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Numerical modelling of floating debris in the world's oceans

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ABSTRACT

A global ocean circulation model is coupled to a Lagrangian particle tracking model to simulate 30 years of input, transport and accumulation of floating debris in the world ocean. Using both terrestrial and maritime inputs, the modelling results clearly show the formation of five accumulation zones in the subtropical latitudes of the major ocean basins. The relative size and concentration of each clearly illustrate the dominance of the accumulation zones in the northern hemisphere, while smaller seas surrounded by densely populated areas are also shown to have a high concentration of floating debris. We also determine the relative contribution of different source regions to the total amount of material in a particular accumulation zone. This study provides a framework for describing the transport, distribution and accumulation of floating marine debris and can be continuously updated and adapted to assess scenarios reflecting changes in the production and disposal of plastic worldwide.

1. Introduction

The purpose of this study is to simulate the transport and accumulation of anthropogenic waste, particularly floating plastic debris, released from coastal locations or dumped overboard on the high seas. The identification and description of oceanic accumulation zones, 'garbage patches' or gyres, characterised by high concentrations of plastic debris (Moore et al., 2001), has attracted worldwide media attention and initiated efforts to address the problem. Convergence zones at subtropical latitudes are well known and related to the overlying anticyclonic wind systems. The average motion of the wind driven layer, known as Ekman motion is to the right (left) of the wind in the Northern (Southern) hemisphere. When in an anticyclonic wind stress situation, the Ekman transport results in convergence zone and downwelling. While there is a considerable body of existing research into the extent and concentration of these accumulation zones (Carpenter and Smith, 1972; Law et al., 2010), there are few, if any, published works describing global-scale transport of floating debris from release into the ocean through to accumulation within one of the gyres. Our study proposes a methodology to track floating debris from source to sink based on realistic descriptions of global waste production and oceanic surface currents.

2. Plastic pollution

The problem of plastic marine debris has come to prominence in recent decades. Since the seminal work of Carpenter and Smith (1972), Colton et al. (1974) and Morris (1980), who reported data describing the distribution and abundance of plastic in the North and South Atlantic Oceans, a steady stream of studies have appeared in the literature describing and quantifying the extent of the problem. Large scale media interest in the accumulation of oceanic debris began in 2001 through the efforts of Moore et al. (2001) who presented data showing that plastic was more abundant than plankton by as much as 6:1. Law et al. (2010) then provided the most comprehensive review of data from the North Atlantic, summarising more than 6000 samples taken over 20 years.

Measurements of the concentration of plastic pollution in the ocean vary significantly and therefore settling on a consistent set of numbers to define the problem is complicated. Early estimates from the US National Academy of Sciences claim that a total of 6.4 million tonnes of trash are released into the ocean every year and of this, 0.7% is plastic (NAS, 1975). A careful reading of this reference suggests that this number is based on an extrapolation of values from estimates of wastes produced by individual households and these inferences that may not be entirely accurate. On the other hand, Derraik (2002) summarises the results from several studies that suggest 60–80% of marine debris is comprised of plastic; this range was further supported by Barnes et al. (2009).

Globally, approximately 225 million tons of plastic are produced every year (APME, 2006 and cited in Barnes et al., 2009). More than one-third of that total is used in disposable packaging

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which is discarded within one year of production (Derraik, 2002; Thompson et al., 2009). While early estimates put the amount of plastic in household waste at just 0.7%, this number has increased dramatically and current estimates put the percentage at anywhere from 5% to 10% world-wide and most indications are that this amount is increasing (Subramanian, 2000; Thompson et al., 2009). It is also clear that in developing countries, plastic consumption is increasing rapidly, while infrastructure for waste management and promoting environmental awareness are not. With the increasing production and consumption of plastic both in developed and developing countries, measures to reduce and recycle are crucial. By 2030, it is estimated that 15% of household refuse in China will be compromised of plastic (The World Bank, 2005).

In 2007, consumption of plastic was on the order of 100 kg per capita in North America and Western Europe with estimates of up to 140 kg per capita by 2015. The global production of plastics has increased by 500% over the last 30 years, while consumption per capita has increased by over 50% in the last decade (Plastinum, 2009). By 2050, global plastic production is projected to reach 850 million tons per year (Shen et al., 2009). Western Europe produces around 500 kg of household waste per capita, the USA around 750 kg and the average in the developed world is around 100 kg per year (Plastinum, 2009). In 2006, 11.5 million tons of plastic were dumped into landfills (Plastinum, 2009).

3. Hydrodynamics and particle dispersion modelling

Our particle tracking model uses a two-stage process; first a hydrodynamic model solves the equations of motion to describe water movements throughout the model domain. In the second stage, virtual particles are introduced into the flow field and allowed to move freely through hydrodynamic forcing. For this study, sea surface currents are extracted from the oceanic circulation modelling system HYCOM/NCODA (Cummings, 2005). The HYCOM model is forced by the US Navy's Operational Global Atmospheric Prediction System (NOGAPS) and includes wind stress, wind speed, heat flux, and precipitation. The model provides systematic archiving of daily ocean circulation on a global scale with output data archived back to mid-2003. By assuming that global circulation patterns have not changed significantly in recent decades, the six full years of available data were looped five times to represent 30 years of ocean circulation. The velocity data extracted from HYCOM were then coupled to the Lagrangian particle tacking model Pol3DD and used to drive the dispersion of floating material across the ocean surface.

The model Pol3DD tracks virtual particles to simulate waterborne dispersion of material including neutrally buoyant anthropogenic material, larvae, oil spills, outfall discharges and estuarine or beach sediment transport. The particle tracking model uses a second-order accurate advection scheme (Black and Gay, 1990) described as follows:

$$\delta x = \frac{\left(u' + \frac{(u_y v' - v_y u')\delta t}{2}\right)\delta t}{\left(1 - \frac{u_x \delta t}{2}\right)\left(1 - \frac{v_y \delta t}{2}\right) - \frac{u_y v_x \delta t^2}{4}}$$

$$\delta y = \frac{\left(v' + \frac{(v_x u' - u_x v')\delta t}{2}\right)\delta t}{\left(1 - \frac{u_y \delta t}{2}\right)\left(1 - \frac{v_x \delta t}{2}\right) - \frac{u_x v_y \delta t^2}{4}}$$

where

$$u' = u + \frac{\delta t u_t}{2} \quad v' = v + \frac{\delta t v_t}{2}$$

and u, v are orthogonal velocity components, t is time, δt is the model time step, u_x, v_x, u_y, v_y are the u and v spatial velocity gradients, and u_t,v_t are temporal gradients. Horizontal diffusion was modelled as a random walk with separate longitudinal and lateral coefficients set to simulate random turbulence. The distance increments moved by the particle at each time step is calculated as:

$$\Delta x = R_N \sqrt{6E_1 \delta t} \quad \Delta y = R_N \sqrt{6E_2 \delta t}$$

where R_N is a random number in the uniform range (−1,1) and E_1,E_2 are the longitudinal and lateral eddy diffusivities, respectively. Since wind driven currents are already expressed in the HYCOM hydrodynamic data, no additional wind stress terms are applied to the motion of particles. Since we assume that debris particles are fully submerged in the water, extra forcing on potentially emerged parts of the debris is neglected.

For this application we modified Pol3DD to track and store the origin, age, and trajectory information of individual particles. This was combined with a polygonal region search method to identify particles in a given area, track their origin and how they arrived in a particular zone. Pol3DD was also modified to model a spherical earth by allowing particles moving off of the eastern boundary to re-enter the simulation on the western side or vice versa. Because the source, age and complete trajectory of each particle are stored by the model, this allows for the complete description in terms of composition, origin and evolution of material present in higher-concentration accumulation zones or oceanic gyres.

The HYCOM model is computed on a Mercator grid between 78°S and 47°N at 1/12° resolution. The model is run over a global grid comprised of 4500 × 3298 grid nodes with an average grid spacing of ∼7 km. While the full HYCOM model contains 32 vertical layers, we only consider velocities in the surface layer as the principal driver of floating particles. Pol3DD was forced by data extracted from HYCOM at every third grid node, i.e. 1500 × 1100 nodes at ∼21 km resolution.

4. Inputs of oceanic plastic pollution

While it is not possible to reliably estimate the amount of plastic input to the ocean (Derraik, 2002; Law et al., 2010), it is obvious that plastic pollution enters the ocean from either marine or land based sources. Faris and Hart (1994) estimate that 80% of the marine litter enters the ocean by land and we assume the remaining 20% is derived from maritime activities such as commercial and recreational fishing, cruises and shipping. Wilber (1987) breaks the input of debris to the ocean into intra-gyral and extra-gyral components. The former refers to debris originating from vessels operating in the mid oceanic system and the latter referring to terrestrial inputs as well as vessels operating in shelf and coastal waters.

Debris of terrestrial origin reaches the oceans mainly through runoff; via storm drains and waterways accessing areas where garbage is not adequately controlled (PRDS, 2005). Rubbish left behind by beachgoers and pushed into the sea by waves, wind or tides is another potential source of debris (UNEP, 2009). While not very common, large amounts of trash can also be swept into the ocean by natural disasters such as tropical storms (Doong et al., 2011) or tsunamis (Prasetya et al., 2011). The latter was exhibited in an extreme manner following the March 11, 2011 Tohoku, Japan tsunami. Of course, the exact source and quantity of input material varies from place to place and depends on the population, the level of urbanisation and municipal waste infrastructure.

To address this problem, we use a scaled approach to define the particle releases. Our input scenarios are based on Halpern et al. (2008), using three of their data layers of impervious surface area, coastal population density and shipping to define the input of particles to the model. Details for our method of converting the source data to particle releases is provided in Appendix A. The first two categories (impervious surface area and coastal population density) are used to define terrestrial input while shipping is used to define the maritime input. Terrestrial inputs are assumed to enter the ocean primarily at coastal release points corresponding to major rivers, cities and urbanised areas while marine based litter is assumed to enter along the major commercial shipping lanes (Fig. 1, Table 1). The amount of material released from each source cell is expressed as fraction of the total amount of material released globally per year. The release frequency at each location is evenly distributed in time over each year of the model simulation.

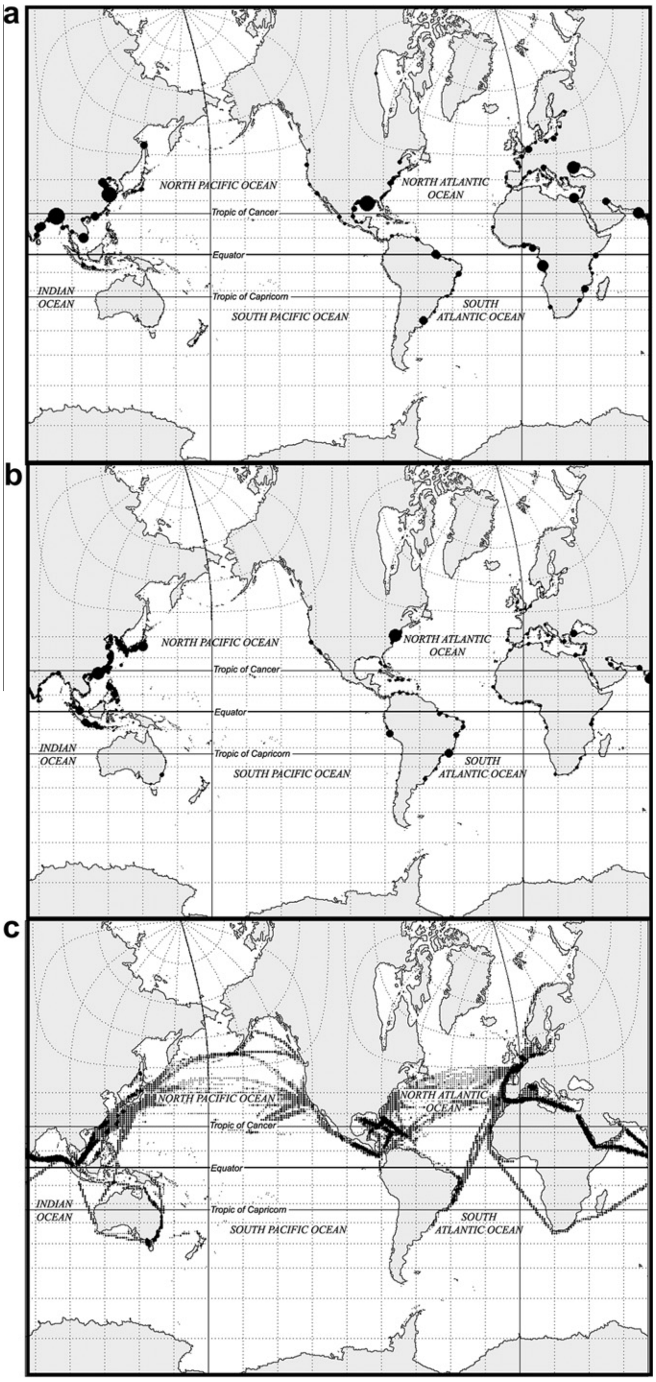

Fig. 1. A graphical representation of the three particle input scenarios. The black circles at coastal release points are scaled according to the relative input of material at each location. (a) Scenario 1 – impervious watershed area (b) Scenario 2 – coastal population density (c) Scenario 3 – maritime inputs over global shipping routes.

Table 1
Top 10 release points as a percentage of the total number of particle released per year for the land based Scenarios 1 and 2.

Scenario 1		Scenario 2	
River	% of Total	City	% of Total
Ganges	6.50	Hong Kong/Macau/Guangzhou	4.26
Yangtze	5.30	Mumbai	2.19
Mississippi	3.20	Shanghai	1.96
Nile	2.30	NYC	1.85
Danube	2.20	Tokyo	1.68
Congo	1.80	Seoul	1.17
La Plata	1.60	Manila	1.12
Indus	1.60	Kobe	0.98
Mekong	1.20	Shantou-Jieyang Chaozhou	0.96
Krishna	1.00	Singapore	0.95

While the overall distribution of released material remains constant through time, the total mass of material represented by the number of particles, increases annually to mimic the growth in worldwide consumption and waste (Fig. 2). The rate of increase in particle release was built on the assumption that the release of marine debris world-wide doubles every decade.

We take impervious surface area as a proxy for the input of plastic debris as it directly relates to the level of urbanisation and runoff volume, both of which are related to the input of material to the marine environment. This driver also contains the influence of population centres located inland which contribute to ocean pollution through rivers and urban runoff. Coastal population density is an obvious alternative driver to the watershed concept described above. A population based approach was used by Yoon et al. (2010) to describe the input of marine litter to their model of floating debris in the Japan Sea. A total of 4509 release points were established for the impervious surface scenario, 3419 points in coastal population density and 4143 points in the marine release scenario. Our approach differs significantly from previously published models describing the transport and accumulation of floating debris on a global or oceanic scale (IPRC, 2008; Martinez et al., 2009) in that these efforts used uniform concentrations of material over the ocean surface as a starting point while we attempt to realistically describe the release of marine litter and debris on a global scale.

5. Method

Over the course of the 30 year simulation, a total of approximately 9.6 million particles were released into the model. To maximise computational efficiency, a series of 10 global models for each land based scenario and two models for the marine based scenario were established. Each simulation covered the releases from a particular geographic region and represented roughly 1/10th (or 1/2 for the maritime scenario) of the total particles released. Once completed, the results were superimposed to give the full distribution of material over the ocean surface. The dispersion simulations were run at hourly time steps for a period of 30 years (262,800 h). The model output updated particles position and the history of particle visits per cell on a weekly (168 h) basis.

A time step of 1h was used as it represents a good compromise between model accuracy and computational time. Since time-averaged maximum current speeds do not exceed 1.4 m/s (5 km/h), a particle is unlikely to travel a distance exceeding one cell (∼21 km on average) per time step. However, current speeds greater than 4 m/s do exist in the hydrodynamic dataset and the cell size is variable with a minimum spacing of 1.7 km in the Polar Regions, thus there is the possibility of a particle existing within a small cell with a high instantaneous velocity potentially leading to inaccuracies in

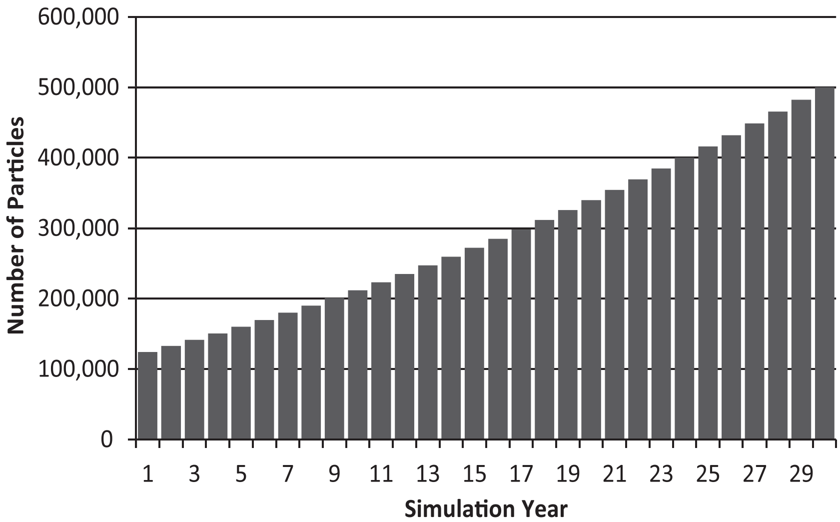

Fig. 2. The number of particles released into the simulation each year.

the particle position. However, due the generally smooth nature of the ocean surface velocity field, such instances are rare and are inconsequential for time-averaged particle positions over the 30 year simulation.

Once the model runs were completed, the 52 final model blocks (covering the last year of simulation) were averaged to determine the number of particles per model cell. This value was then scaled by the total number of particles released over the 30 year simulation (Fig. 3a–c). We defined accumulation zones in the five ocean basins using percentage thresholds of 0.001% for the inner accumulation zone and 0.0001% for the outer accumulation zone. We also considered the marginal and semi enclosed seas (i.e. Mediterranean, South China, Bay of Bengal) as they each presented large areas with concentration values above the thresholds noted above (see Fig. 3d for accumulation zone boundaries). Statistics of the composition of each accumulation zone for the land based scenarios were then compiled for analysis. Such metrics include: the total number of particles, the concentration of particles over a unit surface area, the residence time of particles within the accumulation zone and the distribution of particles as a function of their source region.

6. Analysis and discussion

In general, our results compare quite will with both measured and modelled descriptions of concentrations of floating debris. In particular we show a higher concentration of particles accumulating in the North Atlantic at approximately 30° North latitude and 55° West longitude (due East of Central Florida and due North of Suriname). A peak is shown in this general location in the analysis of Law et al. (2010). Our results also closely mimic both the data and modelling presented in Maximenko et al. (2011), particularly in terms of the location of the accumulation zones. Our results differ from theirs in that we can provide an estimate of the relative concentrations of material based on realistic input models showing much lower concentrations in the oceans of the southern hemisphere.

Looking at Fig. 3, it is evident that the largest accumulation zones are in the northern hemisphere. The prominence of the North Atlantic and North Pacific accumulation zones is obvious; each one covers an area approximately equal to that of Australia or the continental United States. Combined, they carry approximately one-quarter of the total amount of floating debris from Scenarios 1 and 2 and nearly half of the material from Scenario 3. This is in sharp contrast to the southern hemisphere, where the three subtropical gyres combined only contain 8% and 10% of the total particles from Scenarios 1 and 2 and approximately 4% from Scenario 3. This is easily attributable to the higher population and level of economic and industrial activity in the northern hemisphere (Hobbs, 2009) and also noted in Maximenko et al. (2011). Furthermore, wind and current patterns dictate that there is very little exchange between the northern and southern hemispheres, and material only crosses the equator in a few coastal areas. Indeed there is a clear demarcation between the northern and southern accumulation zones stretching across the centres of the large ocean basins. The high number of particles in the northern accumulation zones originating from maritime sources is indicative of the relative importance of intra-gyral inputs (Wilber, 1987) and corresponding efforts to reduce garbage dumping at sea.

At first glance, the final distribution of material from Scenarios 1 and 2 (Fig. 3a and b and Figs. S2–S7) does not reveal significant differences in the overall concentration and distribution of material within the accumulation zones. However, looking at the numbers in Table 2 and Supplementary Tables 1–4 reveals some significant differences. Starting with the Indian Ocean, the change from a watershed model to a population based model significantly increases the contribution from South East Asia/Indonesia and reduces the contribution from Africa. While the regional contributions to the North Atlantic and North Pacific accumulation zones do not change significantly between the two scenarios, there are significant changes between Scenarios 1 and 2 for the South Atlantic and South Pacific. In the South Atlantic, North and Central America's contribution increases while Africa's contribution decreases with the change from a watershed to a population based release model. In the South Pacific, New Zealand and Australia's contribution is halved while the contribution from South America increases by nearly 15 percentage points and South East Asia/Indonesia's share nearly doubles.

For Scenario 1, the largest single accumulation zone is the Bay of Bengal with the North Pacific second and the North Atlantic third. Switching to the population based input model pushes the North Pacific into first and the Bay of Bengal second (Fig. 4). The Mediterranean Sea has one of the highest concentrations of marine litter and retains between 6% and 8% of the particles introduced into the model. This is primarily attributable to the extensive coastal development and maritime traffic. However, a net flow of Atlantic surface water into the Mediterranean and no outlets

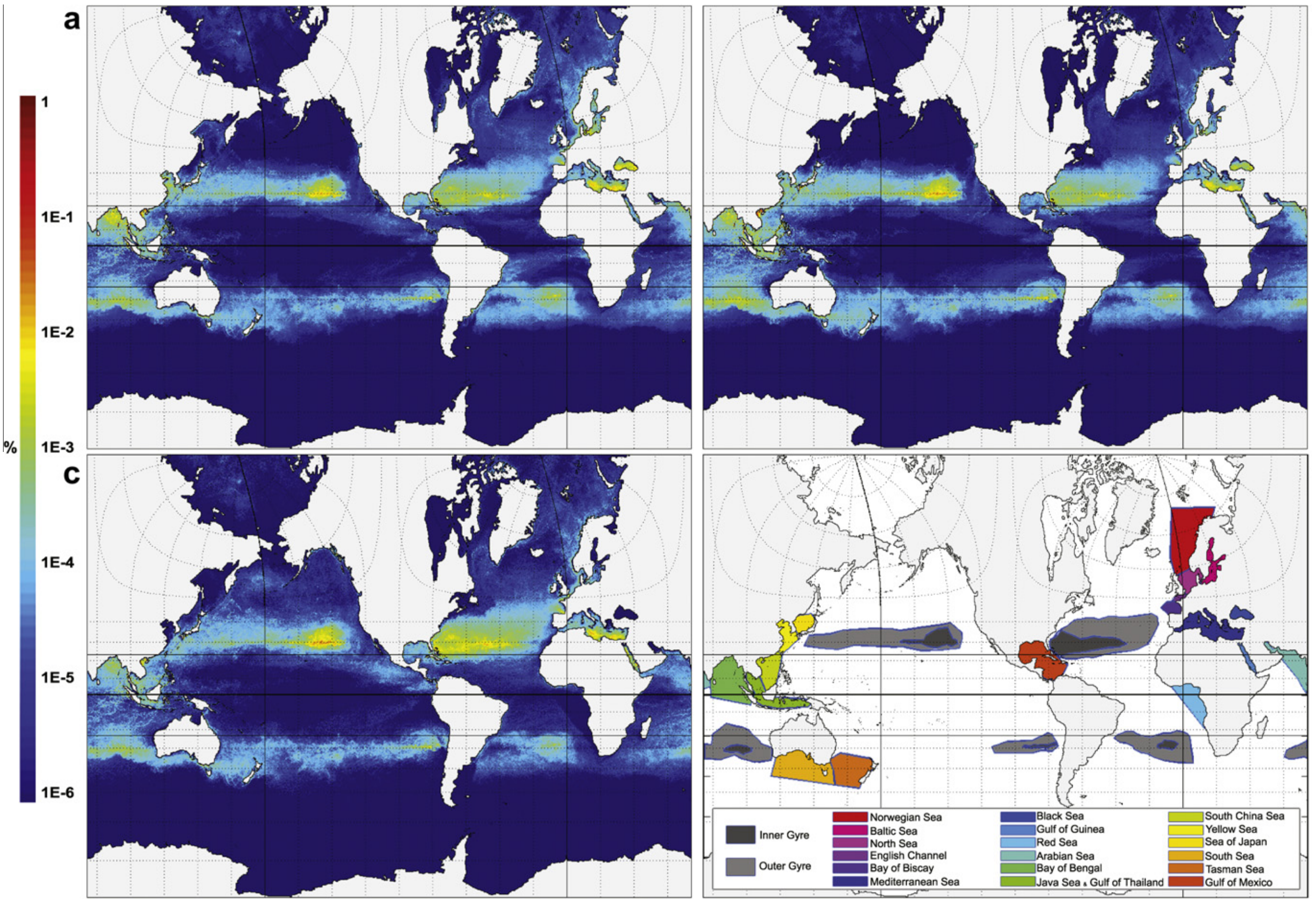

Fig. 3. The accumulation of floating material after 30 years of simulated input and circulation. (a) Scenario 1 (b) Scenario 2 and (c) Scenario 3. Panel (d) depicts the boundaries of the various accumulations zones.

Table 2
Regional contributions to the five major oceanic accumulation zones based on the two terrestrial release scenarios.

SOURCES	ACCUMULATION ZONES									
	Indian Gyre		North Atlantic Gyre		North Pacific Gyre		South Atlantic Gyre		South Pacific Gyre	
Europe			24.004	16.836		0.000	0.000			
Australia/New Zealand	0.106	0.188			0.001	0.000	0.041	0.015	40.713	20.190
South America	7.537	4.435	5.317	6.570	0.049	0.084	58.550	79.592	21.914	36.632
Central & North America	0.009	0.004	64.299	65.771	13.184	8.131			5.588	1.519
Africa / Middle East	29.061	9.111	6.103	10.748		0.000	39.905	17.336	9.884	3.127
India	17.430	8.303					0.890	0.829	1.702	1.128
South East Asia /Indonesia	38.393	65.787			2.734	5.789	0.536	1.989	17.637	33.019
China	7.243	11.588			65.784	58.036	0.076	0.227	2.456	4.114
Japan	0.197	0.578			10.863	27.217	0.001	0.012	0.099	0.271
Russia	0.024	0.007	0.278	0.075	7.385	0.742			0.007	0.002
Total	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000

means that material is destined to accumulate here (Aliani et al., 2003). The same is generally true for any of the semi-enclosed seas surrounded by highly populated and developed areas, as they all show relatively high levels of debris (Barnes and Milner, 2005; Ng and Obbard, 2006). For example, the results from input Scenario 2 suggest that there is more trash in the South China Sea than in the three southern subtropical gyres combined. The amount of material retained in the South China Sea increases significantly from Scenario 1 to 2 reflecting the high coastal population density along China's east coast and a shift in input from Shanghai and the Yangtze River to a more uniform distribution along the coast (Fig. S6). The Gulf of Mexico (Fig. S2), which is connected to the North Atlantic, contains nearly 4% of the total particles in Scenario 1, half that amount from Scenario 2, while maritime sources are seen to have a slightly higher impact (3%). Adding up the material in the five major gyres plus what is contained in the smaller seas,

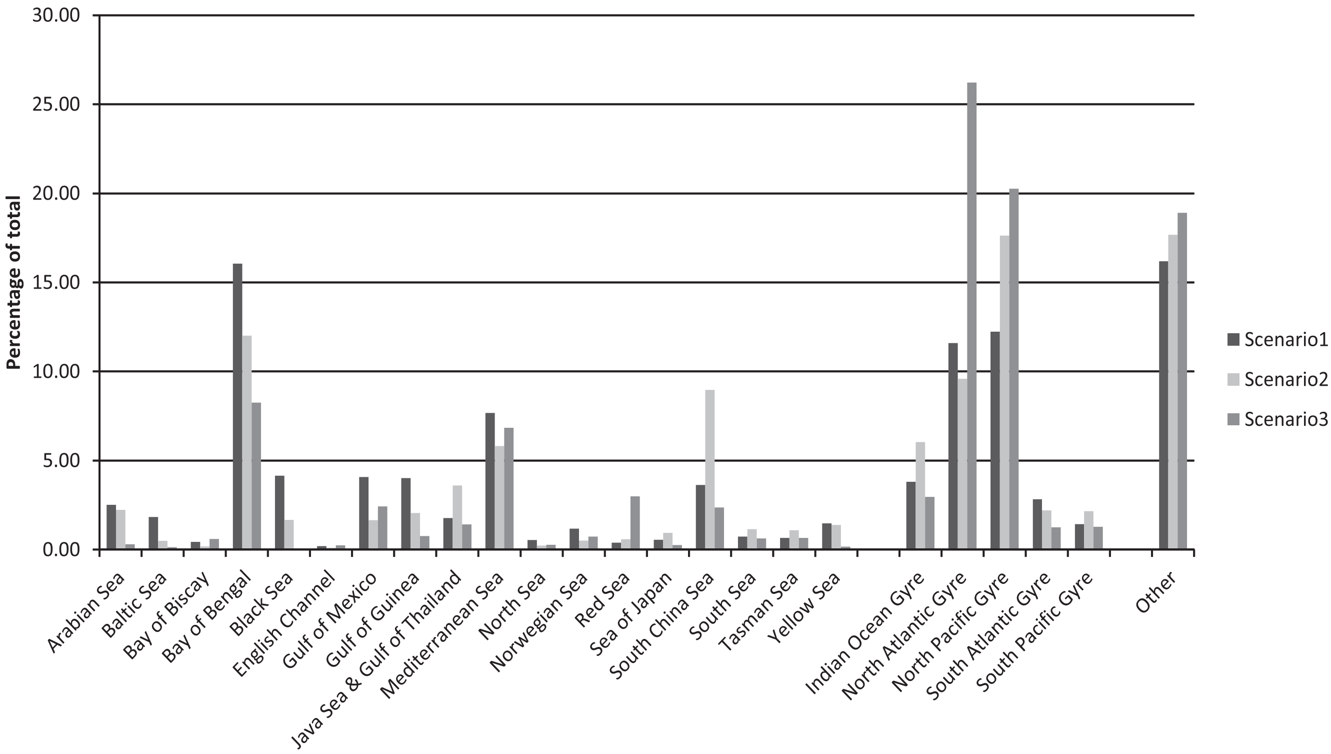

Fig. 4. Percentage of total number of particles existing in each accumulation zone for each release scenario at the end of the numerical simulation.

yields approximately three quarters of the total releases in each scenario. This implies that there is a large amount of debris either distributed over vast areas or washed up on shore.

Indeed, beaching is a significant factor in accounting for marine debris. Analysis of the computed particle trajectories shows the accumulation of material near coastal regions around the world (Fig. 5). While beaching is not explicitly modelled in our simulations we note that the ocean surface currents concentrate drifting particles into certain areas. A particle is considered to be 'beached' if it sits in a shoreline adjacent cell. Comparison of the beaching results in Fig. 5 suggest that material from the maritime release scenario (Scenario 3) is more likely to remain in circulation in the ocean basins than material from the terrestrial input. In total, only 28% of the particles in Scenario 3 were beached while 40% and 36% were beached for Scenarios 1 and 2 respectively. This again highlights the importance of intra and extra-gyral inputs noted by Wilber (1987).

Considering only the two land based scenarios, we then turn our focus to the regional contributions to each accumulation zone. In the northern hemisphere, the largest fraction of material in the North Pacific accumulation zone comes from China at 65% and 58% of the total for Scenarios 1 and 2. The other two major contributing regions (North/Central America and Japan) each contribute smaller, yet significant amounts. Using the watershed area approach (Scenario 1), the contribution of North and Central America is slightly larger than Japan's (13% vs. 11%), however the population based approach changes significantly with Japan rising to 27% and North/Central America falling to 8%. A similar effect is seen for the contribution from Southeast Asia/Indonesia and Russia, as the change from Scenario 1 to 2 doubles the Southeast Asia/Indonesia input (3–6%) and reduces Russia's by a factor of 10 (7–0.7%).

In the North Atlantic, the European contribution varies significantly according to the release scenario (24% vs. 17%), such a discrepancy is not evident for the North and Central American contribution (64% vs. 66%). The difference is then made up with slightly higher contributions from Africa and South America using the population based model (Scenario 2). A significant portion of the European contribution from both scenarios is contained in the Mediterranean and the marginal seas of the North Atlantic (e.g. Baltic, North Sea, English Channel etc.) (Tables S3 and S4).

In the southern hemisphere, the largest contributors to the three major accumulation zones (S. Atl., S. Pac. and Indian) are South America, Australia/New Zealand and Southeast Asia/Indonesia. However, the specific contribution of each region is highly dependent on geography. In the South Atlantic, South America and Africa are the only significant contributors to the accumulation zone. The South American contribution is greater than Africa's for both release scenarios; however it increases significantly for the population based approach (Scenario 2). In the Indian Ocean accumulation zone, the largest contributors are Southeast Asia/Indonesia, Africa and India for Scenario 1. In Scenario 2, the Southeast Asia/Indonesia contribution nearly doubles (from 39% to 66%) while Africa's contribution is reduced by 2/3rds (29% to 9%) and India's contribution is halved. China's contribution increases from 7% to 11% between the two scenarios. The greatest contributors to the South Pacific accumulation zone are Australia/New Zealand, South America and Southeast Asia/Indonesia. In Scenario 1, Australia/New Zealand is clearly the largest, while in Scenario 2, South America and Southeast Asia/Indonesia are roughly equal at 1/3rd each. Australia/New Zealand's contribution is cut in half in the population based approach (Scenario 2), and this is easily explained by the relatively low populations there. The large contribution of New Zealand in the watershed (Scenario 1) model is in our opinion suspect; and may reflect inaccuracies in the data provided by Halpern et al. (2008). The South Pacific accumulation zone also shows the greatest diversity of particle origins, with 7 regions contributing significantly to the total, as compared to two in the South Atlantic and five in the Indian.

While the three accumulation zones in the southern hemisphere are smaller and less concentrated, they show a greater level

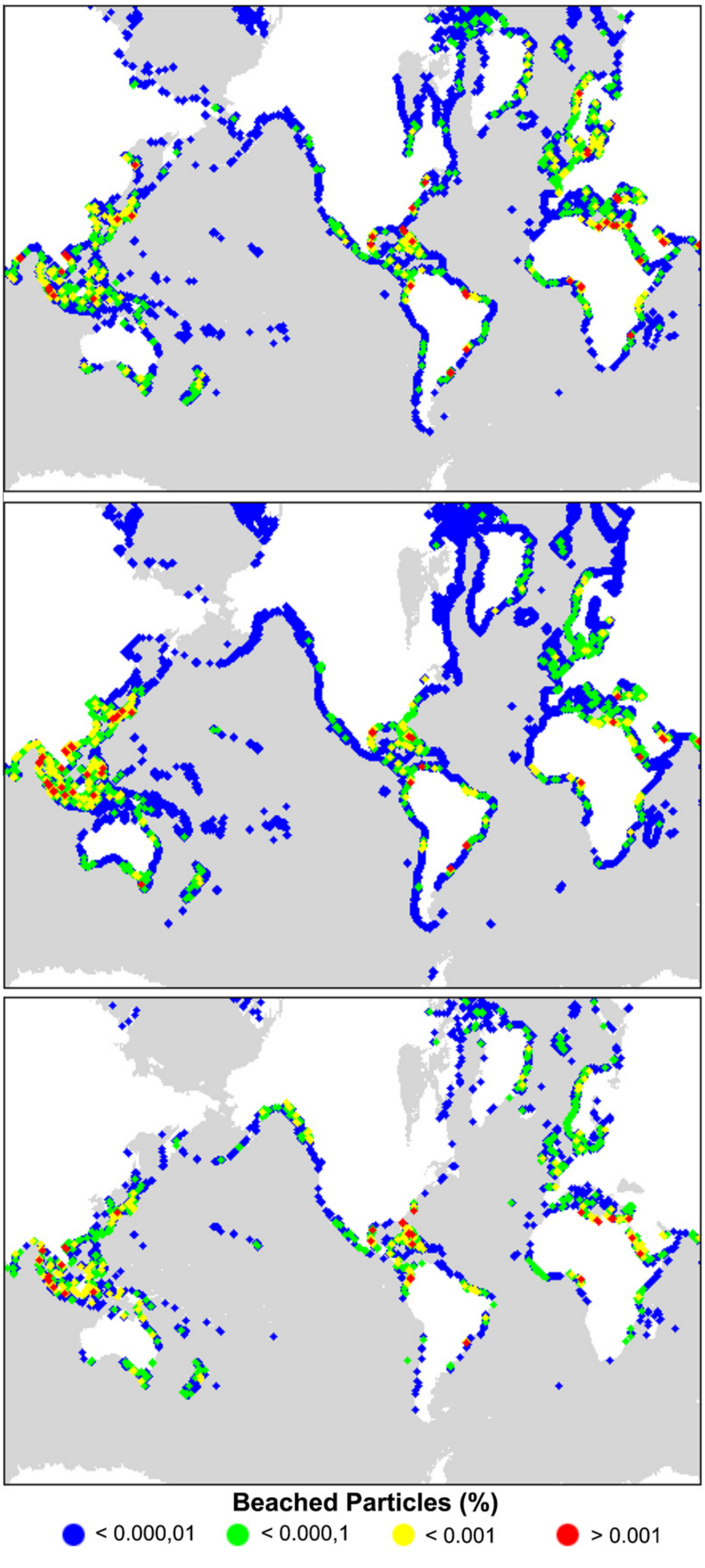

Fig. 5. Number of 'beached' particles for Scenario 1 (top), Scenario 2 (mid) and Scenario 3 (bottom). A particle is considered 'beached' when it is adjacent to a coastal cell.

of connectivity relative to their northern counterparts. By tracking the particle paths, we see that material moves between the accumulation zones on yearly to decadal time scales. For example, particles originating from the South Atlantic and identified in the South Pacific Gyre took more than 15 years to make the journey while particles from eastern South America took as little as

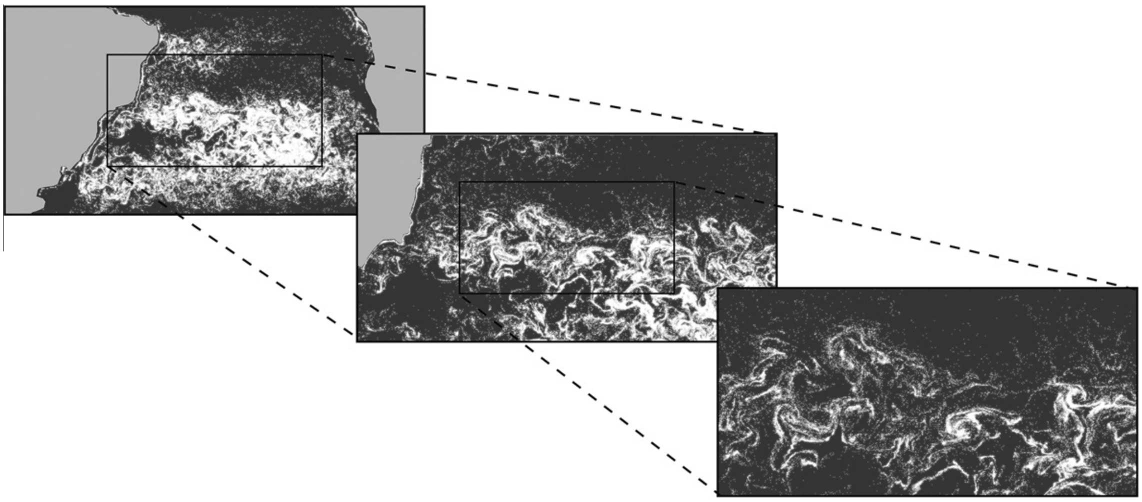

Fig. 6. Close up view of the distribution of particles in the western South Atlantic Ocean. A high degree of variability caused by the surface wind patterns is clearly evident.

11 years. Eventually however, the particles tend to accumulate in the South Pacific west of Chile as the South American continent blocks further transport to the east. This result is consistent with the modelling described in IPRC (2008). Indeed, the model results are in general agreement with these and other modelling efforts.

Looking deeper into the details of the composition of the accumulation zones, we noticed large variations in the concentration and distribution of particles (Fig. 6). Our model revealed patterns of patches within the patch; gyres within the gyre, indicating transport and accumulation on multiple spatial scales (Wilber, 1987). Zooming on one area reveals the repetition of patterns at smaller and smaller scales. Particles are seen to accumulate at the edges of surface currents and eddies created by local winds. Furthermore, this variability in concentration over relatively small space scales is a factor contributing to the sometimes large discrepancies in plastic yields between individual samples (Eriksen, pers. comm). Our model results are not compared to available datasets, since field data is not available at temporal or spatial resolutions necessary for rigorous model calibration. Nevertheless, this model qualitatively describes the distribution and extents of floating debris and can provide valuable inferences on the relative impacts of regional inputs to ocean borne plastic pollution.

7. Summary, conclusions and future work

This study presents a framework for describing the transport and accumulation of floating debris and the formation of oceanic accumulation zones. We use realistic input scenarios of anthropogenic material and ocean circulation to simulate 30 years of debris transport and accumulation. Material origin and pathways are stored and can be analysed to quantify the relative contribution to a particular accumulation zone as a function of source region. Our study, and other studies of this nature, particularly those with a regional (Yoon et al., 2010) or local (Kako et al., 2011) focus have the potential to be part of powerful education and outreach campaigns aimed at reducing marine litter worldwide. Furthermore, these modelling efforts can assess key transport pathways, environmental forcing, material sources and sinks while guiding monitoring and clean-up strategies. All of which are specific objectives laid out in Zarfl et al. (2011) in their discussion of the scientific research tasks necessary to better understand and deal with this issue. Since it is apparent that the lower amounts of debris in the southern hemisphere are related to lower levels of economic activity, this suggests that future efforts on waste minimisation should focus on developing nations in an effort to couple economic growth with improved waste management strategies to ensure that the oceans in the southern hemisphere do not become as impacted as their northern counterparts in terms of marine debris.

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Appendix A. Converting Halpern et al. (2008) spatial data into particle release scenarios

Halpern et al. (2008) provided 17 global data sets of anthropogenic drivers of ecological change. Among these were data layers quantifying impervious surface area in a watershed, coastal population density and shipping. The impervious surface area and coastal population layers were used to define the terrestrial inputs of floating debris while the shipping layer was used to define the marine releases. The raw data from Halpern et al. (2008) is provided as (X,Y,Z) triplets with position information in the Mollweide WGS84 symmetric projection and a corresponding data value. We first re-projected the position information to latitude and longitude in the WGS84 projection. The data was then normalised by summing all the values and dividing each by the sum, thus expressing each as a fraction of the total. The data were ranked by magnitude and plotted. Individual release points were determined by grouping immediately adjacent data points resulting in 4509 release points for 'impervious surface area', 3419 release points for 'coastal population density' and 4143 release points for 'shipping'. We assumed *a priori* a maximum number of particles that the model could handle in terms of computational efficiency (roughly 1 million per simulation) and assigned the number of particles to be released from each point based on the normalised data described above. The total number of particles released is distributed evenly over each year of simulation, while the number of particles released each year increases with time (see Fig. 2).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.marpolbul.2011.10.027.

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