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Master of Science in Meteorology, Physical Oceanography and Climate

Estimating the total oceanic plastic content at the end of 2010

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June, 2015

Abstract

The existence of regions in the ocean with a high plastic concentration is considered to be a substantial environmental problem. Although there are already initiatives for an ocean cleanup, adequate estimates of the total surface plastic content are lacking. The main goal of this study is to determine an estimate of the total quantity of the plastic debris in the surface ocean at the end of 2010. We combine results from waste data, an emission model and ocean tracer motion computations with the available observations to estimate parameters in the emission model. We also investigate whether representations of sinks of plastics, such as through biofouling, can improve the quality of the correlations between modeled and measured plastic concentrations. Our best estimate is that at the end of 2010, the total quantity of plastic that was present in the surface ocean was 7.4 ± 4.9 million tons.

Contents

1. Introduction

Oceans store heat and also act as reservoirs for carbon dioxide (Costanza, 1999), which is an important greenhouse gas. Without the oceans, a higher amount of carbon dioxide would remain in the atmosphere resulting in a higher increase of the surface temperature of our planet. The increase of carbon dioxide in the ocean leads to an increase in acidity that is possibly affecting marine life. Another factor in which life in the ocean is affected by mankind is direct pollution (Schubel *et al.*, 1997; Derraik, 2002). This occurs in various ways, such as dumping of industrial waste, domestic sewage, and agricultural waste. It ends up in the ocean primarily through rivers, municipal drainage systems and streams. A lot of waste is also entering the ocean directly from ships (Goldberg, 1997). One dominant component of this marine litter polluting the oceans is plastic debris (Ryan *et al.,* 2009).

Plastics are synthetic or semi-synthetic solid materials having an organic origin. Despite the fact that there are many types of plastics, they can be classified into two main categories, thermoplastics and thermosetting polymers (Moore, 2008). Over the last four decades, an overconsumption of plastics has been occurred (Derraik, 2002). The increasing use of these chemical products is due to their distinct properties. They are durable, strong, lightweight and cheap (Laist, 1987; Barnes *et al.,* 2009). Due to their vast diversity, plastics appear in a variety in shapes and densities. There are plastics that have low density and are lighter than seawater, and also plastics that have high density and are heavier than seawater (Goldberg, 1997; Ryan *et al.*, 2009). Plastic material can therefore be found discarded in the sea surface or immersed on the seafloor.

As a slowly degradable material, plastics have a long lifetime which depends on several different factors, such as the exposure to UV radiation (Andrady, 2003). It is believed though that the lifetime of a plastic increases under conditions when there is no light and the concentration of oxygen is low (Barnes *et al.,* 2009). In general, plastics need more time to degrade in water rather than on land (Andrady, 2003; Ryan *et al.,* 2009). Once plastic material has reached the ocean it will remain for the next decades (Andrady, 2003), or even for the next hundreds or thousands of years (Barnes *et al.,* 2009). Due to their durability, plastics can therefore be easily accumulate into the oceans and since about 1960 the marine environment has been significantly disturbed due to the deposition of plastic debris.

In the early days it was believed that the only concern of high concentrations of plastics in the ocean was an aesthetic one (Moore, 2008). However, the problem is not restricted anymore just to the ugly aesthetic of floating plastics, such as fishing nets, strapping bands, synthetic ropes, bags, cups and small pellets (Laist, 1987). The problem also includes the deleterious effects that plastics cause on marine biota. In particular, plastic material is consumed by oceanic organisms, such as seabirds, crustaceans, fish and turtles and is affecting their health (Laist, 1987; Goldberg, 1997; Moore, 2008). This occurs because plastics gradually dissect into smaller pieces (Laist, 1987), which cannot easily be

distinguished from natural prey by marine animals. These affected organisms are in turn consumed by bigger animals and eventually by humans.

The movement of plastic material in the world ocean is mainly determined by the surface ocean currents (Goldberg, 1997). These currents are driven mainly by the global wind patterns and affected by the rotation of the Earth. Since most of the plastic has a lower density than seawater, it will remain at the surface and is not transported to deeper layers due to the Ekman pumping (Van Sebille, 2015). The organization of the surface currents into so-called gyres causes an accumulation of floating marine trash in the central areas of each of the five large subtropical gyres (Howell *et al.,* 2012). In this way, islands of trash are formed; two representative examples of ocean regions where a high concentration of marine debris is observed are the eastern and western ''Garbage Patches'' (Howell *et al.*, 2012) located in the North Pacific Ocean. Moore *et al.* (2001) reported a mass ratio of plastic-to-plankton of 6-to-1. This ratio is one of the largest observed in the North Pacific Ocean (Moore *et al.*, 2001) due to favorable conditions for accumulation.

Although there are already initiatives for an ocean cleanup (see http://www.theoceancleanup.com), adequate estimates of the present-day total surface plastic content are lacking. Most observational studies that have been conducted so far are focused in the quantities of plastic litter in specific oceanic areas, for specific depths in the ocean and for particular dates (Lebreton *et al.,* 2012). Cózar *et al.* (2014) have made estimations of the plastic load based on real samples taken from the surface of the open ocean around the world for the period between March 2009 and February 2013. They have estimated that the mean total amount of plastic over this period is approximately 14,000 tons.

However, a report of the US National Academy of Sciences (1975) mentions that 44,800 tons of plastic trash is released every year into the ocean. Recently, Jambeck *et al.* (2015) estimated that the plastic waste that has entered the ocean by the end of 2010 is 4.8 to 12.7 million tons. In particular, Jambeck *et al*. (2015) used population and economic status data of each one of the 192 countries, waste generation rates and percentages of plastic waste. They also estimated that 2% of the total produced waste by each country is littered and that 1.7 to 4.6% of the total plastic waste ends up in the ocean. Estimates of this percentage vary significantly in the literature and values are as low as 0.1% (Cózar *et al.*, 2014).

The purpose of this study is to determine a new estimate of the amount of plastic trash in the ocean at the end of 2010. We first determine plastic waste data from 213 coastal cities of the world between the period 1980 and 2010 and combine it with an emission model of plastic into the ocean. Next, ocean tracer motion computations (Van Sebille *et al.,* 2012) are used to determine possible surface ocean plastic distributions in time. Correlations of the plastic concentrations in specific regions with those in observations (Cózar *et al*., 2014) are then used to estimate parameters in the emission model. Finally, we determine whether idealized representations of plastic sinks can improve the estimates of emission model parameters and hence of the total ocean plastic content.

2. Methodology

There are basically two methods that can be used to approximate the total quantity of plastics in the oceans (Ryan *et al.*, 2009), from direct observations of plastic in the surface ocean and from estimates of the sources and sinks of the plastic material. Direct observations of floating debris can be done by ships, boats or aerial vehicles as also measurements with the use of net trawls (Ryan *et al.*, 2009). In the study of Moore *et al.* (2001), it has been estimated that 334,271 pieces of floating plastic per square kilometer exist just in the North Pacific Central Gyre that corresponds to a density of about 5.1 kg/km^2 (Moore *et al.*, 2001; Ryan *et al.*, 2009). It has been shown that for the Eastern North Pacific Ocean, the amount of the plastic debris at the depth of 10-30 meters below the sea surface is two orders of magnitude less than the amount of floating plastic garbage at the ocean surface (Ryan *et al.*, 2009). The abundance of plastic debris in global environments depends on the location, and it can be between 0 to 7290 items per 10.000 square meters (Barnes *et al.,* 2009).

2.1. Emission model

The second method that can be used for the determination of the global amount of the plastic in the ocean is by estimating directly the total amount that reaches the ocean (Ryan *et al.*, 2009; Jambeck et al. 2015). Here we will use this method by examining the quantities of plastic that have been produced by the largest coastal cities in the world (Google Earth, version 1.1, 2010). According to the application of the Google Earth (version 1.1, 2010) there are in total 590 cities that are the most populated in the world. The criterion for the choice of these 590 cities is to exceed 750.000 inhabitants in population for the year 2007. However, most of these cities were not taken into account for this project. We have only kept the 214 cities whose distance from the sea is in the range from 0 to 50 kilometers.

In our emission model, it is assumed that the quantity of the plastic that is released from each one of these cities depends on three factors: its total population (PP) and the Human Development Index (HDI) and the Gross National Income (GNI) of the country of the city. A population database for the world's largest urban areas is available and provides historic, current and future estimates of the values of PP for the period between 1950 and 2050 (Ahlenius, 2009). An HDI table is provided by the United Nations Development Program (2008), which gives information for 159 countries of the world for the period 1975 to 2005. Myanmar is not included in this table, thus there is no available HDI data for its city Yangon. Despite then the fact that the city of Yangon lies near at a coast, it is not taken into account here, which reduces the total number of cities that are under examination in 213.

The HDI is a number that varies between 0 and 1. When the HDI of a country is between 0 and 0.449, then it is a low developed country. A medium developed country is characterized by an HDI between 0.450 and 0.699, whereas a high developed country is described by an HDI between 0.700 and 1. The GNI data for each country is presented in a

report of the World Bank (2014), and is available for a 31-year period between 1980 and 2010. According to the GNI index, each country belongs in a low, middle or high income category, with GNI values varying from 0-199 billion US dollars, 200-999 billion US dollars, and larger than 1000 billion US dollars, respectively.

In addition to the above data for the PP, HDI and GNI for each city, we also used a table with plastic generation rates (in kg per capita per day) for all years between 1960 and 2010 (Linneman, 2012). The USA is the only country for which there are waste and plastic generation rates for the whole period, provided by the Environmental Protection Agency (EPA). More specifically, waste generation rates are known from 1960 until 2010 and plastic generation rates are known until 1994. From 1995 until 2009, the plastic percentages of the municipal solid waste amounts are available. Based on the data for the USA, Linneman (2012) compiled the maximum values of plastic generation rates, indicated by M_{ij}, for a city in a high-income countries (in kg/capita/day). These rates can also be obtained for cities with other values of HDI and GNI using a conversion suggested by Cointreau-Levin and Gopolan (1999). Since HDI data was not available after 2005, we extended our HDI data until 2010 by assuming the same value that has been found for the year of 2005.

To determine the amount of plastic that is emitted into the ocean (per year) by a specific city of population PP, we need to represent two factors: the percentage of waste that is plastic (w) and the percentage (m) of that plastic which ends up in the ocean (that is mismanaged). With this emission model, we find

$$P_{total} = \sum_{j=1}^{31}\sum_{i=1}^{213} P_{ij} = \sum_{j=1}^{31}\sum_{i=1}^{213} 365\ w_{ij}\ m_{ij}\ PP_{ij}\ M_{ij}\ , \qquad (1)$$

where P_{total} (kg) is the total plastic amount that was released from 213 coastal cities in the world (subscript i) and entered into the ocean for a total period of 31 years, from 1980 to 2010 (subscript j). The product $E_{ij} = w_{ij}\ m_{ij}$ is (for each city i) the percentage of the total plastic part of the waste which enters the ocean each year j. This product is an unknown quantity for each city and hence idealized representations will be considered in the results below.

2.2. Transport of plastic in the ocean

Having built a database of emission of kg plastic per year at 213 different locations, we next calculate the dispersion of this plastic over the surface ocean. The quantities P_{ij} first are converted into particles which are released within a year where one particle corresponds to 10^5 kg of plastic weight. From 1980, and for each year j until 2010, at every location (longitude, latitude) of city i, $P_{ij}/10^5$ particles are released.

The simulation model that we used for this project was taken from Van Sebille *et al.* (2012). It is based on the construction of bimonthly transfer matrices P_b (b = 1, ..., 6) from

ocean drifter data, which model how particles are displaced every two months based on the surface velocity field. A surface drifter is useful in order to determine surface ocean currents as each drifter is equipped with a GPS system, so that positions are available every 6 hours. In Van Sebille et al. (2012) data the Global Drifter Program (Lumpkin *et al*., 2005) was used to construct the transfer matrices. If the vector $v(t)$ represents values of the particle density field at each location on a 1 x 1 degree grid at time t, then density field at t + 60 days is given by

$$v(t+60) = v(t)\, P_b \ , \qquad (2)$$

where b = mod (t/180, 6). Hence, P_1 is the operator mapping the density of particles on Jan/Feb to those of March-April, P_2 the one mapping the latter field into the tracer field for May-June, etc. From given initial conditions $v = 0$ in 1980, plastics will be added every 2 months at the locations of the cities according to (1) and dispersed through the transfer matrices according to (2).

2.3. Model-data comparison

Finally at the end of 2010, a final density $v(t_f)$ is obtained from the simulation model in the previous section, which will be used for comparison with observations. As mentioned in the introduction, between the period 2009 and 2013 Cózar *et al.* (2014) conducted measurements of the plastic mass at different locations of the open ocean. In Fig. 1, taken from Cózar *et al.* (2014), the colored circles show the locations where mass concentration measurements have been taken. We added 18 subdomains in this figure, which were chosen in such a way that each of them contains at least 5 data points from Cózar's *et al.* (2014).

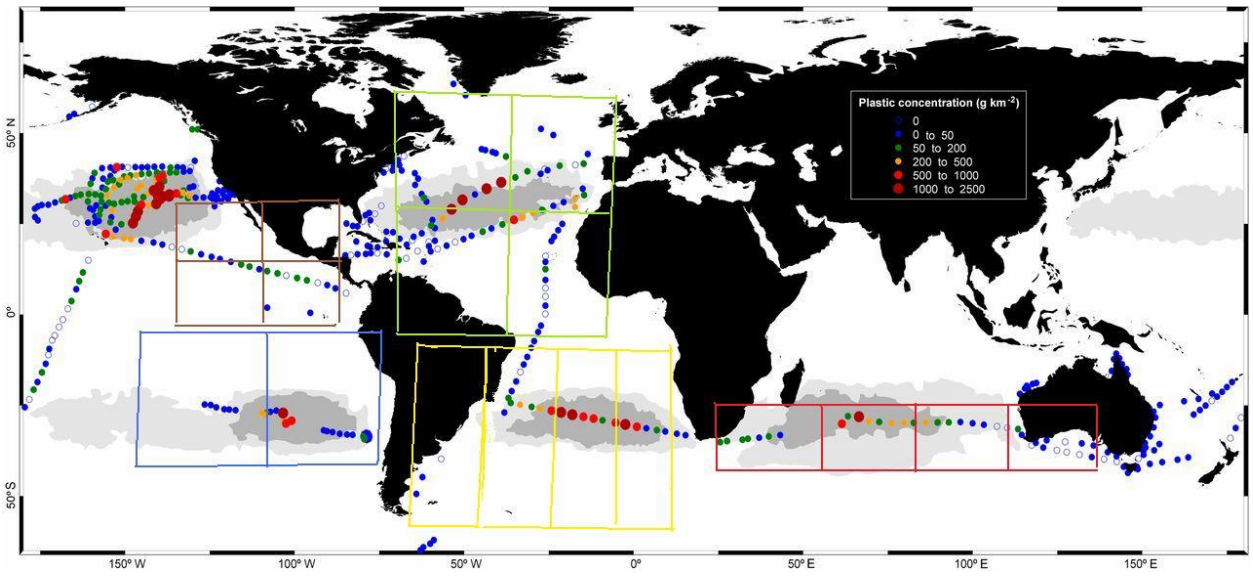


Figure 1: *Subdomains covering different parts of each one of the 5 ocean basins, in which mass concentration measurements (colored circles) have been conducted by Cózar's et al. (2014).*

For each subdomain, we determined the area averaged plastic concentration P_B (in kg) from the particle density field $\nu(t_f)$ through

$$P_B = \frac{\sum_{k,l} P(\varphi_k,\theta_l) cos\theta_{l+0.5} d\varphi d\theta}{\sum_{k,l} cos\theta_{l+0.5} d\varphi d\theta}, \qquad (3)$$

where $P(\varphi_k, \theta_l)$ is the plastic mass in each point (φ_k, θ_l) (on a 1 x 1 degree grid) and P_B is the average plastic mass in each subdomain. We also use values g/km^2 (using the area of each subdomain) of these plastic concentrations to compare with the Cózar *et al*. (2014) data and, if possible, to estimate our unknown parameters E_{ij} in the emission model.

3. Results: standard case

In this section, we present results for the emission data under the assumption that all $E_{ij} = \gamma = 0.1$ in the emission model (1). This value was used in Linneman (2012) to represent the total fraction of the plastic in the waste that reached the ocean and is comparable to the values used in Jambeck et al. (2015).

3.1. Emission data

In Table 1, results are given for the values of M_{ij} (in kg/capita/day) for categories of cities with a different HDI and GNP. Only data for the years of 1980 and 1981 are given, but the data is available for the full period 1980-2010. Table 1 gives us information for plastic generation rates for large and small/medium cities, when the socio-economic situation and the population of each city are known. A large city here indicates a city with more than 500,000 inhabitants. Indeed, plastic emission rates increase when countries have higher income and are relatively larger when the city size increases.

		Plastic emission rates in kg/capita/day		
Year	***Magnitude of the city***	***Low-income country***	***Mid-income country***	***High-income country***
1980	***Large city***	0.024907	0.032883	0.058107
	Small/medium city	0.019927	0.023917	0.042847
1981	***Large city***	0.027082	0.035754	0.06318
	Small/medium city	0.021667	0.026005	0.046587

***Table 1**: Plastic generation rates in kilograms/capita/day for large and small or medium cities of low, middle and high-income countries. These rates are available for the period from 1960 to 2010 (Linneman, 2012) and shown here only for 1980 and 1981.*

3.2. Transient development of plastic densities

Using the data from Table 1 (with fixed $\gamma = 0.1$), the simulation model was applied starting with the release of the plastic litter from the 213 cities on January 1980. In every intermediate year of the period between 1980 and 2010, a new plastic quantity is added to the already existing field of the previous year. All these new quantities of plastic will be transported through the ocean basins until the end of 2010. Figure 2a shows the marine distribution of plastic litter at the January 1981 and figure 2b shows its distribution at December 2010.

Figure 2a shows that the coastal cities that contribute more to the total plastic amount on the oceans lie at the western part of the North Pacific Ocean. This can be explained by the fact that these coastal cities are highly populated, and thus they release high amounts of plastic mass into the ocean. Among these cities are Shanghai (China), Shenzhen (China), Seoul (South Korea), Jakarta (Indonesia) and Tokyo (Japan). These cities belong to the top 10 of the biggest coastal cities in the world, based on their population density.

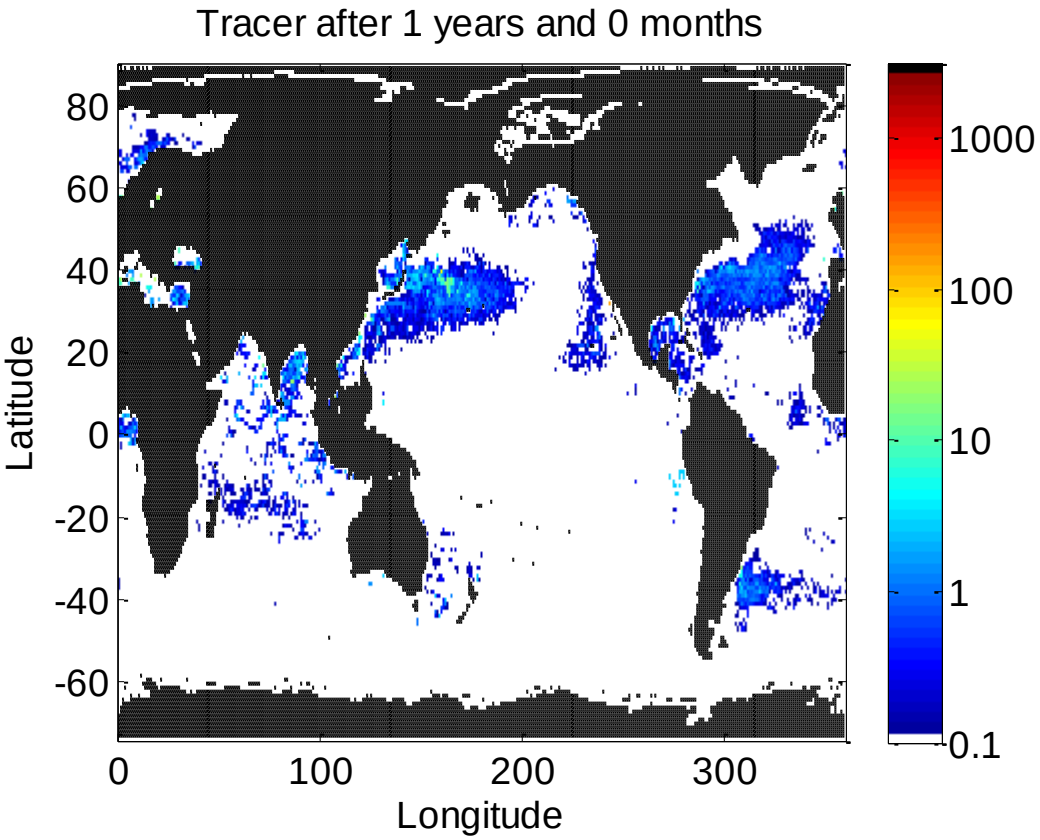


Figure 2a: *The distribution of the plastic debris one year after its simultaneous release from the 213 different coastal points. Units are in* 10^6 *kg/1° longitude × 1° latitude on a logarithmic scale.*

Figure 2b reveals the existence of the main five accumulation zones of plastic litter in the ocean. In particular, the accumulation zones in the North, South Atlantic and in the North Pacific Ocean can be clearly seen. This result agrees with the predicted accumulation zones made by Maximenko *et al.* (2012).

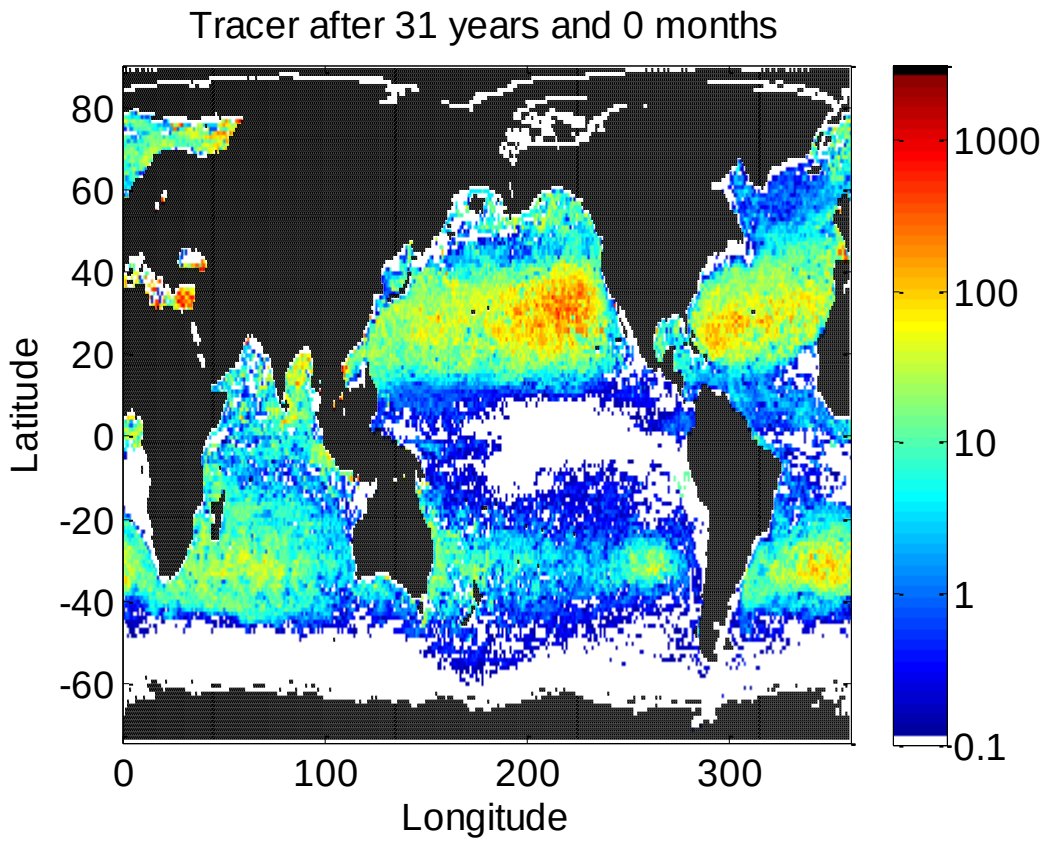


Figure 2b: *The distribution of the plastic debris 31 years after its simultaneous release from the 213 different coastal points. Units are in* 10^6 *kg/1˚ longitude × 1˚ latitude on a logarithmic scale.*

Figures 2a and 2b clearly show that there is a shift of the accumulation zone of the North Pacific Ocean from the West to the East. As it has already been described, our model is based on observational drifters that follow the surface currents. The accumulation zones are associated with Ekman convergence at the surface, which happens in the subtropical gyres of each basin.

3.3. Correlation with observations

Figure 3 shows a scatter plot between the results of the plastic concentration in the 18 different subdomains found with the simulation model in the case of $\gamma = 0.1$ (as in section 3.1 and 3.2) and the data of Cózar *et al.* (2014).

Note that if our emission model was correct, the tracer simulation model would accurately represent the motion of the plastic particles and there were no sinks of plastic, the data should collapse onto a line. This is obviously far from being the case; the correlation is far from linear and also the order of magnitude on both axes is off by about a factor 10. This means that based on the emission data and model, the ocean subdomains contain about 10 times as much plastic as that measured.

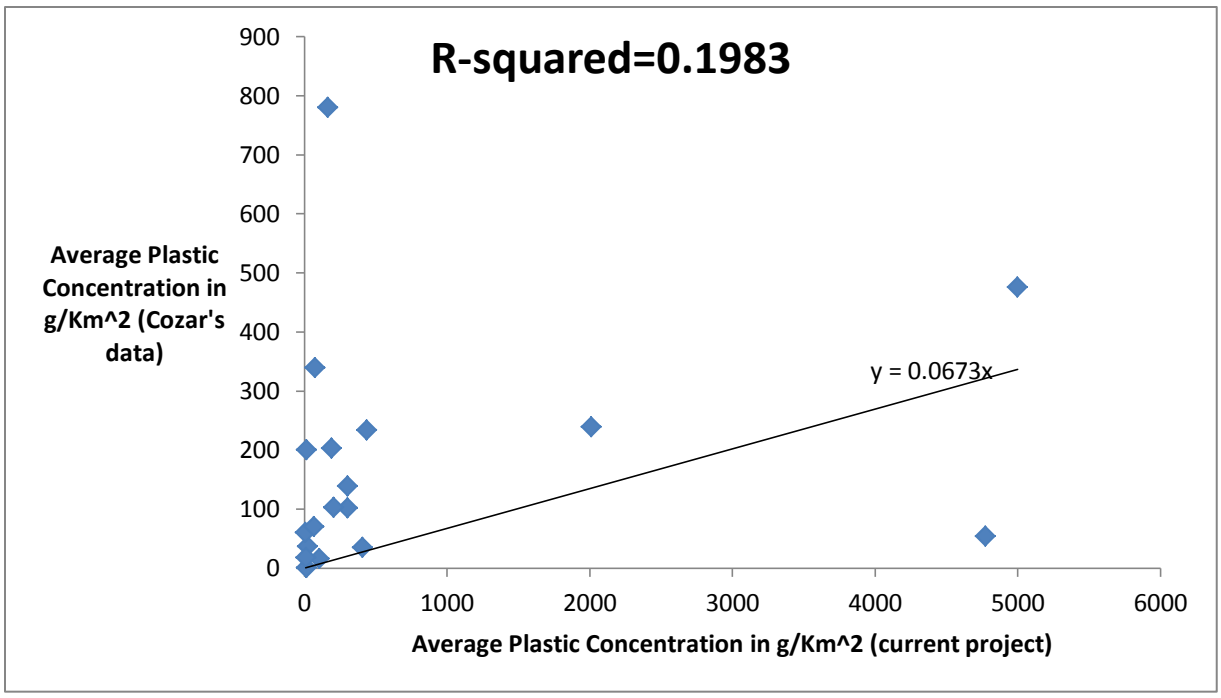


Figure 3: *Scatter plot between the simulation results based on the emission model with* $\gamma = 0.1$ *and the observations of Cózar et al. (2014).*

As a first correction to the emission model, one can assume that all E_{ij} are still constant but that the factor γ should be adjusted. The line in Fig. 3 serves this purpose and leads to a new value of γ, say γ_1, which is found to be 0.0128 ± 0.0061, lower than the originally assumed value, but at the same order with the range of values that was proposed by Jambeck *et al*. (2015).

4. Improving the emission model and the effects of sinks

In this section, we try to improve the emission model (1) and also add a representation of sinks of plastic to get a better correlation between simulation results and observations.

4.1. Recycling effects

According to Barnes *et al.* (2009), recycling rates may reach a 20-40% of the total produced waste, for areas that participate in recycling programs. Troschinetz *et al.* (2008) describes a variety of recycling rates for developed and developing countries (European Union: 18%, US: 30%, Brazil: 20%, Thailand: 14%, Turkey: 30%). Based on the above statements, we defined the recycling rates as 30%, 15% and 0% for cities with high, medium and low HDI respectively. With this representation, the emission model becomes

$$P_{total} = \sum_{j=1}^{31}\sum_{i=1}^{213} P_{ij} = \sum_{j=1}^{31}\sum_{i=1}^{213} 365\ w_{ij}\ \ m_{ij}\ PP_{ij}\ M_{ij}\ (1-d_i), \qquad (4)$$

where the term d_i of the equation represents the recycling rate of each city, based on its HDI.

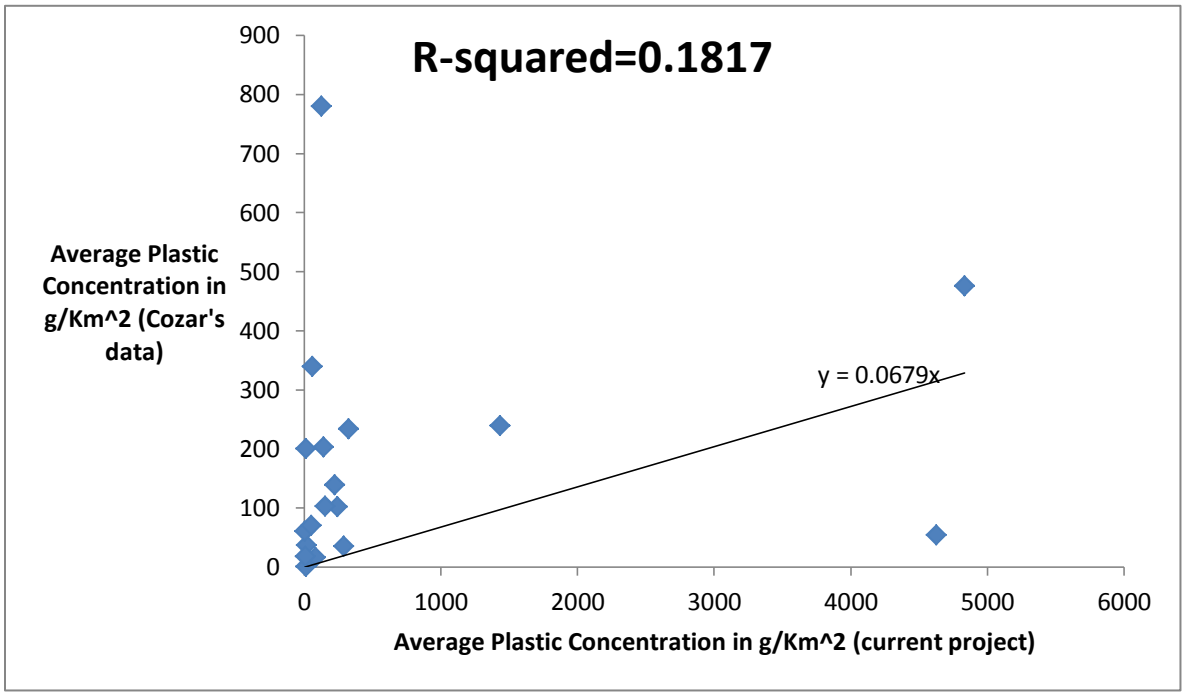


Figure 4: *Scatter plot between the simulation results based on the emission model with* $\gamma = 0.1$*, including recycling according to (4), and the observations of Cózar et al. (2014).*

Figure 4 shows the correlation plot between the data that we take from our simulation model in the case of the existence of plastic recycling rates and the data of Cózar *et al.* (2014). It can be seen that recycling has indeed decreased the simulated plastic concentrations, but the values are still too high compared to observations. Based on this correlation plot, we can again define a new value of the term γ, say γ_2, which in this case equals 0.0168 ± 0.0100 which is indeed higher than for the standard case.

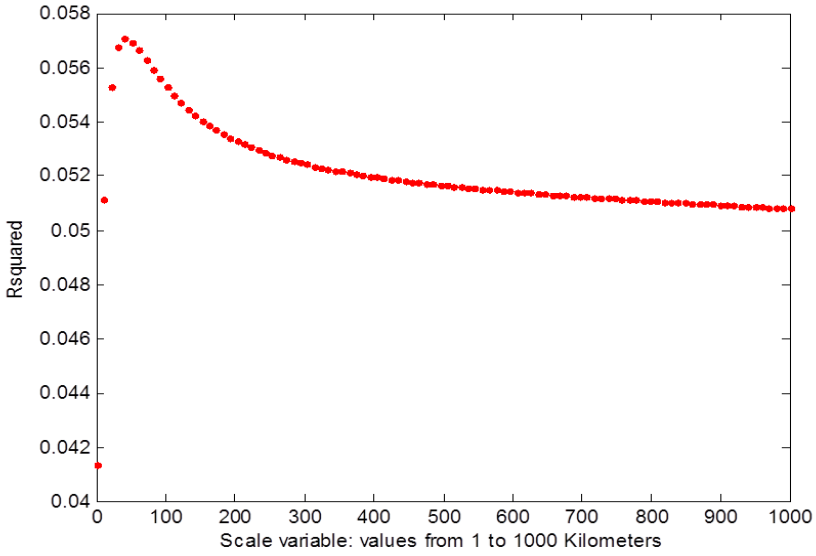
4.2. Effects of coastal sinks

Much of the plastic, which is emitted at coastal cities, will end up at the coastlines. We represent this effect as a spatially dependent sink which is given here by

$$v(t+60) = v(t) \quad P_b \qquad (5a)$$

$$v'_n(t+60) = v_n(t+60)\left(1 - e^{-z_n/s}\right) \qquad (5b)$$

where v' is the new vector after the sink has been applied and z_n is the minimum distance of each location n on the grid to the coast. The quantity s is a scale factor, which determines the spatial extent of the sink; when s is large the sink will be extended of larger regions than when s is small. We will vary s over a range 1 – 1000, with an interval of 10 km.



Figures 5: *Correlation quality between the simulation results and the Cózar et al. (2014) data for the standard with recycling and with a sink represented by the equations (5). The scale factor s is varied on the x-axis.*

Figure 5 shows the correlation quality (the R^2 value of the linear fit) between the simulation data and the data of Cózar *et al.* (2014). It can be seen that the maximum correlation quality is observed for a scale value s that corresponds to about 41 km. Figure 6 shows the correlation plot for this optimal case. Again, based on this correlation plot, we can define another new value of the term γ, say γ_3, which equals now to 0.0172 ± 0.0104.

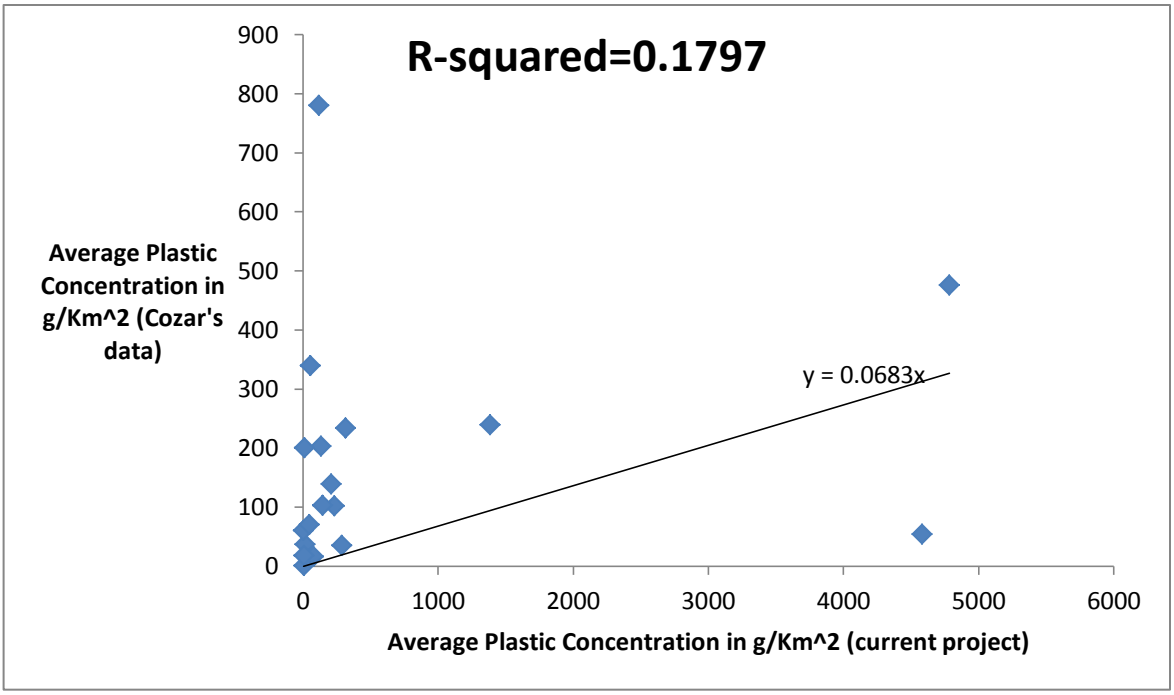


Figure 6: *Correlation plot between the simulation results and the Cózar et al. (2014) data for the standard with recycling and with a sink represented by the equations (5) for s = 41 km.*

4.3. Effects of biofouling

Biofouling is the growth and the accumulation of organisms such as microorganisms, plants, algae or animals on wetted surfaces (Dobretsov *et al.,* 2005, Artham *et al.,* 2009). We are interested in the marine biofouling, since these organisms attach also to the plastic garbage that is distributed around the oceans. This process leads to the increase of plastic densities. By this way, some plastics still remain lighter than the seawater and some other plastics acquire higher densities and become heavier than the seawater. This means that plastic trash can be found discarded in the sea surface or immersed on the sea floor. In order to sum up, after a while of the exposure of a plastic item into the sea water, and due to the biofouling process, its density gets higher and its removal from the ocean surface is observed.

Between February 2006 and February 2007, Artham *et al.,* (2009) conducted marine biofouling measurements on several samples. These samples were of four different types of plastic materials that were submerged in the ocean water in Bay of Bengal in India and were used in order to determine the extent of biofouling. In particular, the stability of these polymer samples was monitored every month, after being removed from the sea water. This study indicates an increasing fouling because of the exposure of these polymers to the sea water, which in turn results to several changes of plastic characteristics. In

general, changes in the chemical and surface properties (roughness, surface energy and hardness) of the polymers were observed, even though that little is known about these changes. The surface roughness of the polymers for instance increased over the exposure period for all types of plastic. However, the degree of biofouling on plastic materials is not only determined by its surface properties. It depends on several factors such as the season, the chemical nature of the polymer, the amount of the diatomic oxygen that is dissolved in the surrounding water (Artham *et al.,* 2009). Among these, the factor that plays an important role in the extent of biofouling is the dissolved O_2 (Artham *et al.,* 2009).

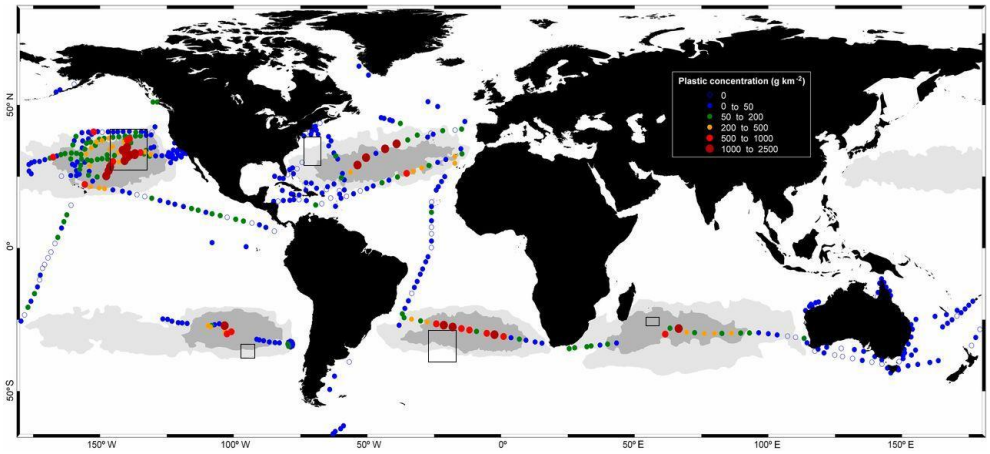


Figure 7: *The black rectangles show the areas where constant plastic sinks have been put in the simulation model as to represent biofouling.*

A similar study was conducted by Muthukumar *et al.,* in 2011. Several material surfaces immersed in marine waters of Bay of Bengal at Ennore Port Limited Chennai in India for a period of one year (July 2008 to July 2009). Samples were removed from the surface and have been analyzed once every two months. This study confirms the fact that biofouling depends on the season. In particular, the accumulation of the biofilm, which is the initial stage of the biofouling process, reached its maximum during July. Under aquatic environments, biofilms mainly consist of bacteria and diatoms (Dobretsov *et al.,* 2005). Biofouling diatoms also adhere to submerged surfaces, and increase the weight of the materials (Molino *et al.,* 2008). The surface characteristics determine the biofouling process at its beginning steps, while afterwards they do not seem to affect the amount of biofouling (Muthukumar *et al.,* 2011).

To represent the biofouling process, we inserted in our simulation model five constant plastic sinks in each of the five ocean basins, as shown in Fig. 7. In these areas, these plastic sinks reduce the marine plastic quantities by half each year. Figure 8 shows again the correlation plot between the data and observations in case we add in our

simulation model the biofouling sink to the sink represented in (5). The correlation does not improve much but based on this correlation plot, we can define another value of the term γ, say γ_4, which now is found to be 0.0203 ± 0.0135. The reason that we take similar results of the term γ as in the previous case is that the oceanic areas that we chose in order to put constant sinks were not in the same areas where Cózar *et al.* (2014) made the measurements.

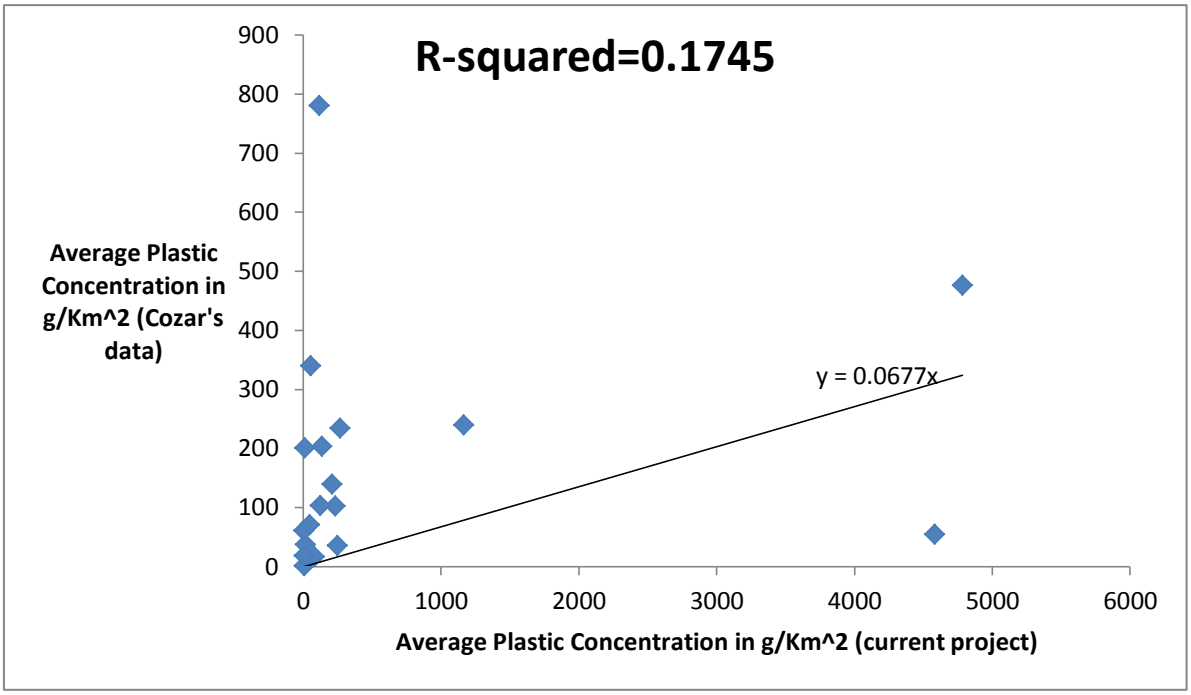


Figure 8: *Correlation plot between the simulation results and the Cózar et al. (2014) data for the standard case with recycling, with a sink represented by the equations (5) for s = 41 km and with a constant sink due to biofouling.*

So far, all terms γ, which represent the percentage of the total produced plastic waste that ends up at the ocean, are acceptable, since they approach the value of literature. In particular, they have the same order to the range of values between 0.017 and 0.046 that was stated by Jambeck *et al*. (2015). Based on the last γ, $\gamma_4 = 0.0203 \pm 0.0135$, which is the most improved value from the initial value, we will estimate the total plastic amount that existed in the ocean at the end of 2010. In total, approximately 7,427,299 ± 4,939,337 tons have been estimated that entered into the oceans for a total period of 31 years, from 1980 to 2010.

5. Summary and Discussion

By using a combination of emission data, an emission model, a tracer simulation model and a comparison with observed data, we have made an attempt to quantify the amount of plastic which was present in the ocean at the end of 2010.

The dataset that was used for this study included the annual plastic amounts that have been entered the ocean from 213 coastal cities worldwide for the period between 1980 and 2010. This dataset was based on a combination of the cities' population, HDI, GNI values of the cities' country and waste generation rate data. In our standard emission model, we do not include recycling rates and sinks into the calculation of plastic density distributions. The simulation model shows that the plastic input accumulates into the subtropical gyres. A comparison with observations shows a low quality fit but from which a first estimate of parameters in the emission model can be made.

By representing recycling rates, coastal sinks and biofouling an attempt was made to improve the correlation between simulation result and observations but without much success. Our 'best' value of γ is γ_4, with $\gamma_4 = 0.0203 \pm 0.0135$., where γ is the percentage of the produced and mismanaged plastic mass that is finally inserted into the ocean. This value of γ_4 (0.0203) is within the range of values (between 0.017 and 0.046) that was proposed by Jambeck *et al*. (2015). Based on this value of γ, we determined the total amount of plastic that existed in the ocean by the end of the year 2010 which is 7.4 ± 4.9 million tons.

We cannot conclude though that this quantity represents the real total amount of plastic that is present in the ocean at the end of 2010. Plastic was first mass-produced in the market from the period of 1950s (Barnes *et al.,* 2009), and thus in our estimation, we did not include the accumulation of plastics in the ocean until the year of 1980. It could be then claimed that our estimation is lower than the actual conditions that happen in the ocean. Before extracting any conclusion, we need to understand the differences between our estimation of 7.4 ± 4.9 million tons of plastic load in the ocean and the estimation made by Cózar *et al.* (2014), approximately 14,000 tons. The estimation made by Cózar *et al.* (2014) was based on real measurements, which show the real plastic load at the ocean. This plastic load includes the amount of plastic that accumulated in the ocean from 1950 until 2010, while it excludes the actual amount of plastic that has been earlier recycled. On the other hand, our estimation is based only on 213 coastal cities, on the period between 1980 and 2010, and on approximate recycling rates.

ACKNOWLEDGEMENTS. We thank Lisa Hahn-Woernle for her crucial contributions to the simulation model that was used.

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