic currents maintained by the balance between sea level gradients and the Coriolis force. These surface currents are detectable from the paths taken by satellite-tracked drifting buoys of the Global Drifter Program[7] (GDP). Drifters and other objects, floating at the sea surface, are also subject to direct wind force, impact of breaking waves and Stokes drift. Computer models, tuned to simulate trajectories of drifters, predict that plastic pollution and other marine debris will likely form accumulation zones within the five subtropical gyres (Maximenko et al., 2012). To our knowledge, no quantitative data existed for the open-ocean South Pacific Subtropical Gyre (SPSG) prior to this study.

Plastic pollution enters the marine environment via rivers, beaches, maritime activities, and illegal dumping at sea (Derraik, 2002; Ryan et al., 2009). Under the effects of UV degradation and hydrolysis, plastic loses its elasticity, and powered by wind and waves, gradually breaks into smaller particles (Andrady, 2003; Thompson et al., 2004; Cole et al., 2011). In other studies of marine debris, primarily from coastal assessments, 60–80% of marine debris is petroleum-based plastic (Derraik, 2002). Petroleum in any form entering the marine environment by anthropogenic means is a pollutant. A wide range of marine life, including marine mammals, reptiles and birds, is impacted by plastic pollution through

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[7] http://www.aoml.noaa.gov/phod/dac/gdp_information.php.

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entanglement or ingestion (Laist, 1987; van Franeker et al., 2011), and the persistent organic pollutants that sorb onto plastic (Mato et al., 2001; Teuten et al., 2007; Teuten et al., 2009; Rios et al., 2010). Plastic pollution also has the potential to transport non-native species to other regions (Astudillo et al., 2009; Barnes and Fraser, 2003; Bravo et al., 2011; Gregory, 2009; Webb et al., 2009).

The coastal margins of the South Pacific Ocean, and the Southern Ocean, are main contributors to plastic pollution in the SPSG (Lebreton et al., 2012). In the western region of the SPSG plastic pollution is an emerging contaminant on island shorelines and adjacent coastal and oceanic waters, impacting fisheries, creating navigational hazards, and affecting tourism by its negative aesthetic appeal (Gregory, 1999a). In the southeastern South Pacific Ocean, surveys of plastic pollution near the coast, including fragments of foamed polystyrene, plastic bags, and food sacks from salmon farms identified aquaculture as the most significant contributor (Hinojosa and Thiel, 2009). Along the Chilean coast, large amounts of plastics also come directly from beach and shore activities (Thiel et al., 2011). Other types of marine debris, including pumice and wood, are injected into the ocean near Patagonian Fjords, with their abundance corresponding to river runoff after spring snowmelt (Hinojosa et al., 2011). Plastic pollution has also been detected in the surface waters of the Southern Ocean (Barnes and Milner, 2005). In a survey of waters near Antarctica, plastic pollution was the only type of marine debris found south of 63°S (Barnes et al., 2010).

While large pieces of plastic pollution have been documented in the southern ocean and in the South Pacific, the presence and abundance of microplastics has not yet been confirmed. In particular, the area of the SPSG remains unstudied. Therefore, in this study we examined the abundance and composition of microplastics along a transect that crosses directly through the SPSG.

2. Materials and methods

To explore the presence and distribution of plastic pollution in the eastern South Pacific, an expedition on the sailing vessel *Sea Dragon* was organized and carried out by the 5 Gyres Institute.[8] The expedition started on March 23rd, 2011 from Valdivia, Chile and sailed to Pitcairn Island, which it reached on April 21, 2011. The weather during the entire voyage can be described as mild, with only one rain event during the second week of sample collection, when the sea state on the Beaufort Scale rose to five during one station. 48 neuston samples, described in this paper, were collected along a single transect from Robinson Crusoe Island to Pitcairn Island in the South Pacific Ocean, shown in Fig. 1. The first sample was taken at 33°05′S, 81°08′W, subsequent samples were collected approximately every 50 nautical miles until reaching Easter Island, and then again every 60 miles along the same transect in the direction of Pitcairn Island to 24°49′S, 126°61′W (Fig. 1).

The transect length and direction was determined by using a computer model developed at the University of Hawaii (Maximenko et al., 2012) to estimate the accumulation zone for plastic pollution in the SPSG. In the model, the entire ocean surface is divided into two-dimensional boxes of a half-degree in size. The probability for a drifter to move between pairs of boxes in 5 days is calculated, using nearly 15,000 trajectories of real GDP drifters. This probability density function can then be used to simulate propagation of floating tracers from various sources. Five-day model steps can be repeated infinitely to study the dynamics of plastic pollution over long time scales. Accurate data of sources of plastic pollution in the ocean are not available which creates a serious problem for modeling. However, plastic debris survives in the ocean many years – time that is sufficient to move across the entire ocean basin making it complicated to retrace plastics to their possible sources. For such tracer studies, the pattern of plastic concentration is determined by ocean currents and winds; given the long run periods of the model, it is not very sensitive to the location of sources and sinks. Model experiments, starting with tracers that are released uniformly over the entire Global Ocean, predict the formation of garbage patches in the five subtropical gyres. This model solution adequately describes the observed distribution of plastic, collected in the accumulation zones of the North Pacific and the North Atlantic subtropical gyres (Law et al., 2010). Note that in reality the maximum values of particle density in Fig. 1 are determined by the unknown amount of plastic dumped in different oceans, which may not be accurately reflected in model simulations. Other models have attempted to predict the abundance of plastic pollution in the subtropical gyres, seas, gulfs and bays, by considering contributions from river mouths, shipping lanes, and densely populated watersheds (Lebreton et al., 2012).

Samples were collected using a manta trawl with a rectangular opening of 16 cm high by 61 cm wide, and a 3 m long 333 μm net with a 30×10 cm^2 collecting bag. The net was towed along the surface on the starboard side using a spinnaker pole to position the towline outside the wake of the vessel. The trawl speed, though kept constant throughout each individual trawl, ranged between 0.5 and 1.5 m s^{-1}, as measured by the onboard knotmeter. The duration of the trawl was kept to 60 min using a stopwatch. Samples were fixed in 5% formalin.

The samples were later rinsed in salt water, which floated most of the plastic to the surface for removal. Using a dissecting microscope, plastic was removed from preserved natural material, and then sorted by rinsing through Tyler sieves into six size classes: 0.355–0.499 mm, 0.500–0.709 mm, 0.710–0.999 mm, 1.00–2.79 mm, 2.80–4.749 mm, >4.75 mm. Individual pieces of plastic were divided into categories; fragment, polystyrene fragment, pellet, polypropylene/monofilament line, film; and then counted.

The area sampled was calculated by using onboard knotmeter data to measure the actual length of sea surface trawled in the 60-min period. The tow length multiplied by the width of the trawl provided the area sampled, allowing particle weight and abundance per km^2 to be calculated.

Using the Beaufort Scale (Beer, 1996), the sea state was calculated using wave height observed by three crewmembers and decided by consensus.

3. Results

Forty six out of 48 net tows (96%) contained plastic marine pollution, with no plastic found in two of the eastern-most samples (Fig. 1). Fig. 1 shows excellent correspondence between tracer distribution assessed by the model (shaded gray areas) and the observed count of plastic particles (color dots). For the comparisons in Figs. 2 and 3, the model has been scaled using the integral values, summed over all stations. Visual evaluation shows good correspondence between the observations (bars in Figs. 2 and 3) and the model (solid lines), all demonstrating bell-shape distributions along the transect. Correlation coefficients were found equal to 0.45 and 0.44, respectively. Somewhat wider model "bells" and their southeastern shift by a few stations may be due the difference between the multi-year mean, assessed by the model, and quasi-instantaneous state of the system, sampled during the 2 months of the expedition.

The average abundance was 26,898 pieces km^{-2}, and the average weight was 70.96 g km^{-2}. 85.6% of the total count and 88.8% of the total weight were collected between 97°09′W (sample 17) and 111°91′W (sample 32), representing the center third of the sampling transect (Figs. 2 and 3).

[8] http://www.5gyres.org.

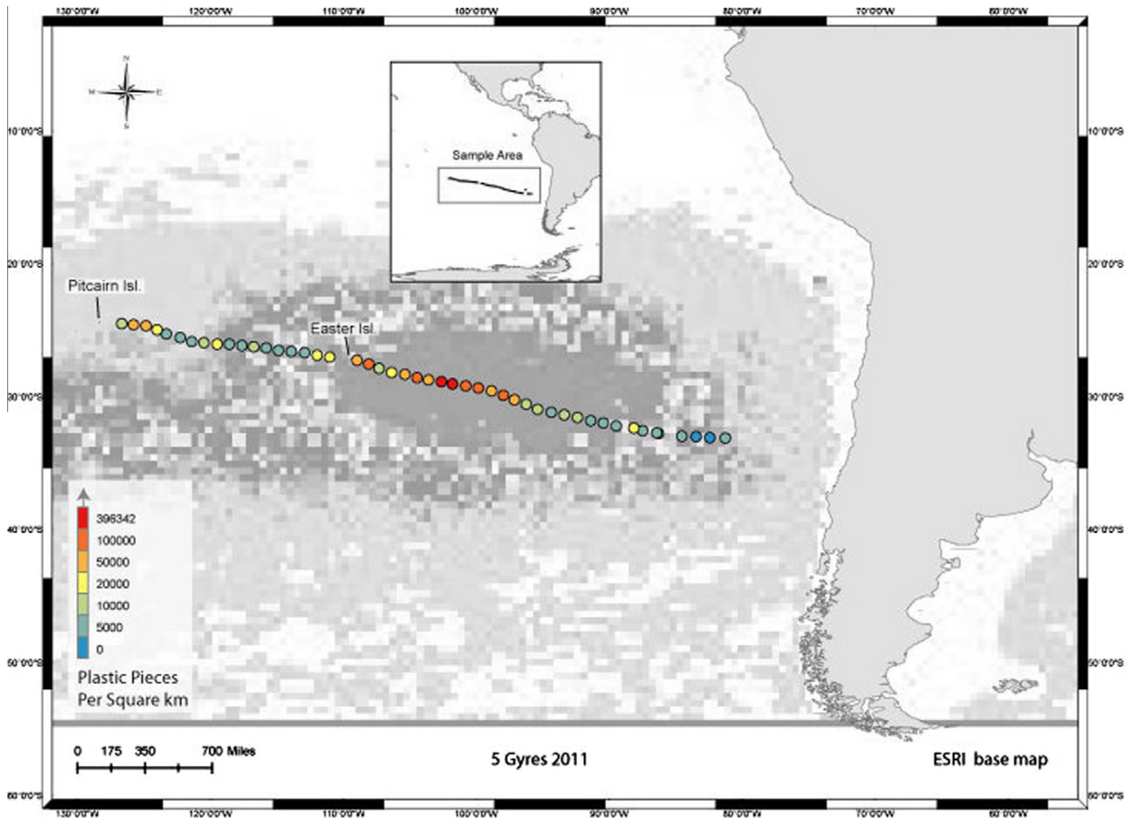

Fig. 1. Locations of 48 samples collected in the South Pacific in March–April 2011 during the expedition of S/V Sea Dragon. Colors indicate plastic particle counts in the samples. The grey background represents the accumulation zone predicted by the computer model.

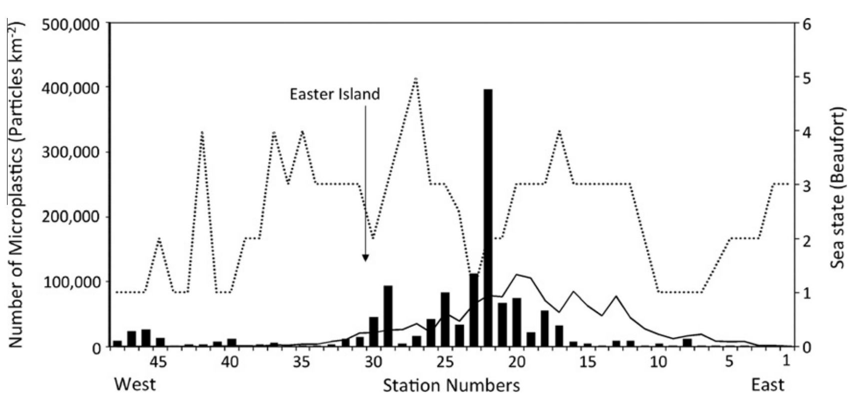

Fig. 2. Particle counts in samples (bars), model solution (solid line), and sea state (dashed line) at 48 stations along the transect. Sampled and modeled values share the *y*-axis on the left.

Plastic particles were found in each of the six size classes, and of the five type categories all were found except for foam, which did not occur in any of the 48 samples (Table 1). The two size classes representing particles 1.00–4.749 mm accounted for 55% of the total particle count and 72% of the total weight (Table 1). Plastic fragments by far dominated the microplastics collected in this study, both by count and by weight. Pellets were found in relatively low abundances, but due to their large individual weight made up 9.6% of the total microplastics weight. Lines and thin films were relatively abundant, but constituted less weight than the pellets.

As shown in Figs. 2 and 3, the sample 22, collected at 29°04′S, 101°73′W, contained 1102 pieces and a total weight of 2.032 g, corresponding to 396,342 pieces km^{-2} and a weight of 732 g km^{-2}, which was the highest count and largest weight in one 60-min tow and was more than three times the count and twice the weight of any other sample collected.

The dashed line in Figs. 2 and 3 represents the recorded sea state at each station, using the Beaufort Scale and measured by visual observation of multiple observers. These data suggest a possible inverse relationship between plastic count/weight and the sea state. More data are needed to examine this relationship more thoroughly. However such a relationship has been tentatively identified in Kukulka et al. (2012) from the North Atlantic. In general, changes between some pairs of samples can be explained by changes in sea surface conditions. For example, lower (compared to adjacent samples) counts in samples 27 and 28 coincide in time

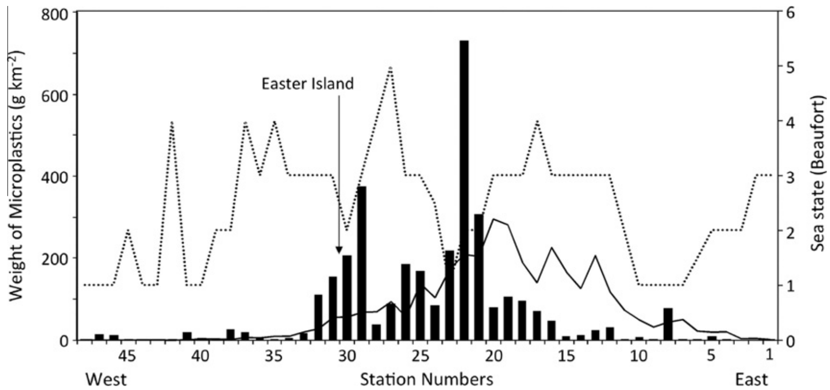

Fig. 3. Total weight in samples (bars), model solution (solid line), and sea state (dashed line) at 48 stations along the transect. Sampled and modeled values share the *y*-axis on the left.

Table 1
Average abundance and weight of plastic pieces by type and size.

	Fragment		Pellet		Line		Thin film		Total	
	Count	wt.	Count	wt.	Count	wt.	Count	wt.	Count	wt.
Abundance of plastic pieces (items km^{-2}) and weight density (g km^{-2}) by type and size										
>4.75 mm	351.9	12.8	6.4	0.4	1879.7	4.4	161.7	0.7	2399.8	18.3
2.80–4.749 mm	2407.5	24.2	347.0	5.5	687.1	0.6	333.0	0.2	3774.6	30.5
1.00–2.79 mm	9612.7	19.6	180.6	0.6	804.2	0.4	591.8	0.2	11189.3	20.8
0.710–0.999 mm	3374.9	0.9	41.5	0	188.6	0	250.0	0	3855.1	0.9
0.500–0.709 mm	2910.4	0.2	17.9	0	55.2	0	0	0	2983.5	0.2
0.355–0.499 mm	2689.3	0.1	0	0	6.8	0	0	0	2696.2	0.2
Total	21346.8	57.9	593.5	6.6	3621.7	5.4	1336.6	1.1		

with the brief and sharp increase in winds. Analogously, high counts and weights in samples 22 and 23 were obtained during a short period of weaker wind.

4. Discussion

The statistical model used herein (Maximenko et al., 2012), based on observed trajectories of drifting buoys, was successfully used to find an accumulation zone of plastic pollution in the SPSG. While this model identifies regions of maximum aggregation of the floating debris, it fails to predict the relative abundance of plastic between different gyres. For example, it predicts the maximum density in the South Pacific to be as much as ten times higher than the maximum density in the North Atlantic. The actual particle abundance in the central region of the North Atlantic, reported between 29 and 31°N, was 20,328 ± 2324 pieces km^{-2} (Law et al., 2010), i.e. the abundance was 1.3 times higher in the South Pacific (26,898 ± 60,818 pieces km^{-2} in this study). This is explained by the setup of the model experiment. The relative maximum in the model South Pacific is dictated by the larger amount of tracer "injected" there in the model due to the larger size of this subtropical gyre. In reality, northern gyres appear to contain more plastics, corresponding to higher rates of production, consumption and loss of plastic to the marine environment in the northern hemisphere (Lebreton et al., 2012). Law et al. (2010) observed no significant increase in plastic marine pollution in a 22-year survey of the North Atlantic subtropical gyre, while during a similar time frame Goldstein et al. (2012) observed a dramatic increase of microplastics in the NPSG.

Overall, the densities of microplastics found in the SPSG are comparable with those observed in other areas of the world (Hidalgo-Ruz et al., 2012). They are, however, lower than those reported for the North Pacific Subtropical Gyre (NPSG). Using a similar approach as Moore et al. (2001), herein we found a mean of ~25,000 microplastics km^{-2} compared to ~330,000 microplastics km^{-2} in the NPSG. The maximum density in the NPSG was ~970,000 microplastics km^{-2} (Moore et al., 2001), whereas the maximum value in the SPSG was ~400,000 microplastics km^{-2}. Thus, while the densities observed in the SPSG remain below those reported for the NPSG, they are within the same range of magnitude.

The fate of plastic pollution in the marine environment is poorly understood. In this study, the count of plastic particles in the size class between 1 mm and 2.79 mm is greater than the combined three smaller size classes from 0.355 mm to 0.999 mm. This is in contrast to the proportions reported for the NPSG by Moore et al. (2001), who observed more items in the small fraction than in the large fraction (1–2.79 mm). The differences between the NPSG and the SPSG are particularly pronounced in the category of fragments. Whether this is due to more advanced degradation of microplastics in the NPSG or due to other reasons is not known at present. Photodegraded and oxidized plastic becomes brittle, then fractured by wave mechanics into ever smaller particles (Andrady, 1990), and therefore a greater abundance of smaller particles would be expected if the sea surface were the last stop for plastic pollution.

When waves are high, a smaller fraction of plastic remains close to the surface and is collected by the trawl. It is possible that turbulence on the sea surface, generated by wind and waves, drives the smaller microplastic particles below the 15 cm depth of our sampling equipment (Kukulka et al., 2012). Possibly, the increased ratio of surface area to volume as particles become smaller because the proportional increase of fouling organisms leads to a decrease in the buoyancy of particles (see also discussion in Hidalgo-Ruz et al., 2012). Beach deposition or ingestion by marine organisms may also account for the fate of microplastics. The relatively small number of microplastics <1 mm in our data set warrants further study.

Most plastic particles (large and small) accumulating in the SPSG likely have their origin in the countries around the South Pacific Ocean (Lebreton et al., 2012). Large amounts of plastic debris enters the ocean along the coasts of South America (Thiel et al., 2011). Even though a large proportion of this plastic pollution probably becomes deposited on nearby shores, a considerable fraction may escape shore deposition and finally accumulate in the SPSG. While coastal sources of plastic debris around the South Pacific arguably might be fewer than in the North Pacific and North Atlantic, the abundance of microplastics in the SPSG are of similar magnitude as in the oceanic gyres of the northern hemisphere. This result is in contrast to the model estimates by Lebreton et al. (2012) who considered geographic variations in plastic sources. They predicted substantially lower amounts of plastic particles in the SPSG compared to the North Pacific or North Atlantic subtropical gyres. Possibly, they underestimated the sources of plastics around the South Pacific. Several studies of the southeastern Pacific revealed plastic densities in coastal waters and on local shores that were of similar magnitude as those observed in the northern hemisphere (Thiel et al., 2003; Bravo et al., 2009; Hinojosa and Thiel, 2009; Hinojosa et al., 2011). Also in the western parts of the South Pacific large abundances of plastics have been reported (Benton, 1995; Gregory, 1999a,b; Cunningham and Wilson, 2003), which could contribute to the high densities of microplastic fragments observed herein in the SPSG. Based on their source-related model outcomes, Lebreton et al. (2012) also suggested that the SPSG might be an accumulation area for plastic particles from the South Atlantic and Indian Ocean.

Alternatively, there might be occasional transfer of plastic debris across the equator through the boundary currents near shores of Indonesia and Ecuador. Consequently, some of the plastic pollution found in the SPSG actually could come from the NPSG. In support of such transfer across the equator, a study on Hawaii and Christmas Island had shown that a large proportion of stranded pumice had its origins in the southern hemisphere (Jokiel and Cox, 2003), indicating that floating debris can occasionally cross the equatorial system. Microplastics may be redistributed among the main oceanic gyres in similar ways as floating pumice, explaining the relatively high abundances of microplastics in the SPSG.

5. Conclusion and outlook

This study validates the existence of a garbage patch of plastic pollution in the southern hemisphere, assisted successfully by computer modeling of ocean currents. The abundances of microplastics observed in the SPSG are comparatively high, yet remain below those reported from the NPSG, most likely due to lower input from shipping and shore activities in the South Pacific compared to the North Pacific. Using the International Pacific Research Center (IPRC) model, the 5 Gyres Institute has begun expeditions to other predicted accumulation zones in order to understand the spatial distribution of plastic pollution globally. Data on contributions of plastic pollution and other marine debris from coastal watersheds and maritime activities are necessary to improve modeling of plastics in the oceans. Understanding the type and abundance of debris lost at sea and accumulating in subtropical gyres will assist efforts to identify and mitigate sources of marine pollution.

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