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Modelling and monitoring of marine litter

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Oceans and Atmosphere Flagship

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Executive summary

The marine plastic pollution issue is a global issue of international concern. Marine litter comes from both land and sea-based sources and it can travel immense distances. Marine ecosystems worldwide are affected by human-made refuse, much of which is plastic. Resolving the biodiversity, environmental, economic, transport, navigation and biological invasion hazards associated with anthropogenic litter in the marine environment requires a substantial, sustained integrated effort from individuals, industry, governments and international governmental organizations at local to regional and global scales. The increase in global plastic production and the recent estimate of approximately eight million metric tonnes of plastic entering the ocean each year points to the need to tackle the problem at a multitude of scales. There is no single solution, rather, a number of local and regional solutions will be required to effect change.

The goal of this work was to develop a report for formal acceptance to the United Nations Environment Program. This report aims to address emerging topics about marine litter modelling and to progress beyond summarizing the existing state of knowledge regarding litter movement in the marine environment. It considers a series of processes including fragmentation and degradation and makes suggestions for experimental research efforts that are aimed to increasing our understanding about how particles move, in addition to considering seldom addressed potential sources of litter (from the atmosphere).

New analyses utilized existing data to model floating marine litter at global and regional scales and applied fore- and hind-casting models to understand and predict key source points and end points for anthropogenic debris. These analyses took into account model predictions of litter losses based upon human population density in coastal areas as well as relevant broad-scale information available on waste management within regions. Models were applied with a view to facilitate monitoring and quantification of marine litter, and to identify key sources of marine plastic debris and microplastics at the global and regional levels.

This report not only identifies information gaps and priority work areas for research. It also highlights the need for appreciating and acknowledging the uncertainty that persists regarding the movement, transportation and accumulation of anthropogenic litter in the marine environment. Importantly, it takes a critical step towards *understanding* the uncertainty that currently persists in our knowledge of global marine litter distribution through discussion and examination of the uncertainty underlying the data, models, and the resulting predictions that stem from these.

We also compared different drift models, developed for different applications and used by different agencies. We explicitly discuss some of the biases in drift models, using the recent aircraft MH370 episode as an example of differences in model approaches and solutions which were made possible once the craft was located. Finally, we provide a summary of existing ocean circulation models, the environmental drivers that are available for them, including the spatial and temporal resolution, limitations to the models and their availability.

By garnering the information needed to identify sources and hotspots of debris, increasing our understanding about the uncertainties that currently persist in our modelling efforts on litter in the oceans, and identifying those critical areas where filling data gaps can have result in the best

outcomes, we can better develop effective solutions to tackle the global marine litter issue. Working together, scientists, industry partners, coastal managers and citizen scientists can make significant strides to reduce marine litter inputs and impacts in coastal areas and in the oceanic environment.

1 Modelling of marine debris

1.1 Introduction

Marine debris or marine litter is defined as any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment (UN Environment Program, 2009). This litter can be observed in seas around the world, from high concentrations that are reported in the accumulation zones or gyres where floating plastic may exceed 600,000 pieces per km^2 (Law *et al.* 2010) to more remote regions such as the waters of the Arctic (Bergmann *et al.* 2015) and the Antarctic (Barnes *et al.* 2010) where fewer plastic pieces are observed. No matter where on the planet we are, evidence of human's discarded litter can be found.

There are research, educational, community engagement and outreach activities being carried out around the world to understand, quantify, identify and reduce litter entering the ocean. With these activities comes a variety of monitoring opportunities. Such monitoring is fundamentally important to assess the efficacy of measures being carried out to reduce the abundance of plastic litter in the ocean and along the coastlines of the world. Monitoring is complicated however, by both the spatial and temporal heterogeneity in accumulation, movement and multiple pathways that litter can take along its course.

Monitoring plastic litter in the environment is most often carried out in coastal areas, but can also take place at sea or through sampling wildlife that have encountered debris. Most often monitoring and surveys of litter take place in coastal regions, often as part of clean up activities or other community events. Such monitoring may be idiosyncratic, may have uneven sampling, and often is accompanied by sporadic or patchy data collection. While monitoring surveys can provide important estimates of the types of debris and their relative abundances, such surveys may be biased in a variety of ways.

Litter can also be surveyed in the ocean, though coastal and high seas monitoring can be expensive and difficult to replicate. Typically, oceanic monitoring of marine litter takes place through surface trawl sampling, which is biased towards items within a particular size range – those that are small enough to be sampled and 'caught' in nets, and large enough to be discerned by the human eye. Surface sampling will capture floating objects only and, given the vastness of the ocean, ocean circulation patterns and wind mixing, samples are often highly variable. At-sea sampling also requires large sample sizes facilitate statistical analysis required to detect potential changes in distribution and abundance, given the high spatial and temporal heterogeneity of plastics in the ocean (Barnes *et al.* 2009).

Efforts have been taken to survey sub-surface marine litter (e.g. Reisser *et al.* 2015) and the ocean floor (van Cauwenberghe *et al.* 2013; Katsanevakis and Katsarou 2004; Galgani *et al.* 2000; others). Quantifying litter on the seabed has lagged significantly behind coastal and surface sampling, though a variety of methods have been employed including bottom trawl nets, sonar, submersible, snorkelling, scuba diving and manta tow (reviewed in Spengler and Costa 2008). This is likely because of additional costs and time involved to carry out such surveys.

Around the world there are a number of different data collection strategies that have been developed and employed to monitor marine and coastal litter. While it is important to recognize that different questions require different monitoring approaches, the importance of standardization of approaches cannot be overstated (Barnes *et al.* 2009). To date, global harmonization of monitoring methods and data recording have remained unrealized, but working towards this remains an important goal. Monitoring is crucial to assess the efficacy of measures implemented to reduce the abundance of plastic debris, but it is complicated by large spatial and temporal heterogeneity in the amounts of plastic debris and by our limited understanding of the pathways followed by plastic debris and its long-term fate. To date, most monitoring has focused on beach surveys of stranded plastics and other litter. Infrequent surveys of the standing stock of litter on beaches provide crude estimates of debris types and abundance, but are biased by differential removal of litter items by beachcombing, clean-ups and beach dynamics.

Long term monitoring is also costly, time consuming, and difficult to sustain. Importantly, however, though there are a number of long term monitoring efforts such as OSPAR's marine beach litter program in Europe (www.ospar.org), the International Coastal Cleanup (ICC) which is organized by the Ocean Conservancy (www.oceanconservancy.org) and NOAA's marine debris program which monitors coastal litter using multiple monitoring approaches (www.marinedebris.noaa.gov). These long term initiatives are important not only to detect long term trends and patterns, but also allow one to evaluate the efficacy of legislation, to identify changes in sources, deposition, material types and potential impacts to wildlife. Furthermore, long term monitoring can help to identify opportunities for impact through local actions.

Given the challenges of monitoring plastic both before it arrives at and in the marine environment, combining empirical data and modelling approaches can be useful to help predict, or forecast, where plastics occur in the marine environment. Numerical modelling can also be applied to back track or hindcast from where plastics in the ocean may have come. Oceanographic current models can further be used to identify where oceanic accumulation zones are most likely to occur. Coupling such tools and approaches with species distribution maps and other ecological information, we can combine disparate data types to predict or identify hotpots of risk to taxa or geographic regions of interest. We can also identify movement pathways or trajectories, identify hotspots, and develop scenario analysis tools to identify potential sources and sinks. We can further evaluate effectiveness of local actions and activities, predict risk of invasion along pathways and evaluate costs of inaction and action.

1.1.1 Focus

There are a wide range of modelling activities that have been undertaken related to marine debris, ranging from models focused on the distribution at sea (Maximenko *et al.* 2012), to those incorporating emphasis on sources (Lebreton *et al.* 2012), to models focused on ecosystem responses (e.g. Troost *et al.* 2015), and models evaluating ecological risk (Wilcox *et al.* 2015; Schuyler *et al.* 2015) or even ecological impact (Wilcox *et al.* 2014, 2015). Here we focus on models concerned with the sources, transport, distribution, and fate of debris. We largely leave aside questions of ecological impact, except as they relate to the ultimate fate of the debris.

1.1.2 Reservoirs: Where does plastic occur?

Plastic occurs throughout the ocean from the surface, throughout the water column to the deep ocean floor. It can reside in sediment, biota, and ice, and may be trapped along the coastline or in estuaries, waterways and lakes, and can be trapped in the atmosphere. The reservoirs deemed most relevant for modelling movement of plastics in the ocean includes the following compartments: surface, coastline/estuaries, ocean floor, sediments, ice, biota and water column. While it was acknowledged that there are other reservoirs (e.g. the atmosphere, lakes and waterways), those were considered to fall outside of the current scope and focus.

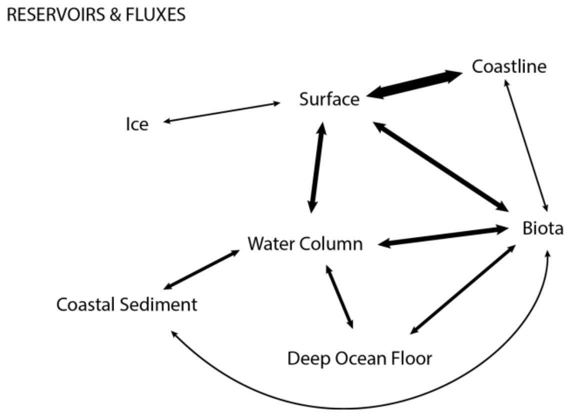

Figure 1. Schematic representation of reservoirs and fluxes for marine plastics. The weight of the arrow indicates the magnitude of marine debris flux hypothesised to occur between compartments, and the fluxes or flows between them.

Evaluating budgets (losses, sources and sinks into the environment) or leakage between these reservoirs or compartments requires understanding several key processes. Those highlighted as particularly important include rates of fragmentation, buoyancy/sinking/re-floating rates, as well as the rates and quantities of inputs of litter to the ocean and time trends for plastics in ocean.

When assessing the reservoirs, identifying in which reservoirs there is the greatest uncertainty will facilitate a ranking of transitions on which efforts could be focused, taking into account the key question (whether that relates to sources, losses between transition zones or impacts).

Table 1. Transfers from reservoirs to reservoirs, with the approaches required to increase our understanding and improve models. Hashes indicate a lack of direct interaction between compartments (e.g. movement takes place through an intervening reservoir; see Figure 2).

	Surface	**Ocean floor**	**Sediment**	**Ice**	**Biota**	**Coastline**	**Water column**
Surface	Lagrangian modelling, field tracking experiment	Lab experiment/ modelling/ empirical	-	Modelling/ Field measurement	Field measurement / Spatial analysis	Lab and field experiments.	Lab experiment/ modelling/ empirical
Ocean floor	(Lab and field experiment)	Field experiment	Lab/ field experiment	Field experiment	Empirical sampling	-	Lab/ field experiment
Sediment	-	-	-	Field experiment	Lab experiment	-	Modelling/ experiment
Ice	Modelling	-	-	Modelling/ Field observations	-	Field observation	Modelling
Biota	Lab/ field	Lab/ field/ spatial analysis	Lab/ field/ spatial analysis	-	Field/ lab/ modelling	Lab/ field/ spatial analysis	Lab/ field/ spatial analysis
Coastline	Field, modelling	-	-	-	Field/ lab/ modelling	Field/ lab/ modelling	Field/ lab/ modelling
Water column	Lab/ modelling	Lab/ modelling	Lab/ modelling	-	Field/ lab/ modelling	-	Lagrangian modelling, field tracking experiment

1.1.3 Identifying key fluxes (movement between reservoirs)

There are five main fluxes that were considered to be of highest priority. Those are the fluxes that occur between the ocean (whether surface, water column or floor) and biota; movements between the ocean and the coast; movements from biota to the ocean, and the coast to ocean interface. The two reservoir fluxes considered to be of highest priority for increased understanding are those occurring between the ocean to coast and those occurring from the coast to ocean. Part of the driver for identifying the coast and ocean interfaces as important is that the nearshore environment is where most plastic must pass through to reach the open ocean. This is also a zone of high biodiversity and hence, where much of the biological impact is likely to occur.

This does not rule out the importance of ocean to ocean movement between reservoirs or movement between the surface and water column, rather it highlights the critical need for better understanding of movement between key reservoirs. Fluxes between ice and other reservoirs were considered to be of lesser importance, though there is agreement that modelling fluxes between ice and other reservoirs may not be particularly difficult.

It was widely believed that information can be gathered to evaluate fluxes between the ocean surface and water column, surface to coastline fluxes and litter in coastal reservoirs. In contrast, due to lack of data, fluxes from biota to the water column (and other reservoirs) would be difficult to constrain, as would be movement from the deep ocean. One of the main challenges is the disparity between what is recognized as the most important fluxes to understand, and our current knowledge not only of fluxes, but of the plastic residing in those key reservoirs.

Both for a mass balance modelling approach and to evaluate impacts, understanding of the accumulation of plastic in biota is needed. Importantly, this is a 'sink' where empirical data *can* be collected – whether through necropsies of deceased animals, through excreta, or with non-invasive sampling techniques. There is a growth in the number of papers reporting on the interactions between plastics and marine fauna (see Gall and Thompson 2015), with ingestion of debris, entanglement, and chemical contamination increasingly reported in the literature. It might now be reasonable to estimate microplastics residing in biota, but to date, an estimate of the overall mass of debris in wildlife has yet to be carried out.

1.2 Models of surface to surface fluxes

The most well developed area of research on the flux of plastics in marine systems is the flux between coastal regions and the surface layer of the ocean. This is in part due to the availability of models for representing the dynamics within this portion of the system, the availability of data, and relative ease of study. In the sections that follow, we focus on this portion of the system and dynamics.

1.2.1 Published Models

A number of models have been applied to predict the distribution of plastic debris in the ocean. The initial modelling effort by Maximenko *et al.* (2012) focused primarily on describing the distribution of plastics, using a particle tracking model which could represent the effects of surface currents. The Maximenko model (Maximenko *et al* 2012) applies a transition matrix approach, which is based on the probability of particle travel between ½° bins. These bins are calculated from trajectories of a historical global set of satellite-tracked drifting buoys (http://www.aoml.noaa.gov/phod/dac/index.php). In this model, microplastics are represented as a virtual tracer and they are advected through the ocean by iterating the transition matrix for 10 years. The Maximenko employs a uniform distribution over the global ocean as the source function. Results from this model showed a high concentration of microplastics builds up in the five subtropical gyres in 2-3 years. In this model approach, microplastics have the potential to persist for hundreds of years before washing ashore.

The Lebreton model (Lebreton *et al* 2012) uses ocean velocity fields from the 1/12° global HYCOM circulation model (httpo://hycom.org). Virtual microplastics are sourced from major river mouths proportionate to urban development within individual watersheds. This model considers coastal input as a function of coastal population. The Lebreton model releases microplastics continuously, in increasing amounts, based on the global plastic production data (sensu Plastinum 2009). Particles are advected by the ocean surface velocity field for thirty years.

The van Sebille model (van Sebille *et al* 2012, van Sebille 2014) advects microplastics in ocean currents captured in a transition matrix built from the trajectories of drifting buoys, in a manner consistent with the Maximenko model. Here, the source function is assumed to be proportional to the human population within 200 km of the coast, scaled to the amount of plastic waste available to enter the ocean, on a country by country basis in 2010 (based on Jambeck *et al* 2015). The van

Sebille model continuously releases microplastics at each coastal location for 50 years (1964-2014), increasing in time based upon global plastic production data (Plastics Europe 2013).

The three ocean circulation models treat microplastics sinks differently: the Lebreton and van Sebille models allow for *no* sinks (all released particles remain in the ocean indefinitely). In contrast, microplastics in the Maximenko model can "wash ashore" or beach when they enter grid cells with a shoreline. None of the three models allow for loss from the surface due to ingestion, biofouling or sinking. Furthermore, none of the three models incorporate fragmentation. Hence, they treat particle count concentrations similar to mass concentrations.

1.2.2 Integration with observational data and comparison among models

One of the major applications of the models described in section 1.1.4 is in providing a surface which can be used to interpolate the global distribution of plastics, given limited at-sea observations. Three research teams have taken this approach. Eriksen and colleagues (2014) use the model developed by Lebreton *et al.* (2012) to estimate there are more than five trillion plastic pieces in the ocean (or 66 thousand metric tons); Cozar and co-authors use a simplified surface derived from one of the models to estimate between 7,000 and 35,000 tons of plastic occurs in the open ocean (2014). However, on major uncertainty is the mismatch between the amount of plastic these models predict to be in the ocean and the estimates of annual input. Jambeck *et al.* (2015) estimate that between 6 and 12 million metric tonnes of plastic *enters* the ocean each year. The differences in approaches, reporting methods and data collection methods can make it challenging to understand the discrepancies in reports.

Recently, van Sebille and colleagues (2015, in press), compared estimates of microplastic abundance and mass using a rigorous statistical framework. In this paper, the authors standardized a large global dataset of plastic marine litter based on surface trawl surveys (of more than 11,000 samples). They also compared the three ocean circulation modelling approaches of Lebreton *et al.* (2012), Maximenko *et al.* (2012) and van Sebille *et al.* (2014), using each to estimate the global standing stock of small floating plastic litter. Importantly, they resolved sampling biases and other variations by applying a statistical model to standardize the dataset to appropriately scale the three model solutions. They compared where the models converge and identify regions where discrepancies need to be resolved between the modelling approaches.

The resulting estimates of plastic litter are roughly similar, which is very encouraging, given the methodological differences between the modelling approaches. However, the model solutions do vary, with estimates from 93 to 236 thousand metric tons of small floating plastic in the ocean, depending on the model used (van Sebille *et al.* in press). The variations in model solutions emphasize the under-sampling that persists in oceanic sampling of floating plastic, particularly in the southern hemisphere. The least well-sampled regions are those with low plastic concentrations – where models predict that anywhere from 30-70% of plastic particles may occur. Quantifying the densities in these regions will be critical for understanding the global load of plastic, and potentially for resolving the mismatch between the estimated annual input of 6 to 12 million tonnes per year, and the standing stock of only 236 thousand tons in total.

1.3 Critical Assumptions

1.3.1 Inputs to the Ocean

1.3.1.1 Recent approaches

As discussed in Sections 1.1.4 and 1.1.5, the representation of the sources of plastic inputs to the ocean has become more realistic with time. Early models, such as those of Maximenko *et al.* (2012) ignored the source dynamics altogether, starting with plastic particles uniformly distributed throughout the ocean. This is a reasonable starting point, if one assumes the system is largely an equilibrium one. In this case, the starting distribution of plastics is fairly irrelevant, as the strong dynamics of surface transport will rapidly erase the effect of the starting distribution. This model was successful in reproducing the general patterns observed, with the highest frequencies of plastic particles concentrated in the oceanic convergence zones (Maximenko *et al.* 2012).

1.3.1.2 Incorporating more realistic source dynamics

Subsequent modelling efforts, including Lebreton et al (2012) and van Sebille et al (2012), have used source functions that attempt to integrate information about land-based sources into the analysis. This is a critical improvement, as recent research has shown that there is significant variation in the expected inputs to the ocean (Jambeck *et al.* 2015). In particular, countries with large coastal populations, increasing incomes, and relatively underdeveloped waste management practices and infrastructure are predicted to make disproportionately large contributions to the plastic input to the marine system.

Given that the predicted input to the ocean, 6-12 million tons per year, is substantially larger than the predicted standing stock in the ocean, 236 million tons, it is very likely that the underlying dynamics of marine debris are very far from the equilibrium assumptions initially used in modelling the system. This non-equilibrium nature suggests that consideration of both source dynamics and the possible sinks for inputs of plastic from land will be critical considerations in developing accurate models for the dynamics of marine debris. Ultimately, the mismatch between the estimates of the standing stock of plastic in the ocean and the annual inputs suggests that the ocean may represent a transitory state for plastic, not storage location.

1.3.1.3 Current state of the Art

The most recent modelling analysis of the plastic distribution in the global oceans, by van Sebille *et al.* (in press) utilizes the plastic losses to the ocean from Jambeck *et al.* (2015) to scale the estimated inputs by country in simulating the distribution of plastic. This scaling accounts for the differential inputs by country, however, it is important to keep in mind that this approach does not use the actual input volumes from Jambeck *et al.* (2015), but instead scales the inputs in the same relative way across countries. The resulting predicted distribution of plastics in the ocean is then scaled using a dataset of over 11,000 at-sea observations which has been standardized statistically to remove effects of sampling conditions such as wind, year, and other factors and to address sampling variation across sites. This rescaled surface is then used to estimate the distribution of plastics at the global scale, and by integrating across it, the standing stock of plastics in the oceans.

1.3.2 Transport only by surface currents

All three of the existing models of plastics transport and distribution developed to date (Maximenko et al 2012, Lebreton *et al.* 2012, van Sebille *et al.* 2012) use surface currents inferred from a variety of sources to simulate transport of plastic particles in the ocean surface layer. These models, and the more recent expansions, have generally ignored wind forcing on floating plastics, aside from that encapsulated in the surface currents. They have also ignored wave transport, or Stokes drift. Wave transport could be relatively important, particularly near coastal regions where wave transport will be consistently toward shore, and thus transporting material out of the marine environment. The models have also ignored direct wind transport, which is potentially relevant for items that are larger and more buoyant. During high wind events these items may actually be lofted by waves and subsequently transported in the air, largely loosing contact with the water. This effect would presumably be biased toward larger and more buoyant items, due to both their chance of leaving the water surface and the cross section exposed to the wind.

There is some evidence to suggest that wind and Stokes drift are important, particularly for larger particles. Evidence from surveys of marine debris off Africa and Japan suggest that the size distribution of items decreases in samples further from shore (Isobe *et al.* 2014, P. Ryan, pers. comm.). In some cases this has been attributed to biofouling, which shows some sign of being more important on larger items (P. Ryan, pers. comm.). However, modelling and analysis in the Japanese case both suggest this is probably due to increased shoreward transport of larger items, fragmentation due to wave, wind and exposure to sunlight in shallow coastal regions, and subsequent oceanward transport of larger items (Isobe *et al.* 2014).

It is also worth noting that to date most analysis has focused on floating plastics. However, approximately 2/3 of plastic produced is negatively buoyant. This material likely follows very different trajectories, either remaining concentrated around sources such as stormwater and sewer outfalls, coastal sites, and areas of high vessel traffic. There is some possibility of transport by currents, and in particular tides in coastal margins, however, there has been little investigation of this negatively buoyant material to date, and even less work on its transport and fate.

1.3.3 Sensitivity to Assumptions about particles

Model tracking of Lagrangian particles requires decision making regarding a number of choices with respect to particle traits. These include the buoyancy (density) of the particles, windage of the particles, the size and shape of the particles, and the extent to which wave action (Stokes drift) affects them.

So far, there has not been a comprehensive modelling study on the sensitivity of the particle pathways to these traits. It is therefore unclear which of the traits are the most important to incorporate and which may be less important to consider. While the answer to the trait importance ranking will depend on the question/process being investigated, it would be insightful to perform such comprehensive modelling studies for a few selected tracking scenarios. These can include different scales (local to global, weeks to decades) and source functions.

A comprehensive set of sensitivity studies can help guide research priorities into parameterisations of particle traits, similar to approaches used to evaluate the historical movement of plankton (van Sebille et al, 2015). In this case, the authors quantified the lateral distance that planktonic species can move, incorporating regional variability based on surface currents and variations in surface current movements (van Sebille *et al.* 2015). They further included life history traits of the target species such as depth, sinking speed and lifespan. Such approaches can also be applied to particle tracking of plastics whereby plastic traits, rates of degradation/breakdown, likelihood of ingestion and other 'behaviours' can be incorporated.

1.3.4 Lack of feedback from particles

Almost all plastic particle modelling to date assumes that particles carried by ocean currents do not in turn feed back on these currents. It is this assumption that allows for offline particle tracking. However, the validity of this assumption is not entirely clear. There are myriad factors that influence particle movement. The behaviours of microplastics in the ocean have recently been reviewed, focusing on physical, chemical and 'bio' behaviours of plastic (Wang *et al.* 2016).

There is some literature suggesting that plankton has an effect on ocean circulation through shading. As sunlight penetrates the upper few meters of the ocean, it matters for the stability of the water column how deep that sunlight is absorbed. If there is suspended matter in the upper ocean (plankton, and possibly also plastics), that changes the penetration depths, and thereby the stratification of the upper ocean.

It is as of yet completely unclear whether this shading by plastics has a discernible effect on the ocean. However, if it turns out that plastic does shade sunlight on scales that matter, this means that particle models might need to be run online, so that they can feed back on the hydrodynamic model itself. Whether these 'active particles' are needed should be further investigated.

1.3.5 Losses of particles from the system

None of the global scale models published to date represent the loss of particles from the system in any detail (Maximenko *et al.* 2012, Lebreton *et al.* 2012, van Sebille *et al.* 2012, van Sebille *et al.* in press). In fact, two of the three large scale models do not incorporate loss of particles at all (Lebreton *et al.* 2012, van Sebille *et al.* 2012, van Sebille *et al.* in press). Given the significant mismatch between the estimated standing stock of no more than 230 thousand tons of plastic, and the estimated annual input of 8.4 million tons, Cozar et al (2014) attempted to estimate the losses from the system, and the sink to which they are moving. These authors conclude that the most likely sink is settling to the benthos, due to biofouling (Cozar *et al.* 2014). However, the patterns of benthic plastic distributions appear to reflect local deposition around sources, such as areas of fishing, coastal urban regions, and river outlets (Corcoran 2015). There is some evidence that coastal regions may be a major sink, in particular given the shoreward bias of wind transport (Isobe *et al.* 2014, Kako *et al.* 2014). Experimental studies suggest similar results, with substantial local retention near coastal sources (Carson *et al.* 2013). There has also been some suggestion that the biota may be a sink for debris (Cozar et al 2014). There are a wide range of studies suggesting significant levels of debris ingestion across hundreds of species (Gall and Thompson

2015), from zooplankton (Deforges *et al.* 2015) to whales (Fossi *et al.* 2012), it is not clear if this biological reservoir is significant in terms of the unaccounted for losses in the system.

2 Expert workshops on modelling marine debris

2.1 Purpose of the workshops

The objective of the work undertaken is to increase awareness on marine litter by reviewing the state of knowledge and to apply modelling approaches to identify sources, sinks, distribution and movement of marine litter, including microplastics. The aim of this increased understanding is to increase our ability to identify key areas where new data will be most informative, to make recommendations that will facilitate an improved understanding of plastics movement, sources, fate and distribution, and to employ tools that can help to identify important geographic regions where increased sampling would be of benefit.

At the two workshops, we set out to summarize the current state of knowledge (based upon the expertise of the participants (see Appendix I) in order to inform and outline key areas in need of further research. By focusing on identifying the state of knowledge across the globe, we can better discern gaps in knowledge, such as the perceived gaps in regions such as the Caribbean, South Pacific and Eastern Africa.

We specifically brought together experts from around the world whose research focuses on oceanographic modelling. This is because this UNEP sub-project aims to apply modelling approaches to consider the broad spectrum of marine plastic debris (from mega, macro and meso to micro and nano, following NOAA definitions), given that particles break down from large to small and they will have different physical and chemical effects on a wide variety of organisms. Furthermore, pathways and fates may differ, depending on the size and properties of the plastics themselves.

2.2 April Workshop Summary

Immediately following the GESAMP microplastics working group meeting hosted by the Food and Agricultural Organization campus in Rome, Italy from 20-23 April, 2015, CSIRO organized a one day modelling workshop which included some of the participants of the prior (WG42) working group.

The modelling workshop was associated with the UNEP/CSIRO collaboration project '*Modelling and monitoring marine litter movement, transport and accumulation*'.

The following participants contributed to the one day workshop which took place on Thursday, 24 April 2015 (Table 2).

Table 2. Workshop participants, April Modelling Workshop 2015

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The objective of the one day workshop was to identify approaches, knowledge gaps, and data required to increase awareness on marine litter. The day's conversation began with participants reviewing the state of knowledge and discussing the utility of combining empirical data with modelling approaches to identify sources, sinks, distribution and movement of marine litter. While some of the conversation focused on microplastics, we discussed that we are not solely focused on microplastics, but that they are an important component to consider. We brainstormed about key areas where new data will be most informative, as well as the types of (and priority for) information that would be optimal for improving our global, regional and local understanding of marine litter movement.

The workshop was structured with an introduction about priority questions, approaches to address the issue, and the data required to answer key questions. The discussion then moved to the utility of applying models to test hypotheses, and particular mention was made of the advantage of having empirical data against which to compare model outputs.

There was vigorous discussion about the utility of models, their appropriateness, information that could be used to improve model accuracy, and the need for integration of models in space, time, and depth. Importantly, it was noted that while models will not tell us where the plastic is, they can be used to interpolate and predict where things are going (e.g. inverse modelling).

It was highlighted that there is little information on fragmentation, but that understanding fragmentation processes is clearly importantly. Fragmentation is a function of wind speed, solar UV radiation, and other physical processes. The question was raised about what do the factors that affect fragmentation do to the size distribution plastic. We discussed looking at the spatial distribution of different sized fragments (the size spectra), specifically asking *where do we find large vs. small fragments?* It was acknowledged that there are quite sparse data on both buoyant floating plastics and on the vertical distribution of plastic debris (particularly for micro and nan-sized particles) and this was identified as an important knowledge gap to fill.

It was also discussed that if sources and sinks are known and models are overestimating sinks, one could perform inverse calculations to look at how much biofouling is required to have model solutions match what is actually observed. Furthermore, a focus on *processes* was identified as fundamental. To make the most effective use of models requires knowledge about litter inputs, flows and outputs (e.g. the mass conservation problem identified in Thompson's 2004 Science paper entitled "Lost At Sea: Where is all the Plastic").

It was worth pointing out that we want to consider checking assumptions. For example, do polymers change specific gravity? Putting in the appropriate caveats is important, but is not something to preclude doing the work. In some regions more than in others, this sort of detail may be more important. For example, there are good data from Korea and the Mediterranean. For carrying out modelling work at regional or subregional scales, need to consider other sources outside of those regions.

One of the identified gaps is the need to develop a clear theoretical model which explicitly considers the 'black boxes' and gaps. This would be useful to also explain to users the complexity of problem. Within such a theoretical model it would be good to include both two and three dimensions and incorporate upwelling, down welling, and other important processes that affect movement, distribution and fate of plastics in the marine environment.

The importance of quality data was mentioned throughout discussions, as was the importance of communicating clearly. One example of this is with the terminology 'hotspots' and 'accumulation zones'. Hotspots, rather than accumulation zones are something that UNEA would consider as high priority (e.g. Gulf of Biscay, Caribbean, etc.). Hotspots are regions that may be considered higher priority than gyres. Hotspots may be associated with proximity to source, however, some are in transition regions and others may be accumulation zones.

Communication will be most effective when targeted appropriately. There are opportunities for science and outreach, and integrating the two is perceived as positive. There is also a need for different tools and communication strategies for scientific vs. lay audiences. Considering how data are presented is important. For example, maps can leave a lasting impression that may not always be entirely correct, but they are powerful means of displaying and imparting information. While it is worth showing accumulation areas (gyres) as those areas where particles will always go, it is also appropriate to note the dynamic nature of accumulation zones.

Emerging issues that were identified by participants included:

- The need to better **understand ageing, fragmentation and biofouling**. There are some experiments being carried out to look at fragmentation (Delft, Netherlands) and incorporating modelling work with fragmentation and biofouling experiments.

- The need to **evaluate the likelihood of deep sea bacteria to consume plastics**. A team of scientists in Brazil are running an experiment at depths of 1500m and 3000m. Samples are sitting on the bottom for a year in an oligotrophic environment, off the Brazilian coast. The question being addressed is whether, and at what rates, do bacteria consume oil (in the form of plastics).

- The need to **identify the appropriate data for use in assessments**. Is it appropriate to use reports and grey literature or do you restrict assessment to peer-reviewed journal articles?
- The importance of **taking lessons from other ocean movement research** which is rigorous and has applicability to modelling litter movement. For example, lessons can be learned from larval dispersal models, as similar processes take place. Larval movement is likely also driven by tide and wind direction, storms, and bathymetry, shoreline, and other processes that affect litter movement). Investigating similarities and differences in approaches could inform debris model transport.
- The importance of **the nearshore zone needs to be more fully considered**. Typically researchers ignore the zone between shore and 25km or 50km offshore due to lack of data in global models. Global models are poor at incorporating regional processes, and current regional models cannot be scaled to global.
- **Vertical and temporal resolution is an issue** with our current movement/transport models.
- There are also **opportunities to engage with citizen scientists**. There is a group called ‘Sailing with a Purpose group’ which engages with ca. 30 boats around the world. Sailors are taking photos of the water to look at chlorophyll. A similar approach could be used to look at debris as well. Kara’s data has huge variability in sampling/concentration. Can’t model on a global scale.
- **Ideally there would be a global model that is useful, sufficiently detailed, user-friendly and accessible to countries, governments, researchers and citizens around the world.**

In discussing potential data types and sources to explore, potential approaches or research groups with whom to engage might include:

- Data from/groups working on larval dispersal or iceberg movement models.
- Data from/groups working on mercury transportation in biota.
- Data from/groups working on extreme event models (e.g. GNOME NOAA model used for tsunami response).

Some key challenges and opportunities include:

- Many current models retain all particles (e.g. there is no loss; ADRIFT). While it may not be difficult to take into account sinking, fragmentation, and other processes, models such as ADRIFT require data/parameterization to make these improvements.
- There are data gaps in many models due to areas with no or poor drifter data.
- Many of the current models include surface drifters only.

- Time series resolution needs to be appropriate for the question/region being studied, particularly in light of the importance of seasonal variability in litter movement and deposition.
- Models such as ADRIFT are flexible. For example, sources can be added to the model, can be labelled tracked and followed.

One of the first and most significant improvements would be to add a loss term to look at losses in the environment. One of the big ‘black box’ areas in this work is in suspension/resuspension rates back on shore. The question raised was *can we establish a reasonable loss term for coastal regions*? If so, what would be required? Adding a loss term would be an improvement and having data from standing stock surveys to look at the *Coast-Ocean-Coast* (C-O-C) suspension and resuspension would be critical.

Additional information required might include data on:

- Wind and Tides.
- Forcing models and advection models.
- Removal terms.
- Rates and/or frequency of active biofouling (whether due to plankton concentrations or other processes).
- Solar radiation.

To improve modelling efforts, the ideal situation would include having a comprehensive list of datasets that can be used. These data sets would be geographically dispersed, long term, and with a high frequency of data collection. Addressing the C-O-C knowledge gap was identified as an area of great interest that would yield new insights.

To address the C-O-C knowledge gap, one way forward would be to have a transfer function from the coast to ocean and back again. Perhaps the best way to incorporate this into existing models is to find a few locations where there are long term data of coastline litter stocks. Analysing such an empirical data set, coupled with relevant covariates (wind speed, direction, tides, etc.) would be useful. The ideal data set would be a long time series with frequent sampling intervals.

Specific datasets that may be useful for modelling plastic movement include:

- ➢ The North Sea fisheries data. There is a high quality long term dataset from the North Sea Fisheries. With records of bird nests that contain fishing debris. Fisheries will be important to include as a source of plastic debris in the ocean.
- ➢ Midway and Tern Island both ran long term experiments and there are approximately 20 years of coastal debris data where they performed bi-weekly cleanings of sites. There has been a time series analysis to look at when debris arrives on shore (given the population of the islands). Extreme events appear to drive debris deposition and there are non-linear processes that result in local deposition
- ➢ OSPAR long term dataset

- NOAA data may be suitable (long term time series with high frequency and reasonable geographic spread).
- NOPAC region data
- Japan data
- Korean data from OSEAN

The meeting finished with a discussion of potential participants for the second workshop, as well as logistical considerations of dates, travel and duration.

2.3 August Workshop Summary

The second modelling workshop was a multi-day workshop associated with the UNEP/CSIRO collaboration project '*Modelling and monitoring marine litter movement, transport and accumulation'*. The workshop was held at UNESCO offices in Paris, France from 31 August - 3 September, 2015.

The following participants contributed to the workshop (Table 3). See Appendix IV for the workshop agenda.

Table 3. Workshop participants, Aug/Sept Modelling workshop

Name & title	Affiliation	e-mail
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Dr. Chris Wilcox	CSIRO	chris.wilcox@csiro.au
Ms. Heidi Savelli	UNEP	Heidi.savelli@unep.org

* Remote participation via skype

The workshop started with an overview of UNEP and GESAMP activities which was provided by Heidi Savelli. This was followed by introductions by each participant, a reminder of the goals of the multi-day meeting, and a potential roadmap for discussions.

This modelling sub-group aims to provide content that contributes to a larger body of work that will inform the UNEA report. As such, a main goal of the workshop is to identify gaps and key areas on which to focus future research needs and directions, while providing information about the state of knowledge, challenges and opportunities.

Generally, those participating in the workshop focus on larger scale models of marine litter movement (at the global or large geographic regional scales). It was acknowledged that this research focus may result in a bias in perspectives.

Overall, the group was united in the view that there are two ultimate goals: to **improve our understanding of plastic budgets and impacts of marine debris**. Identifying where, how and why plastic enters (and leaves) the ocean is very different than understanding the biodiversity, economic, and environmental impact plastic is having in the marine environment. With an understanding and evaluation of budgets and impacts, however, there is the opportunity to develop a policy responsive. Importantly, whereas modelling may take place at a global or regional scale, waste management policy happens at small spatial scales. Striking a balance between the spatial scale at which the research takes place and the scale at which policy decisions occur requires thinking about outcomes and impacts at very different scales.

The marine litter problem is a source, pathway and sink issue. If there is a clear understanding of each of these three, there is no need for models. Where, however, there is a knowledge gap in any of three, models can aid in the resolution. Essentially, modelling can act as a hypothesis testing tool. There are multiple modelling approaches that can be (successfully) employed to confront a problem and achieve resolution. Clearly identifying the region, focal question, key issues and what the modelling aims to achieve is a fundamental first step.

It was highlighted that improvements can be made in process models, but it is useful to consider whether improvements are worth the effort in areas where there may be insufficient or particularly noisy data. Some of the noise at large scales can be smoothed if the aim is a mass balance (whereby the noise becomes a statistical anomaly).

There was significant discussion around the key issues, with a focus on the following questions:

What are the sources?

- What is the source of the litter or microplastic?
- Is the plastic or microplastic primary or secondary microplastic?
- In absence of knowledge of sources, can we model the behaviour of microplastics from coast to ocean and back to coast?
- What are the rates of inputs to ocean (better empirical estimates).

How does it move?

- How can laboratory experiments improve models of plastics in the oceans?

- On what time/spatial scale do we need information to be able to address issues of risk or harm?
- What improvements can be made on litter budgets and losses in the marine environment?
- What are rates of fragmentation?
- What is the/are the buoyancy/sinking/re-floating rates?
- What are the priorities in understanding movement through the ocean?

What is the fate?

- Where are the plastic reservoirs?
- What is the impact or harm that results?
- How can we apply knowledge gained for policy impact.

Central to improving our understanding at all scales, and in relation to each of the priority research actions identified remained the core question: Would it be possible to have a *global, centralized data repository* where data could be made available? The group did not extensively focus on what that might look like, where it might be hosted or the permissions that would be required for use, rather the group noted the utility of such a data repository. Such a repository could be utilized not only for researchers, but for countries, governments and policy makers.

Reservoirs: Where does plastic occur?

Plastic occurs throughout the ocean from the surface, throughout the water column to the deep ocean floor. It can reside in sediment, biota, and ice, and may be trapped along the coastline or in estuaries, waterways and lakes, and can be trapped in the atmosphere. The reservoirs deemed most relevant for modelling movement of plastics in the ocean includes the following compartments: surface, coastline/estuaries, ocean floor, sediments, ice, biota and water column. While it was acknowledged that there are other reservoirs (e.g. the atmosphere, lakes and waterways), those were considered to fall outside of the current scope and focus.

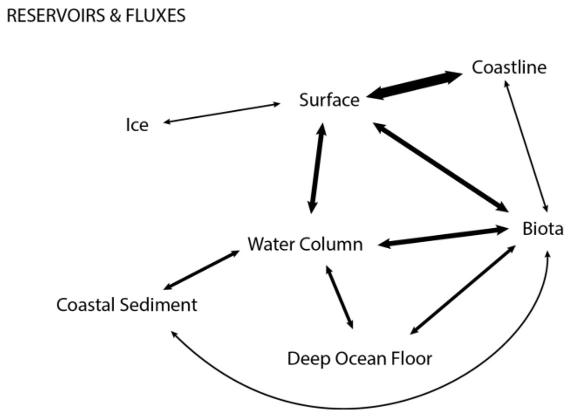


Figure 2. Schematic representation of reservoirs and fluxes for marine plastics. The weight of the arrow indicates the magnitude of marine debris flux hypothesised to occur between compartments, and the fluxes or flows between them.

Evaluating budgets (losses, sources and sinks into the environment) or leakage between these reservoirs or compartments requires understanding several key processes. Those highlighted as particularly important include rates of fragmentation, buoyancy/sinking/re-floating rates, as well as the rates and quantities of inputs of litter to the ocean and time trends for plastics in ocean.

When assessing the reservoirs, identifying in which reservoirs there is the greatest uncertainty will facilitate a ranking of transitions on which efforts could be focused, taking into account the key question (whether that relates to sources, losses between transition zones or impacts).

Table 4. Transfers from reservoirs to reservoirs, with the approaches required to increase our understanding and improve models. Hashes indicate a lack of direct interaction between compartments (e.g. movement takes place through an intervening reservoir; see Figure 2).

	Surface	**Ocean floor**	**Sediment**	**Ice**	**Biota**	**Coastline**	**Water column**
Surface	Lagrangian modelling, field tracking exper.	Lab exper./ modelling/ empirical	-	Modelling/ Field measure.	Field measure./ Spatial analysis	Lab and field exper.	Lab exper./ modelling/ empirical
Ocean floor	(Lab and field exper.)	Field exper.	Lab/ field exper.	Field exper.	Empirical sampling	-	Lab/field exper.
Sediment	-	Field sampling of ocean floor sediments	-	Field exper.	Lab exper.	Monitoring /sampling of sediment cores	Modelling/ exper.
Ice	Modelling	-	-	Modelling /Field obs	Field obs	Field obs	Modelling
Biota	Lab/field	Lab/field/spatial analysis	Lab/field/spatial analysis	Field obs	Field/lab/ modelling	Lab/field/ spatial analysis	Lab/field/ spatial analysis
Coastline	Field, modelling	-	Coastline monitoring for sediments	-	Field/lab/ modelling	Field/lab/ modelling	Field/lab/ modelling
Water column	Lab/ modelling	Lab/ modelling	Lab/ modelling	Field obs	Field/lab/ modelling	-	Lagrangian modelling, field tracking exper.

Identifying key fluxes (movement between reservoirs)

There are five main fluxes that were considered to be of highest priority. Those are the fluxes that occur between the ocean (whether surface, water column or floor) and biota; movements between the ocean and the coast; movements from biota to the ocean, and the coast to ocean interface. The two reservoir fluxes considered to be of highest priority for increased understanding are those occurring between the ocean to coast and those occurring from the coast to ocean. Part of the driver for identifying the coast and ocean interfaces as important is that the nearshore environment is where most plastic must pass through to reach the open ocean. This is also a zone of high biodiversity and hence, where much of the biological impact is likely to occur.

This does not rule out the importance of ocean to ocean movement between reservoirs or movement between the surface and water column, rather it highlights the critical need for better understanding of movement between key reservoirs. Fluxes between ice and other reservoirs were considered to be of lesser importance, though there is agreement that modelling fluxes between ice and other reservoirs may not be particularly difficult.

It was widely believed that information can be gathered to evaluate fluxes between the ocean surface and water column, surface to coastline fluxes and litter in coastal reservoirs. In contrast, due to lack of data, fluxes from biota to the water column (and other reservoirs) would be difficult to constrain, as would be movement from the deep ocean. One of the main challenges is the disparity between what is recognized as the most important fluxes to understand, and our current knowledge not only of fluxes, but of the plastic residing in those key reservoirs.

Both for a mass balance modelling approach and to evaluate impacts, understanding of the accumulation of plastic in biota is needed. Importantly, this is a 'sink' where empirical data *can* be collected – whether through necropsies of deceased animals, through excreta, or with non-invasive sampling techniques. There is a growth in the number of papers reporting on the interactions between plastics and marine fauna (see Gall and Thompson 2015), with ingestion of debris, entanglement, and chemical contamination increasingly reported in the literature. It might now be reasonable to estimate microplastics residing in biota, but to date, an estimate of the overall mass of debris in wildlife has yet to be carried out.

Progressing our knowledge

Modelling efforts have greatly improved in recent years, and as computing power increases, so too does our ability to incorporate additional parameters into marine debris modelling. There are presently a variety of modelling approaches available, including circulation models, risk models and bioaccumulation models (ecosystem scale modelling). Each has a relevant role to play in increasing our knowledge and understanding of marine litter transport, and the development and employment of different modelling approaches depends upon the question asked, the region studied, and the overall aim of the research.

One of the advantages of applying modelling approaches to the marine litter issue is that modelling can allow us to apply a variety of approaches at a multitude of scales. With models we can focus on major drivers at a global scale that can scale down to consider local processes. There currently exist global data on wind, tides, waves, pressure and other processes that are identified as critically important. These global data can be scaled down to achieve model solutions at more local scales. While there may be some loss in resolution through such scaling, these approaches will nevertheless improve our ability to map risk – and impact - to marine biota, regions, and ecosystems.

Where possible, researchers should aim to validate models with independent data. Independent validation of models can be used to not only increase model utility and confidence in results, but also increases our understanding of uncertainty. Quantifying, and indeed, acknowledging uncertainty in model solutions can help identify research opportunities and key knowledge gaps. Validating models against empirical data may also yield greater insights to processes, highlight regions or taxa of greater (or less than) predicted risk, provide additional opportunities for policy impact, as well as improve model calibration.

It is generally recognized that coastal areas are especially important due to much higher space and time variability of atmospheric and oceanic conditions, frequent erosion and sedimentation processes, anthropogenic activities (especially fishing), sewage discharge, use of beaches for recreation, presence of industries that manufacture plastics, transport of materials by large vessels, boats maintenance and cleaning, and several engineering operations, like dredging and marine building. Preferably, coastal models will have very high spatial resolution (e.g. 10 m in the horizontal and less than 1 m in the vertical) and include the parametrizations of several bio-geo-chemical processes (such as fragmentation and beaches deposition). Ideally, the time scale would consider short-term effects (periods of few minutes) up to seasonal and decadal variabilities. Interactions with atmosphere, rivers, land and deep ocean areas would all ideally also be included (as highlighted previously). While the general view is that the greater the resolution the better, the importance of acknowledging the significant contributions to be made with poorer resolution (both vertically and horizontally) cannot be overstated.

Tracing plastics to their sources is often highlighted as critical. This can be difficult in part due to variability between and within regions, which is often greater than realized. Models can, however, be tuned to consider empirical data collected in various regions (e.g. incorporating country, region or basin specific inputs, waste mismanagement and other covariates). Even in the absence of complete data (e.g. from all regions), including sparse or incomplete data can still prove valuable.

Overlapping spatial mapping (for example, with accumulation models) with species distributions facilitates our ability to quantify the risk of plastics to biodiversity and marine ecosystems. Dynamically modelling of the risk or impacts becomes critically important not only for individuals and populations, but also for marine species that are exposed to multiple threats to survival and persistence. Identifying key geographic regions and taxa at higher or lower threat from marine plastics (e.g. Wilcox *et al.* 2015; Schuyler *et al.* 2015) can provide a useful lever to drive policy.

2.4 Key Challenges and Recommendations

Workshop participants identified a number of challenges and knowledge gaps and made specific recommendations to improve our understanding of marine litter movement and for marine litter monitoring. The recommendations from the workshop participants include various aspects of litter inputs, plastic movements, impacts to biota and opportunities for policy impact.

Some challenges and specific recommendations

Data gaps remain a significant challenge. While there do exist some large datasets of floating marine litter, for most regions there are **no data for longer time frames** (e.g. 30 years or more). The recommendation is to have *repeated sampling in consistent areas over a large geographic expanse and for decades* would provide significant opportunities to increase our understanding. In the north Pacific and north Atlantic there may be sufficient data, but generally, there are data limitations.

There are currently data from surface trawls, beaches/coastline through coastal clean ups and other efforts, sediment cores, riverine inputs and other sources. However, many or mo*st studies are limited in time and space* due to resources, time and other logistical constraints. *Making use of proxies* for areas in which data are lacking can improve model solutions and is an approach that has been under-utilized. Further exploration of the use of proxies in combination with statistical and process models (particularly considering missing data) will undoubtedly prove useful.

While data gaps remain a challenge, there are untapped communities who can (and are eager to) contribute to fill data and knowledge gaps. Public participation in scientific research (citizen science), has long been used to tackle research questions that would otherwise not have been addressed due to lack of resources, time or geography. These *citizen scientists can play an integral part in scientific data collection* and may include beach goers, recreational sailors, SCUBA divers, school groups, corporate groups and other interested members of the public. Using data on population density and waste mismanagement will facilitate model projection over the next century and can be ground-truthed with empirical data from a subset of sites with repeated surveys through time. Even something as simple as asking people to weigh or count litter collected from cleaning activities or fishing for litter programs would significantly contribute to fill a critical knowledge gap. We do suggest that such activities include surveys not only 'hot spots' or accumulation zones, but also areas that do not have a high density of litter.

To date, there has been a **lack of standardized reporting**. Consistency in reporting could be achieved via a centrally hosted website with open source, freely available methodology and datasheets. Hotlinks to other research projects applying particular methodologies would also increase communication. Improved reporting would improve our ability to compare between types, sources, quantities, around the globe.

It is widely acknowledged that there is **uncertainty in the Coast-Ocean-Coast zone.** This coastal and off/nearshore mismatch is of potentially greater concern than the finer resolution details in the models. If there is a significant over – or under – estimate of how much litter is entering the marine environment, bounding those estimates and the uncertainty around them would be useful. Currently, models typically fail to present uncertainty and to date, model solution assume there are not transitory dynamics along coastal regions (as well as within or among countries or geographic regions). Incorporating uncertainty and transitory dynamics in the C-O-C through scenario modelling will provide a tremendous advance that would likely enable significant policy engagement.

Air pollution is potentially a significant source of pollution, particularly for micro and nano plastics (textiles, manufacturers, etc.), but most model efforts to date fail to consider atmospheric deposition. Experiments, identification of monitoring sites and inclusion of air pollution as a contributor to microplastics would be of benefit. Furthermore, establishment of monitoring sites around the globe would facilitate the identification of important sources, the documentation of which is an important step in regulation.

Few studies have considered the **interaction between climate change and plastics**. Ocean currents are changing, migration routes and species distributions are changing, so understanding the interaction between climate and plastics may be particularly relevant for understanding impacts to biodiversity. For example, as the ocean's surface warms more quickly than does the deeper ocean and there is greater density contrast, this may require consideration. In the arctic, it may be that there is more plastic entering and then recirculating. While there has been some discussion of plastics trapped in or stored in ice, there has been relatively little discussion on the new habitat availability on plastics (plastisphere). Modelling efforts that specifically address plastics movement between compartments with consideration of changing temperatures and associated processes will improve our predictive ability particularly for risk to wildlife. Would more buoyant plastic polymers occur at the surface due to vertical differentiation? If so, this would result in differential availability for surface feeding species? These are some of the challenging questions. The vertical distribution of plastics may be particularly important to visual predators (turtles, fish and some seabird species). If winds increase as well, that may drive additional mixing.

The risk that plastic pollution poses to marine fauna is still poorly understood. **Evaluating the effects of plastic contamination on the food chain and environment is difficult**, but necessary. A combination of *modeling and experimental approaches* (including meso or microcosm experiments) would be useful here. Experiments could provide needed data on endpoints that correlate to energy (e.g. growth, mortality and reproductive output); and DEP modelling (dynamic energy budget modelling) can be employed to look at effect of productivity on trophic levels of the food chain).

We still know relatively little about the impacts of pollutant concentration in and on plastics and the associated effect on marine biota. **Plastics** may contain, **accumulate and carry pollutants**, inserted as additives or absorbed by the environment, which may act as soon as they are delivered to organisms. These plastics accumulate in oceanic and coastal areas and can be ingested by marine fauna in coastal, benthic and pelagic zones. However, the risk of such ingested material depends on the type, size and amount of plastic present in the environment, the presence of contaminants in plastic and contact with sensitive biota. Additional *experiments to evaluate pollutant assimilation, accumulation and transport between tissues* are needed to more fully quantify ecological risk at individual, population and species levels.

Other significant opportunities that can aid in advancing the state of knowledge include *environmental accidents* and *extreme weather events*. Taking advantage of such can be fruitful. Environmental catastrophes or similar occurrences can be used to train or improve models as they provide opportunities for large scale 'natural' experiments. Further opportunities exist with creative thinking. For example, combining oceanic plastic movement models with shipping data and fishing effort data could be used to better estimate and quantify at-sea losses into the ocean and community level surveys to address waste management, flows and loss rates from coastal communities can be applied to tune models with respect to the coastal component.

Overall, it was highlighted that research should relate small to large-scale sampling, monitoring and modeling, considering:

1) Identification of plastic sources in coastal areas.

2) Cataloguing historical and recent releases.
3) Regular and permanent monitoring.
4) Standardization of sampling methods.
5) Coverage of known impacted and not impacted sites (standardized random sampling).
6) Measurements in the atmosphere, rivers, sandy beaches (surface and deep sampling), sea surface and water column, sediments (surface and below.
7) Implementation of several data banks on plastic data recording and dissemination, (single data bank that is mirrored in multiple sites).
8) Use of circulation and tracking drifters models.
9) Improvements on the representation of plastic bio-geo-chemical processes in the models.
10) Analysis of plastic concentration transfer from atmosphere – land – ocean – sediments compartments.
11) Standardization of modeling techniques, including time and space resolutions, (perhaps use particular sites with detailed information to inform particular models).
12) Model results validation and model calibration.
13) Use of inverse lagrangian models to detect potential sources of plastics: using hindcasting to see where things come from. A main point of consideration is not to be deterministic to appreciate stochastic processes).
14) Evaluation of the influence of climate change in the plastic dispersion.
15) Integrate expertise of several scientific areas (e.g. ecology, medical, other fields, chemists, ecotoxicologists into discussion).
16) Evaluating the effects on plastic contamination on the food chain and environment. Experimental approaches would be useful here, use DEP (dynamic energy budget modelling to look at effect of productivity on trophic levels of the food chain). Can do some experiments for this – what is needed is data on endpoints that are related to energy (growth, mortality, reproductive output).
17) Use of biomarkers as indicators of toxic effects.
18) Estimates of contamination on sandy beaches by Persistent Organic Pollutants (POPs) and heavy metals due to plastic dispersion.
19) The utility of including scenarios about potential environmental risks.
20) Multiple means to effectively dissemination data and model results (e.g. science communication).
21) The need to inform and support governmental policies on pollutants control.

Experimental research would also benefit from:

1) Laboratory experiments, particularly those which focus on fragmentation rates.
2) Experiments (whether lab based or in situ) to look at sinking rates.
3) Field particle tracking experiments are required to improve model fits of geostrophic currents, stokes drift, wind waves, windage, water drag.
4) Exploration of fine resolution satellite observations to increase knowledge of surface currents.
5) Strandings-release experiments (standing litter stock monitoring) for coastal exchanges.
6) Toxicological impacts experiments to evaluate risk and impacts to biota.
7) Experiments to quantify ingestion, filtering and transport from biota to compartments.
8) Field experiments to document atmospheric deposition.

In summary, our understanding of litter sources, fate and movement is rapidly increasing. This is an exciting time in marine debris research as it is a growing field that can adapt, integrate and benefit from learnings in other related research areas. While there remain a number of knowledge gaps with respect to marine litter modelling, there are significant advancements that can, and are, being made in our understanding. Importantly, many of these advancements are being applied to underpin and inform policy and decision making at several scales, and we are seeing an increase in a collaborative approach to addressing the issue. While global plastic production continues unabated, the public's interest in and appetite for engagement through volunteering and citizen science can be provide both broad and deep opportunities for data collection, outreach and behavioural change.

3 Monitoring marine litter

The stock of plastics in the ocean can roughly be divided into five non-overlapping compartments. Plastic can be on or near the ocean surface (including the mixed layer), on the seafloor, on shorelines, in the water column, and finally in biota. The physical and chemical processes acting on the microplastics in each of these reservoirs are different, and the risks and opportunities for mitigation might also be very different. Separating the total stock of plastic into these five compartments will therefore help better understand the location of hotspots, and the processes that lead to their formation.

With the exception of perhaps the surface ocean, there is a severe paucity in data on the amount of plastic in each of the compartments, and there is even less known about the fluxes of plastic between the compartments. Closing the global plastic budget will require large-scale, targeted sampling of all of the compartments. However, it may be possible to prioritize these investigations according to ease of sampling and likely important, based on our current understanding of their relative contribution to the total volume of plastic in the environment.

3.1 The ocean's surface

Of all the compartments, the surface ocean is probably best sampled. Decades of extensive plastic trawling data (Law et al 2010, 2014, Cozar et al 2014, Eriksen et al 2013, 2014) have recently combined in a global data set of more than 11,000 trawls (van Sebille *et al.* in press). While coverage of this data set is still strongly biased towards some regions such as the North Pacific and North Atlantic, this data set reveals clear patterns of plastic abundance.

Approximately half of the floating plastic detected from surface sampling resides in a few relatively confined hotspots, mainly the garbage patches in the centres of the subtropical gyres, where abundances can be a million time higher than in other regions such as the tropical Pacific and Southern Ocean (van Sebille *et al.* 2015). To first order, physical oceanographic understanding including Ekman theory can explain these patterns, where the plastic accumulates in areas where wind causes convergence of the surface flow (van Sebille *et al.* 2015).

However, the remaining half of the plastic debris is estimated to be in areas that are relatively under sampled, such as the southern portions of the Atlantic and Pacific Oceans, in the Indian Ocean, and in the Southern Ocean. There is also a size bias in the data, as most of these surface data are the product of nets designed for plankton, which typically sample items in the range between 300 µm and 25 cm, due to mesh size and size of the mouth of the net. However, there are a number of observations that suggest larger items follow the same general pattern, although with higher concentrations near coastal and oceanic sources (e.g. Ryan 2013).

Monitoring methods

Sampling methods are relatively well established for at-sea measurement of marine plastics. Larger items are often sampled using visual surveys (sensu Thiel et al. 2003; Eriksen et al. 2015; Ryan 2013; Hinojosa and Thiel 2009; others), with analysis using distance sampling methods (e.g.

Ryan 2013). While this approach can provide quantitative estimates of densities, there remain issues with combining estimates across surveys due to differences in observability and other factors (Ryan 2013). Smaller debris have been sampled using various types of surface nets, developed for plankton sampling (e.g. Law *et al.* 2010, Reisser *et al.* 2013; 2014). These methods were relatively well established and standardized, prior to being applied to marine debris. As a result there has been a reasonable measure of success in combining measurements across surveys for analysis (e.g. Cozar *et al.* 2014, van Sebille *et al.* 2015). Remote sensing has been explored as an alternative method for estimating densities of plastics in marine systems (NOAA Technical Report 2010). Satellite and drone based instruments have not provided useful data in this respect, largely due to a mixture of the analytical complexity of identifying items automatically and the size of the size distribution of the items (NOAA Technical Report 2010). There is some possibility for the use of ship-based instruments, particularly on ships of opportunity. However, some technical feasibility analysis remains to be done (C. Wilcox, unpublished data).

3.2 The sea floor

Microplastics have been reported in marine sediments worldwide (Claessens *et al.* 2011; van Cauwenberghe *et al.* 2013a and 2015, Woodall *et al.* 2015) but the first report in subtidal sediments date back to 2004 (Thompson *et al.* 2004). Deep sea sediments were demonstrated more recently to also accumulate microplastics (van Cauwenberghe *et al.* 2013a; 2015, Woodall *et al.* 2015) with composition that appears different from surface waters, as fibres were found at up to four orders of magnitude more abundant in deep-sea sediments from the Atlantic Ocean, Mediterranean Sea and Indian Ocean, than in contaminated sea surface waters (Woodall *et al.* 2015). Sediments are suggested to be a long-term sink for microplastics (Cozar *et al.* 2014; Eriksen *et al.* 2014; Woodall *et al.* 2015). Logically, plastics with a density that exceeds that of seawater (>1.02 g cm^3) will sink and accumulate in the sediment, while low-density particles tend to float on the sea surface or in the water column. It has been suggested however that even low-density plastics can reach the seafloor. Biomass accumulation due to biofouling can lead to an increase in density resulting in the sinking of the microplastic (Andrady, 2011; Zettler *et al.* 2013). Indeed, analysis of polyethylene bags submerged in seawater showed a significant increase in biofilm formation over time, accompanied by corresponding changes in physicochemical properties of the plastic, such as a decrease in buoyancy (Moret-Ferguson *et al.* 2010; Lobelle and Cunliffe, 2011). These studies suggest that biofouling can contribute towards the settling and eventual burial in sediments of previously buoyant plastic and biomass accumulation on plastic may even partly explain the open-ocean surface estimates to be two orders of magnitude lower than expected from estimates of plastic releases in the marine environment (Cozar *et al.* 2014; Eriksen *et al.* 2014). The situation is however probably more complex as one may argue that after sinking, biofilms and fouled organisms may not survive and disappear, also from grazing, enabling vertical movements back to the surface layers (Song and Andrady 1991). Alternatively, aggregation with organic matter (i.e. marine snow) was also considered as a main route of transport for microplastics to deep-sea sediments (van Cauwenberghe *et al.* 2013a).

A number of oceanographic processes could aid in the transfer of microplastics to depth. As stated in Woodall *et al.* (2015), these processes include dense shelf water cascading, severe coastal storms, offshore convection and saline subduction. All these induce vertical and horizontal transfers of large volumes of particle loaded waters, including grains of various sizes and nature, as well as litter and contaminants, from shallow ocean layers and coastal regions to deeper ones, with submarine canyons acting as preferential conduits as for larger debris (Galgani *et al.* 1996, Pham *et al.* 2014).

Mechanisms influencing microplastic distribution on the sea floor are not so well understood. Microplastic fragments are also more likely than larger items to be influenced by advection and, more generally, circulation patterns at all ocean levels, because of their small size (Woodall *et al.* 2015). Ocean dynamics could then explain the accumulation of plastics in the deep sea or shallower waters. Some empirical results appear to suggest this might be the case. For instance, Vianello *et al.* (2013) detected the lowest microplastic concentrations where water currents are higher (Venice Italy, outer lagoon, >1 m s^1) when the inner Lagoon, which is characterized by lower hydrodynamics had higher fine particle (<63 mm) fraction in the sediment.

On the deep sea floor, circulation is not well explained and pathways are different from surface circulation. Thus, the prediction of distribution patterns will require a better understanding of circulation patterns to locate the most probable areas of accumulation, if any. Submarine topographic features may also favor sedimentation and increase the retention of microplastics at particular locations such as canyons and deeps or smaller scale structures (Holes, Rocks, geological barriers, etc.). As for larger debris, human activities may also affect composition and repartition, as shown with the high densities of MPs found in harbor sediments (Claessens *et al.* 2011), reaching up to 391 micro plastics/kg of dry sediment. Similarly, In Slovenia (Bajt *et al.* 2015), concentrations were found between 3 and 87 particles per 100g generally with coastal areas more affected.

Finally, our understanding regarding the dynamics of transport, accumulation and associated spatial distribution has been extremely limited. Robust temporal and spatial distribution must be considered in order to estimate globally the quantities that are present and, as for surface, to predict sea floor plastic accumulation.

Table 5. Abundance of microplastics in subtidal sediments worldwide. Location and location specification (Modified after van Cauwenberghe *et al.* 2015).

Continent	Location	Location specification	Depth	Particle size	Measured abundance	Reference
America	US	Maine subtidal		0.250 mm-4 mm	105 items/L	Graham and Thompson, 2009
	US	Florida subtidal		0.250 mm-4 mm	116-215 items/L	Graham and Thompson, 2009
	Brazil	Tidal plain		1 mm-10 cm	6.36-15.89 items/m^2	Costa *et al.* 2011
Asia	India	Ship-breaking yard		1.6 mm-5 mm	81.4 mg/kg	Reddy *et al.* 2006
	Singapore	Mangrove		1.6 mm-5 mm	36.8 items/kg dry	Nor and Obbard, 2014
Europe	UK	Estuary			2.4 – 5,6 fibres/50 mL	Thompson *et al.* 2004
	Sweden	Subtidal		2 mm-5 mm	2-332 items/100 mL	Noren, 2007
	Belgium	Harbour		0.38 mm-1 mm	166.7 items/kg dry	Claessens *et al.* 2011
		Continental Shelf	0-200m		97.2 items/kg dry	
	Italy	Subtidal		0.7 mm-1 mm	672-2175 items/kg dry	Vianello *et al.* 2013
	Slovenia	shelf	Infralittoral (<50m)		30-800items/kg dry	Bajt *et al.* 2015
Oceanic sediments	polar ocean, Mediterranean, North Atlantic, Gulf of Guinea	Deep sea	1176-4848	5 mm-1 mm	0.5 items/cm^2	Van Cauwenberghe *et al.* 2013
	NW Pacific	Deep sea trench	4869-5766	0.300 mm-5 mm	60-2020 items/m^2	Fisher *et al.* 2015
	Subpolar /North Atlantic	Deep sea mount Slope	1000-2000	0.032-5mm	10 - 15 pieces per 50 ml	Woodall *et al.* 2015
	North East Atlantic	Canyons/ slope	1400-2200	0.032-5mm	6 - 40 pieces per 50 ml	Woodall *et al.* 2015
	Mediterranean	Canyons/ slope/Basin	300-3500	0.032-5mm	10-35 pieces per 50ml	Woodall *et al.* 2015
	SW Indian	Seamount	500-1000	0.032-5mm	Up to 4 pieces per 50ml	Woodall *et al.* 2015

Monitoring of macroplastics on the seabed has shown mixed patterns to date, with some evidence for increased levels of plastic debris in proximity to cities, but conflicting evidence showing offshore areas to have higher densities of debris (Corcoran 2015). Both patterns are possible, given that materials on the seabed are likely derived from a mixture of four sources: 1) materials that are negatively buoyant, were deposited at the marine system boundary and have been transported along the benthos, 2) materials that were positively buoyant due to interior voids, attachment to other items, or other characteristics, which have subsequently broken up and settled, 3) materials that are negatively buoyant but were transported offshore prior to deposition, such as materials lost from vessels at sea, 4) positively buoyant materials that have changed, due to fouling or other processes. Moreover, these sources are likely to interact with transport processes, which are in turn affected by characteristics of the plastic itself, including morphology, composition, use, size, and density (Corcoran 2015).

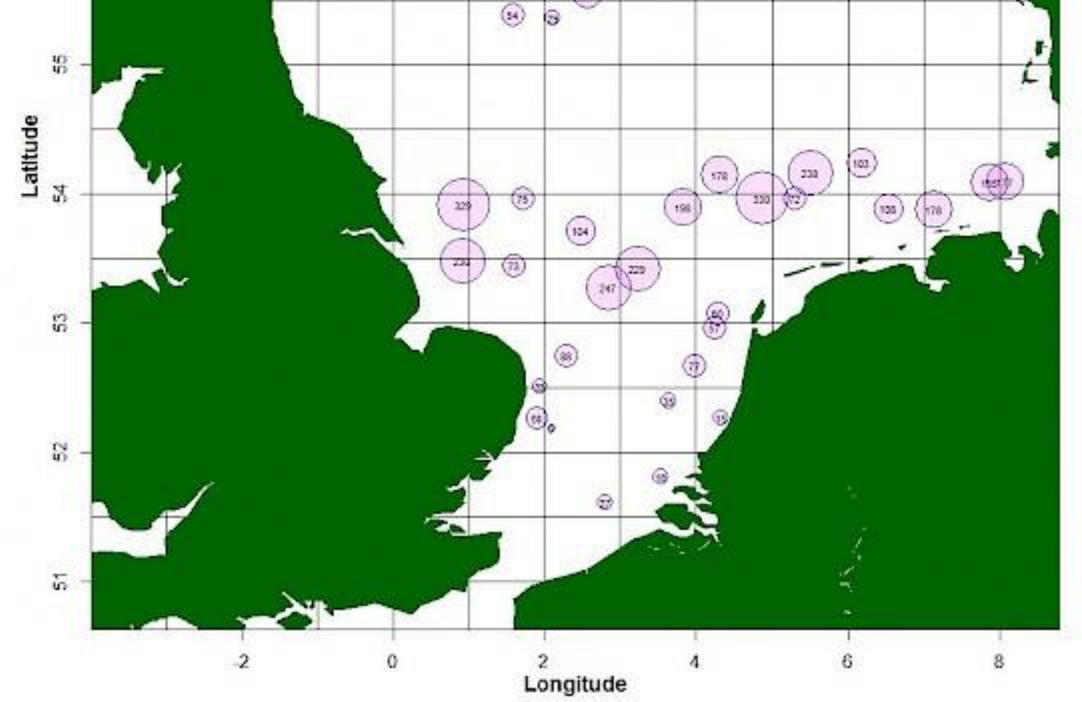
Monitoring methods

One challenge in monitoring plastic debris on the seabed is the difficulty of sampling in this environment. Sampling can be divided into active, using sediment coring for instance, and passive methods, using sediment traps for instance. Most analysis to date has used active sampling, through a mix of video, sonar, and trawl sampling. All three methods are challenging in the context of sampling for plastics. Video sampling is very intensive to process, as it generally involves substantial manual processing. It generally also covers relatively small areas, making it difficult to use except in areas of very high debris density. Sonar has been used in a number of studies, and while it overcomes some of the sampling scale issues associated with video, it is limited by the balance between spatial coverage, spatial resolution, and signal strength. In contrast to video or sonar, trawl sampling requires relatively little processing and can be done on-board vessels as they operate. However, trawl sampling is typically done using fish or invertebrate trawl gear and is frequently an add-on to the operation, not its primary purpose. Thus trawl sampling is typically done using mesh sizes greater than 100 mm, limited to locations with soft sediment substrates, and only done in areas of interest to commercial fisheries, leading to spatial bias and overrepresentation of fisheries wastes.

Sediment coring and grab sampling do not suffer from the same bias as trawl sampling, however, they have even smaller coverages than any of the other active methods, implying that they will have very low detection rates except in the most polluted locations. One advantage is the potential for estimating time patterns of deposition, using markers to age sediment cores in areas with sediment deposition. Passive sampling, for instance using sediment traps, could provide an alternative, as it does not necessarily have the same spatial bias as trawls and it is possible to develop relatively low cost equipment. However, it will suffer from bias in how materials are captured, if the equipment is not directly relevant for the transport mechanisms. For instance, many sediment traps capture descending materials, but this will mean that they miss any laterally transported materials such as those washed along the bottom by tides or currents. Passive sampling equipment also suffers from low coverage, making it difficult to use in a representative way without either very large sampling effort or very high plastic densities.

OSPAR benthic monitoring as an example

Seabed litter is the newest of the marine litter indicators that have been developed by OSPAR. It assesses the trends in the amount of litter deposited on the sea floor, including analysis of its composition, spatial distribution and, where possible, source. The monitoring is done through the International Bottom Trawl Surveys (IBTS) for fisheries management which have adopted a protocol to monitor 39 commonly found litter items caught in their nets. The 39 types are split in 6 categories: plastic, metal, rubber, glass/ceramics, natural products/clothes and miscellaneous. The advantage of using fisheries trawls is that all the information about gear type, area swept and trawling speed are already collected allowing the number of items per km2 of seabed to be calculated.



Taken from OSPAR website: (http://www.ospar.org/work-areas/eiha/marine-litter/marine-litter-indicators)

3.3 The shoreline and coastal margin

Approximately 80% of plastic comes from land based sources, with the most recent estimate suggesting that approximately 8.4 million tons of plastic enters the ocean on an annual basis (Jambeck *et al.* 2015). Models using this flux to estimate the standing stock in the ocean predict approximately 2 orders of magnitude more plastic than is currently found in the ocean (Cozar *et al.* 2014, Eriksen *et al.* 2014, van Sebille *et al.* in press). Given this mismatch, one clear possibility is that much of this material is deposited along the coastline near its sources. It has long been reported anecdotally that coastal debris increases near urban centres, suggesting local deposition of debris transported by the marine system for nearby urban sources (Hardesty *et al.* 2014).

Recent research using a robust sampling approach and a statistical model to correct for bias and the confounding effect of direct inputs from land to coastal environments supports the assertion that coastal sediments are a reservoir for debris from the marine system (Hardesty *et al.* in press). Local marine transport of debris from land-based sources onto the coastline may account for a substantial portion of the missing debris thought to be lost from land, with an estimate of 5.2 items per meter of coastline in Australia (considering only items > 2 mm diameter, on sediment surface; Hardesty *et al.* 2014, Hardesty *et al*. in press). Preliminary modelling results support this inference, suggesting onshore transport mechanisms deposit up to 90% of marine debris on the coastline near the source (section 4 this report; C. Wilcox *et al.* unpublished data).

Studies show increased coastal litter near urban centres, suggesting local deposition of debris transported by the marine system from nearby urban sources (Browne *et al.* 2011, Claessens 2011, Hardesty *et al.* 2015). Coastal debris surveys often report an increase in beach deposition of litter following storms or large rain events in which litter is washed landward, (Frost and Cullen 1997; Gabrielides *et al.* 1991; Vauk and Shrey 1987) further supporting the importance of local contributions to marine litter, and subsequent transport to shorelines.

Existing estimates of the distribution of debris along coastlines (e.g. Hardesty *et al.* 2015), particularly for microplastics, may substantially underestimate the total standing stock. A recent estimate for microplastics suggests that the surface may contain as little as 10% of the total stock in the coastal sediments (Turra *et al.* 2014). Even in remote areas, shorelines contain substantial amounts of debris. Samples from isolated beaches in the outer Hawaiian Islands found over 23 grams of plastic per 20 liters of sediment, on average (McDermid and McMullen 2004). This is potentially driven by deposition from high concentration areas in the nearby marine environment, and is similar to patterns found on Easter Island, which adjoins the high concentration area in the southern Pacific (Hidalgo-Ruz and Thiel 2013).

Particularly in developing regions, we find that the capacity of the waste management system influences whether waste is in the control of the municipalities management system, dumped into the environment or picked over by the informal sector. The capacity of available vehicles for collection coverage, the availability of staff for collection, the condition and ability of containers to hold waste as well the capability of the final disposal site influence the path of waste from the household. (Dangi *et al.* 2013; Losses from coastal regions can readily make their way to the shoreline through surface transport, waste mismanagement, storm water transport, roadways and local users.

Given the global interest in marine debris, engaging with communities, particularly in coastal communities, provides opportunities for citizen science engagement and coastal clean-ups activities and awareness raising opportunities, as evidenced by increasing numbers of participants in International Coastal Cleanup efforts (ICC, 2015; Storrier *et al.* 2006) and other coastal clean-ups that take place in communities around the world, some of which have been ongoing for decades.

Patterns of beach use may also change through time, altering coastal source-sink dynamics (Ryan *et al.* 2009). Even on remote beaches with difficult access litter is found (Hardesty *et al.* 2014; Santos *et al.* 2009) and costs associated with coastal litter not only include impacts to biodiversity and human health risks, but also are associated with decreases in tourism revenue, which can be significant (Jang *et al.* 2014; Ofiara and Brown 1999; others).

Monitoring Methods

Coastal litter monitoring has most commonly taken place through coastal clean up activities. There are local, regional, national and even international clean up programs around the globe. One of the most well-known is that organized by Ocean Conservancy (http://www.oceanconservancy.org) which has been operating in more than 70 countries, the International Coastal Cleanup (ICC), which has been in operation annually for nearly 30 years. One of the challenges, however, is with consistent data collection and methodological consistency for repeated surveys. This is particularly a challenge for volunteer collected information that relies on goodwill and is often recorded and reported intermittently, incompletely or not at all. Such irregularity in monitoring can hamper the ability to perform large scale, statistically robust analyses which can yield important insights about the effectiveness of litter policies, awareness campaigns or other activities. Furthermore, there may be statistical approaches that can be applied to overcome these challenges to some extent.

Coastal litter monitoring typically uses individuals (often volunteers, but also trained participants or paid staff) to record information that are identified visually. This means there tends to be a size bias for items detected and recorded, which is limited by human visual acuity. Also, items with monetary value or large items may be more likely to be collected than smaller particles, dangerous, or difficult to identify objects.

However, there are some sampling methods focus on smaller items (e.g. micro and nano particles). Such monitoring approaches require different survey methodologies, which are focused on identification and capture of small particles and are similar to those mentioned in section 3.2 on ocean floor (see review by Cole *et al*. 2011). NOAA also recently released a protocol for analysing and quantifying synthetic particles both in the water and in sediments (Masura *et al*. 2015).

Another approach to monitoring coastal litter that has recently gained popularity is that of litter traps. Litter traps and boom systems are generally designed to collect floating litter (and other debris). They are one form of passive sampling gear that can be used to monitor litter in coastal environments and can be particularly effective for reducing floating litter (typically larger items) before they reach the ocean. Litter traps can continue to work regardless of tidal flux or changes in water levels, and as they can operate without impending water flow, they can be an important monitoring (and litter reduction) method. In high flow situations, such as extreme weather events however, they can break loose or reach overcapacity. Floating litter traps also require a system for collection and removal. One novel litter trap that has recently reached notoriety not only for its effectiveness in removing litter but for its value in raising awareness of the issue is the Baltimore Water Wheel http://baltimorewaterfront.com/healthy-harbor/water-wheel/) which has proven to be highly successful.

Remote sensing is another monitoring approach that can be used for shoreline and coastal monitoring. Whether by balloon with camera, drones or satellites, the technological advances in ground based imagery, have made remote sensing a more viable option for litter monitoring (see Kako *et al*. 2012; Jang *et al*. 2015). Identification of small items can be challenging however, and image processing time can be restrictive, but there is the potential for automated image processing that may make remote sensing a more practical monitoring tool in the near future.

3.4 The water column

The vertical distribution of marine debris have been documented in the surface and subsurface portions of the water column (Lattin *et al.* 2004, Lusher *et al.* 2015, Reisser *et al.* 2015), although it is less well understood how much plastic resides just below the ocean surface. Recent modelling (Kukulka *et al*. 2012) and observations with vertically stacked trawl nets (Reisser *et al*. 2015) has shown that, depending on sea state, a significant fraction of plastic may be mixed down due to wave breaking and mixing in the upper few meters of the ocean surface. Since most 'standard' trawls only skim the top 10 cm of the ocean surface, they may miss a considerable part of the plastic, especially in rough seas.

The most extensive sampling of the vertical distribution of plastics in the water column to date examined the abundance and mass of plastic debris with depth in the North Atlantic gyre, an area of high plastic concentration. This study found an exponential decay in abundance and mass with increasing depth to a maximum of 5 meters below the surface. The study also documented relationships with wind and sea conditions, where higher wind resulted in increased downward mixing. The distribution of smaller plastic items was more strongly affected by these conditions, driven by slower rising rates of these less buoyant particles (Reisser *et al.* 2015).

This pattern of wind-driven mixing complements analysis done by van Sebille and colleagues of the global microplastics dataset (van Sebille *et al.* 2015). Analysing the effects of sampling conditions on the densities observed in 13,000 at sea samples, the authors found a significant negative effect of wind on the densities observed (van Sebille *et al.* 2015). The effect of wind was a linear first order one, suggesting that increasing wind velocities mix plastic debris down below the surface layer available to the standard plankton tows used for debris sampling (van Sebille *et al.* 2015).

Both empirical measurements of the depth profile of debris (Reisser *et al.* 2015) and statistical analysis of debris fields (van Sebille *et al.* 2015) have noted that the existing physical models of downward mixing underestimate the observed mixing (Kukulka *et al.* 2012). More recent developments of these physical models of mixing may improve the characterization (Kukulka *et al.* 2015). Overall, empirical studies, statistical models, and physical models suggest that debris in the water column is primary confined to regions near the surface and ocean floor.

Monitoring Methods

To date, however, there are no large scale synoptic datasets that include vertical stratification in sampling (aside from the uppermost meters to tens of meters of the ocean surface). Sampling using bottom trawl and subsurface trawl nets provide one approach to sampling the water column for non-buoyant litter items. Applying video, still photography and other visual imagery capability to oceanographic surveys provides additional opportunities for sampling below the ocean's surface. There are also opportunities to affix video or other cameras to oceanographic sampling at fixed locations for other long-term survey projects. Continuous Plankton Recording (CPR) surveys that are underway to evaluate marine ecosystem health, such as takes place in Australia's oceans could also incorporate plastics sampling. Utilizing below surface sampling and towed behind ships of opportunity, this low-cost sampling approach is a promising survey tool that could be applied to gain a better understanding of sub-surface and water column marine litter abundance, density and movement.

3.5 Biota

Plastics accumulate in oceanic and coastal areas and can be pollutant vectors, promoting effects on marine biota. However, the risk of such impacts depends on the type, size and amount of plastic present in the environment, the presence of contaminants in plastic and contact with sensitive biota.

Biological processes (e.g. fouling, ingestion, aggregation), and their interaction with the above physical processes, will influence whether and how plastics are transported within and between different ocean habitats. Properties of the particles themselves (e.g. type, density) will affect how they interact with these biological processes. For example, polypropylene is a common type of plastic used in rope and has a density of 0.9 g/cm3 (Hidalgo-Ruz *et al.* 2012). It will therefore float in seawater (assuming an average sea water density of 1.02 g/cm3), which means that surface-feeding pelagic organisms are more likely to ingest it. Heavier plastics such as those composed of polyvinyl chloride are more likely to sink and therefore be ingested by benthic organisms. Through time, however, low density polymers that would otherwise have buoyancy in seawater may become fouled and sink (Morét-Ferguson *et al.* 2010; Long *et al.* 2015), in which case such plastics may become available to benthic organisms.

Marine organisms from microbes to invertebrates have always attached to natural floating substrates (macroalgae, feathers, wood, pumice), but one important difference between these natural materials and plastic is the longevity of plastic relative to most of the natural substrates. This longevity allows more mature communities to form and persist, thus facilitating the transport of viable populations further than would have been possible in the pre-plastic era. The distribution of plastic is different from that of natural substrates, and plastic has substantially increased the available substrate in oligotrophic open ocean regions, potentially altering the distributions of marine organisms (Goldstein *et al.* 2012).

Some marine animals are indiscriminate feeders that will ingest anything in the appropriate size range. Others, such as seabirds and turtles may use visual, chemical, and electrical cues for finding and selecting food, so the probability of whether plastic is ingested depends not only on size and encounter rate, but also on a number of other cues including shape, colour, smell, and taste (Acampora et al. 2013; Schuyler et al. 2014; 2015). Encounter rate, however, is a good predictor of ingestion for some marine taxa (Wilcox *et al.* 2015). Fish eggs and other biological material can effectively cover and functionally 'hide' plastic from consumers, which may also increase the likelihood of ingestion. The smell and taste of plastic also can be influenced by the microbial biofilm on the surface, and microbes colonize plastic in seawater very quickly; within a week most of the surface may be covered. This thin layer of living organic matter and by-products make the plastic smell and presumably taste like nutritious particles. This increases the likelihood of ingestion by animals that use chemoreception to select food particles. Both the likelihood of ingestion and the potential impact on the organism ingesting it will vary depending on the composition of microbial community including whether it includes potential pathogens. The microbial community associated with plastic in the ocean also varies regionally and seasonally (Oberbeckman *et al.* 2014), as well as on larger scales such as between the Atlantic and Pacific oceans (Amaral-Zettler *et al.* in press) suggesting that risk management approaches to addressing the issue will require appropriate resolution of risk factors in both space and time.

Monitoring Methods

As mentioned above, carrying out marine monitoring can be costly, time consuming and difficult due to a number of constraints. There are, however, opportunities for using marine species as indicators of ecosystem health and to identify hotspots of marine litter in the ocean. Surveys of marine vertebrates for diet and plastic studies have included fish taxa (Boerger et al. 2010; Rochman et al. 2015; others), marine mammals such as whales (de Stephanis et al. 2013; Sechi et al. 1999, Jacobsen et al. 2010, others) and dolphins (Baird et al. 2000), all of which have been found to ingest plastic. For the last several decades, researchers have also reported on plastic ingestion in seabirds (Ainley *et al*. 1989, Ryan 1987, Spear *et al*. 1995).

While historically, seabirds were shot on the wing and plastics ingestion was identified as part of diet studies during necropsies of deceased individuals (Ainley *et al*. 1989, Spear *et al*. 1995), increasingly, monitoring ocean plastics through seabird dissections or necropsies takes place from beach washed or beach wreck birds (van Franeker *et al*., 2009; 2011, van Franeker and Law 2015; Carey 2011, Acampora *et al*. 2013; Ryan2008; 2015; others). As evidence of the value of using marine fauna as indicators of marine ecosystem health, the Oslo and Paris Convention (OSPAR) initiated tan Ecological Quality Objectives (EcoQOs) which directly applies monitoring of seabirds to associated targets for acceptable ecological quality. The northern fulmar (*Fulmaris glacialis*) is the key EcoQO indicator species for monitoring plastic debris in the North Sea, based upon the abundance of plastic debris that is ingested by the species as part of long term monitoring. The EcoQO target defined for plastic pollution in the North Sea is for fewer than 10% of fulmars to have more than 0.1 g of plastic in the stomach, based on sampling beach-washed birds. A similar approach is being considered but with loggerhead turtles (*Caretta caretta*) to act as ecosystem monitors in the Mediterranean (Hardesty *et al*. 2015).

Because marine species are often difficult to study on the ocean, surveys of faecal pellets and boluses (Hutton *et al*. 2008, Nilson *et al*. 2014) are another monitoring approach which can be used to identify the frequency of plastic ingestion in marine fauna, and, importantly, to identify regions of the ocean with high concentrations of plastic. Animals in captivity for rehabilitation purposes (such as marine turtles) have been known to excrete plastic that they have ingested. Linking foraging areas and risk of plastic ingestion (sensu Wilcox *et al*. 2015; Schuyler *et al*. 2015) provides an excellent opportunity to identify risk hotspots, risk species, and regions to focus on reduction of litter inputs to the marine environment.

Lavage of live animals (as reviewed in Karnovsky et al. 2012) or through endoscopy (e.g. Sievert and Sileo 1993) can also be used to assess the frequency and quantity of plastic ingestion and has long been used for seabirds. Lavage of live birds can be stressful to birds, however, and does not result in voiding of the entire gastrointestinal content (Barrett et al. 2007; Neves et al. 2006). Endoscopy is difficult, time consuming and cannot yield indigestible matter below the stomach oil surface (Sievert and Sileo 1993) and necropsy of dead birds typically represents a biased sample

(Hardesty *et al.* 2015). There are, however, recent advances that provide promise. There is a newly described method for assessing live seabirds exposure to plastics through minimally invasive means (Hardesty *et al*. 2014). This approach provides a way to assess the ubiquity of plasticizers occurring in multiple species with different body sizes, foraging strategy, and geographic distributions, and a similar approach has been trialled to detect phthalates in stranded whales (e.g. Fossi et al. 2012). Identifying traces of chemicals used in plastic production may increase our ability to sample additional species, geographic regions and to identify geographic regions of greatest concern and is an area that shows great promise.

4 Current gaps in knowledge

4.1 Uncertainties in Models and Data

As has been highlighted throughout the literature, plastic pollution in the ocean is an emerging global environmental issue. Recent estimates suggest land based sources add 8.4 million tons of plastic waste to the oceans annually (Jambeck *et al.* 2015). Sampling at sea has demonstrated that this input has resulted in pollution of the oceans at the global scale, particularly in areas where ocean surface currents and winds concentrate floating materials (Law *et al.* 2014, Law *et al.* 2015). These empirical measurements of floating debris from at-sea samples have been used to infer the distribution of plastic at the global scale, throughout the world's oceans (Lebreton *et al.* 2012, Maximenko *et al.* 2012, van Sebille *et al.* 2012, Cozar *et al*. 2014). Predicted distributions in turn, have been used to estimate exposure to wildlife from plastic pollution (Wilcox *et al.* 2015, Schuyler *et al.* 2015).

Yet, despite the significant inferences being made from the at-sea sampling data and the models used to extrapolate global densities from them, there has been very little examination of the uncertainty underlying the data, models, or the resulting predictions. A notable attempt to include uncertainty is the recent global estimate of debris by Cozar *et al.* (2014). The researchers aggregated patterns of predicted plastic density into high, intermediate, and low density regions, then utilized mean values across these regions based on samples to infer the average across the region. The resulting density estimates were then integrated across the entire area for each density level to produce a total debris estimate at the global scale (Cozar *et al.* 2014). Cozar and colleagues (2014) do attempt to bring error estimates through in their analysis, however, the error estimates are primarily derived from the estimates of the means of the 1127 net tows they average for each of 442 spatial blocks, which are then averaged to produce debris estimates in 15 global scale polygons (3 accumulation levels by 5 ocean basins). This ignores a range of sources of error, from sampling error in their at-sea trawl data to spatial errors in their model derived accumulation zone boundaries.

A recent analysis has compared predictions made by three of the models available for interpolating the debris surface at the global scale based on at-sea sampling data (van Sebille *et al.* 2015). This analysis finds the models in general concordance in terms of major zones of debris concentration in the open oceans. However, there are substantial differences in closed basins, such as the Mediterranean, and in coastal zones. Both of these differences appear to be due to structural differences in the models, such as the inclusion of debris source dynamics and the spatial resolution of the underlying models (van Sebille *et al.* 2015). This analysis also attempted to incorporate sampling error explicitly, using a statistical model to correct the 13,000 trawl samples for effects of wind, time, and other variables that affect either debris density or the efficiency of sampling. Estimates of sampling error at the individual trawl level were then used to put uncertainty estimates on the projections emerging from the models. Never the less, this analysis still ignores a number of important sources of uncertainty in the analysis.

Although authors have not propagated uncertainty through the analyses as they have made global projections of the debris fields, there is good evidence that both uncertainties in the models and sampling error in the data could have significant effects on the projections. For instance, Reisser *et al.* (2015) examined the role of wind and wave driven mixing in reducing plastic debris at the ocean surface, finding that up to 70% of plastic can be below the surface and unavailable to the typical surface trawls. Moreover, this downward mixing varied by the shape and density of the item, resulting in potentially complex biases in surface samples. Reisser *et al.* (2015) also noted cases where the observed mixing did not match theoretical models that have been used to correct surface trawl data for mixing effects (Kukulka *et al.* 2012). The models underlying the global debris surfaces also have errors associated with them. In some cases these models are based on drifter trajectories (e.g. Maximenko *et al.* 2012), which can contain errors due to aspects of the conversion of drifter trajectories to drift rates driving the modelled surfaces (e.g. Katsumata and Yoshinari 2010). These empirical models also contain uncertainty due to sampling error, driven by the number of drifters available to estimate transitions between locations and the coverage of the underlying variability in the drift trajectories due to changing conditions. For instance, seasonal changes such as the strengthening of the trade winds increase the sampling required to accurately estimate surface velocities in affected regions.

We explored three aspects of the gaps in our current knowledge of the distribution of plastic pollution in marine systems. First, we examined which zones of the ocean have been well sampled and where sampling is either absent or sparse. Second, we used a spatial statistical model to estimate the distribution of debris, taking account of sampling biases, and its variability to identify locations with sampling but at which there remains significant uncertainty. Third, we compared these standardized data to the distribution of debris predicted by an oceanographic model, identifying areas where there was a lack of concordance between the predicted and observed densities. Together these results provide a picture of where additional sampling or further analytical effort should be allocated.

Methods

Data assembly

We used data assembled for a recent global estimate of the global standing stock of debris, described in van Sebille *et al.* (2015). This data included 11,854 surface trawls from 27 studies carried out between 1971 and 2013 covering all major oceans except the Arctic. Samples were collected using plankton nets varying in mesh size from 0.15 mm to 3.0 mm, although more than 90% of the observations were collected with manta or neuston nets with mesh sizes between 0.333 mm and 0.335 mm. All data was converted to counts per volume of water sampled for analysis. There is an established effect of wind-driven mixing on debris at the ocean surface, however, many studies did not report wind speeds during sampling. We used daily average wind speed from the ECMWF ERA-Interim global atmospheric reanalysis (Dee *et al.* 2011) to interpolate the wind velocity for each trawl date – location combination. ERA-Interim reanalysis data are available as of January 1, 1979 thus trawls prior to this date (222 trawls) were excluded from the analysis. For further details on the dataset, including a list of data sources, see van Sebille *et al.* (2015).

Quantifying observational variability

We used a generalized additive model implemented in the mgcv package of the R statistical language to model the observational data on plastic density in the ocean (Wood 2006, R core team 2014). We investigated a number of possible variables that could account for variation in the data, including year of the survey, wind speed, trawl length, and study. We used a smooth term to initially explore the relationship between the continuous predictor variables to evaluate the potential for non-linearity. We subsequently fit both second and first order polynomials for terms as appropriate based on the smooth term.

All models we evaluated included a spherical smooth to represent position on the globe. This smooth forces values near to each other to have some relationship, and assists with estimation of the relationships of the variables driving sampling error, such as wind velocity. We also evaluated the importance of allowing a discontinuity at the Americas, at the boundary between the Caribbean Sea and the tropical Pacific Ocean to account for the lack of connection given the proximity of the basins. We fit each of the possible models incorporating the potential covariates, and identified the best fitting model based on AIC (Burnham and Anderson 2002). We checked the best-fitting model for overdispersion, and tested the fit of the final model using a goodness of fit test on the deviance residuals.

We use the residual deviation between the at-sea samples and fitted values from our best model to evaluate the accuracy and bias in estimates of the debris density at the global scale. The residuals represent the remaining variation around the mean value predicted by the model for each observation. We fit a spatial model to these residuals to look for spatial patterns in the residuals. We use the absolute value of the residuals, to measure the unexplained variability in the observational data, and the signed value of the residual to measure bias. Regions with strong bias will have strongly negative or positive residual values.

Identifying deviations from expectations

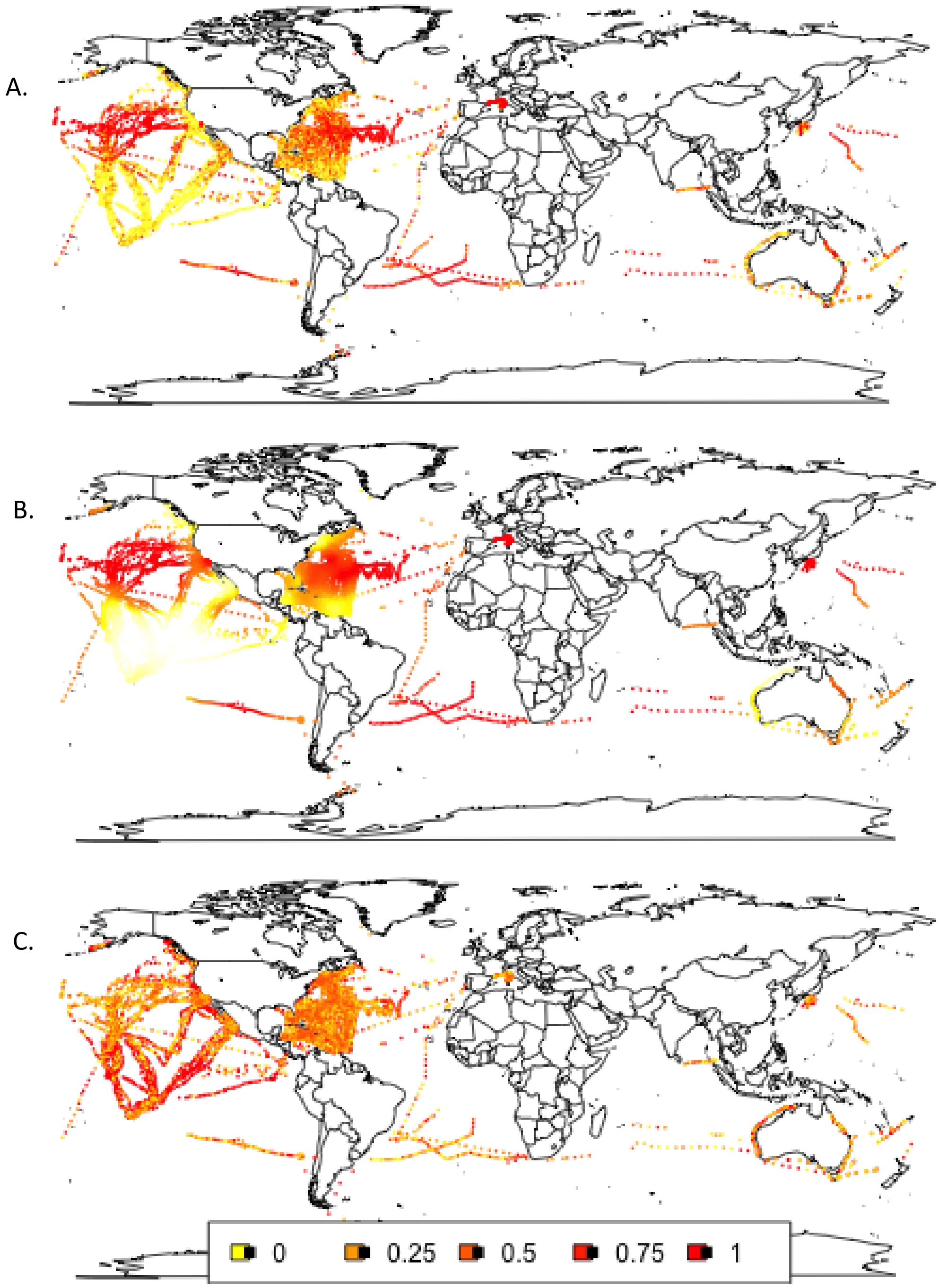
We utilized a predicted distribution of plastic density in the ocean, based on methods described in van Sebille *et al.* (2015). The model we used was the one adapted from van Sebille *et al.* (2012). The method assumes that plastic is lost from the coastline in proportion to the population within 200 km of the coast, scaled by the amount of plastic estimated to enter the ocean by country from Jambeck *et al.* (2015). Simulated plastic is released from the coastline on a monthly basis, starting from the year 1950. The volume of plastic released from each coastal location increases on an annual basis, in proportion to the increase in global production as estimated by Plastics Europe (2013). Drifting trajectories of this plastic are then modelled using a statistical model estimated from the global drifter data set, on a bimonthly basis. Modelled distributions were interpolated to a 1 degree latitude by 1 degree longitude grid.

We fit this predicted distribution to the standardized global dataset of plastic observations using a linear regression of the predicted densities on the observations. We then evaluated the patterns of mismatch based on the residuals of the linear regression. We evaluated the residuals for both a global model, and for a model allowing separate regression coefficients for each ocean basin. As for the standardization model, we used a spatial model of the absolute value and the signed value of the residuals to investigate patterns of precision and bias.

Results

Data coverage is by far the most extensive in the western North Atlantic Ocean and the eastern tropical and north Pacific oceans (Figure 3a). There is relatively less coverage in the eastern and southern Atlantic. The southern and western portions of the Pacific and the Indian Ocean have the least coverage. Neither the Arctic nor the Antarctic has significant sampling at this point.

Figure 3. Observed, standardized, and residual values for the global plastic observations. Panel A) relative density of plastic debris in surface trawl data around the globe. Data are presented in rank order of density, instead of raw densities, due to the long-tailed distribution of density values. Panel B) rank ordered fitted values for the density of plastics in samples from the best fit model for the observational data. Panel C) rank ordered residuals between the best model and the observed data.



Sampling in coastal regions is relatively poor, with extensive sampling only occurring along the central coasts of North America, off Japan, in the Mediterranean, and around the Australian continent (Figure 3a). Of the five major accumulation zones in the world's oceans, only the north Atlantic and north Pacific zones have been extensively sampled. Even in these two cases, intensive sampling only covers a portion of the expected area of high plastic densities.

The best fitting statistical model for the observational data included terms for wind speed, study year, and a nonlinear term at the dividing the Pacific and Caribbean basins at the Americas (Table 6A). The wind speed in the model was represented as a second order polynomial, with a decreasing incremental effect of wind speed at higher velocities (Table 6B). There was a significant positive and linear trend with time (Table 6B). Allowing for a discontinuity at the Caribbean Sea – Pacific Ocean boundary improved the overall model fit, although it was not significant in its own right as a term in the model (Table 6A&B). In terms of overall effect, the intercept term had a larger effect than any other term at the median of the covariate value. Following the intercept, wind speed was next most important followed by study year, in determining the plastic density observed during sampling.

Table 6. Adequacy of the candidate standardization models and coefficients of the best fitting model. Model codes in panel A are: 0 – intercept only, S – spherical smooth, W – wind speed, Wsq – wind speed squared, Bd – Atlantic – Pacific discontinuity, Bd2 - Atlantic – Pacific discontinuity squared, Ay – Year (since 1950). The median effect column in panel B is produced by multiplying the coefficient estimate by the median value of the corresponding covariate, and gives a measure of the relative magnitude of the effect of each term in the model.

A. Model Fit		B. Best Fit Model Coefficients				
Model	AIC	Coefficient	Estimate	Std. Error	p value	Median Effect
SAyWWsqBd2	159533.3	Intercept	7.3	3.4	0.033	7.3
SAyWWsqBd	159537.7	Year (since 1950)	0.016	0.005	0.0012	0.86
SAyWWsq	159538.2	Wind Speed	-0.34	0.045	1.40E-13	-1.8
SAyWBd	159541.9	Wind Speed Squared	0.011	0.0044	0.015	0.32
SAyWBd2	159541.9	Atlantic – Pacific Boundary Squared	3.7	8.4	0.67	1.4
SAyW	159542.4					
SWWsq	159592.8					
SW	159598.4					
SWsq	159727.7					
S	160546.3					
0	177503.4					

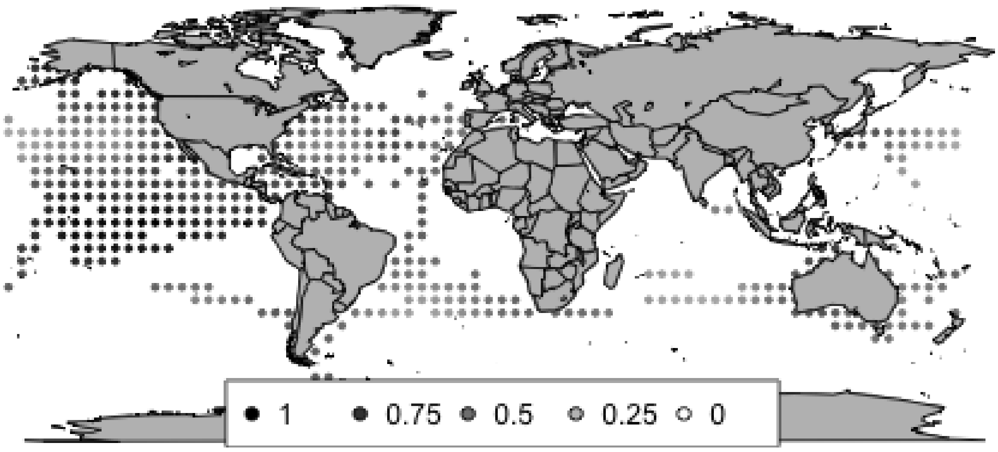
While the global model of debris distribution does in general match the patterns in the observational data, with most of the major oceanic accumulation zones modelled, there are a number of locations where the fitted and observed values differ (Figure 3a&b). In particular at the coastal margins, such as near Japan, in the California Bight (near Los Angeles), along the north-eastern coast of Australia and the northwest coast of Australia (Figure 3a&b). In the highly populated regions, such as the California and Japanese coasts the model suggests that the observations should be higher than they are, once standardized (Figure 3a&b). By contrast, the coasts of Australia are predicted to have lower debris densities relative to other samples after standardization. Turning to patterns of fit, the model of the observations appears to fit relatively well to the sample dataset around the globe, with the exception of samples in the central tropical

Pacific and in the central north Atlantic at the edge of the main region of sampling effort (Figure 3c).

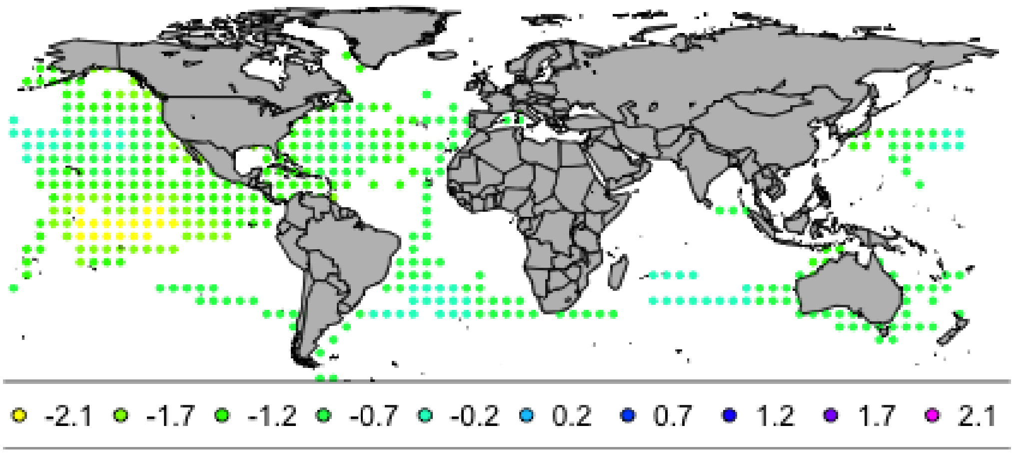
Looking at the spatial patterns in these residuals as a measure of variation in the data, after the sampling effects from wind and other sources have been controlled for, we see elevated variation in the observations in the central tropical Pacific (Figure 4a). There is also some evidence of high variability in the observations in the north Pacific, along the coastal margins of Alaska and Canada (Figure 4a). Turning to bias in the residuals, there appears to be a negative bias (i.e. the predicted values in the standardization model are greater than the observed values from the sample) in the central tropical Pacific (Figure 4b). The bias analysis suggests there might be a slight negative bias elsewhere, particularly along the coastal regions (Figure 4b). There was no bias in areas of high debris densities, such as the north Pacific gyre (Figure 4b).

Figure 4. Accuracy and bias in the statistical model used to correct the global debris data. Panel a) the magnitude of the residuals. Values are estimated from a global surface fitted to the residuals from the model of debris density in the at-sea surveys. Points are displayed for locations with empirical measurements within 5 degrees latitude or longitude. The scale bar shows the relative magnitude of the absolute residual values, scaled from zero to one. Panel b) the bias in the residuals from the statistical model fitted to the global debris surveys. Although the model of the residuals is global, only data points within 5 degrees of a survey location are displayed.

A.

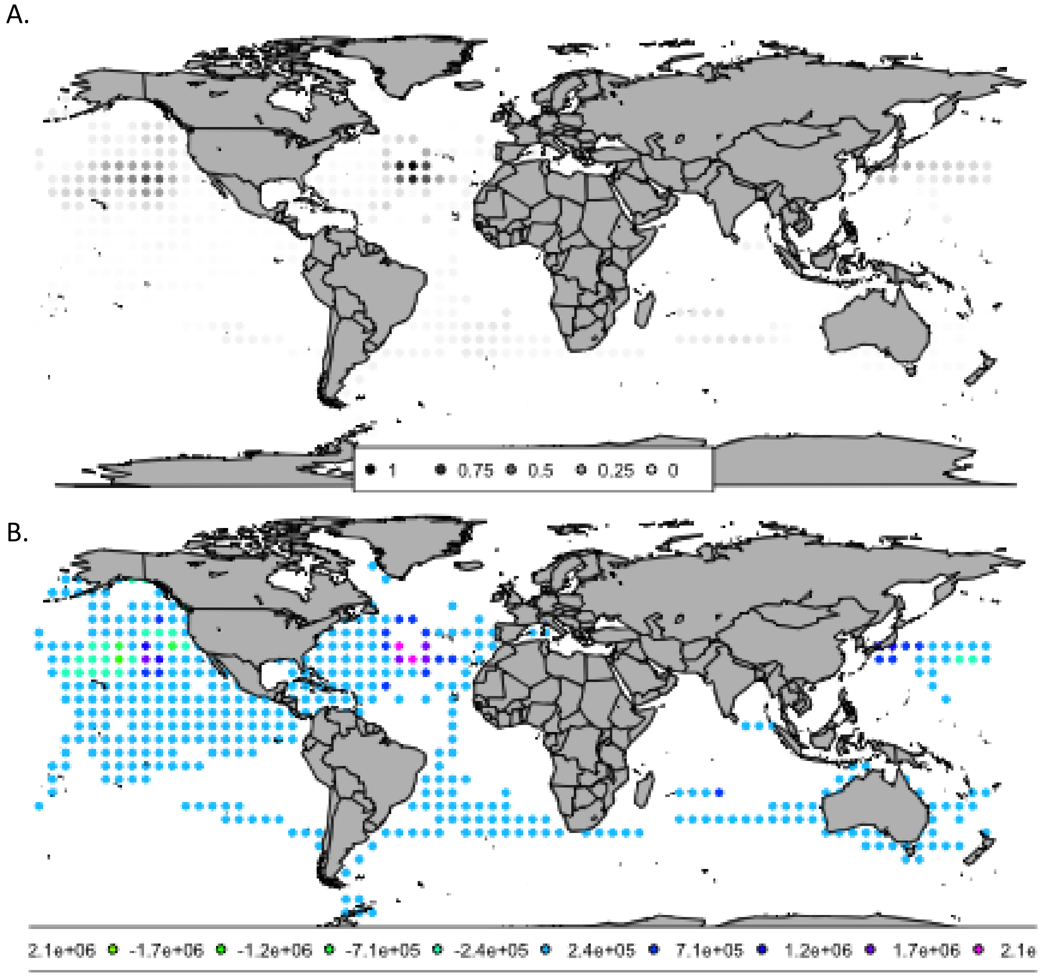


B.



Evaluating the fit of the predicted debris distribution from the oceanographic model to the standardized at-sea survey data, one can see areas of high variance and bias, particularly concentrated in central north Pacific and western north Pacific (Figure 5a&b). Most regions of the globe appear reasonably approximated by the predicted debris distribution from the oceanographic model. However, the two regions of poor fit appear to have both significant unexplained variation (Figure 5a), and a bias toward underestimating the observed values (Figure 5b).

Figure 5. Accuracy and bias in the fit of the oceanographic model used to infer the global distribution of plastic densities. Panel a) the magnitude of the residuals. Values are estimated from a global surface fitted to the residuals resulting from the fit of the oceanographic model of debris density to the standardized data. Points are displayed for locations with standardized observations within 5 degrees latitude or longitude. The scale bar shows the relative magnitude of the absolute residual values, scaled from zero to one. Panel b) the bias in the residuals from the statistical model fitted to the global debris surveys. Although the model of the residuals is global, only data points within 5 degrees of a survey location are displayed.



Discussion

There are clear limitations to our current ability to accurately predict the distribution of marine debris at the global scale. Data coverage is limited, with only the western north Atlantic and the eastern Pacific having substantial sampling. These data are highly variable, due to sampling conditions such as wind mixing and due to changes in the availability of plastic in the ocean. Even after correcting for sampling conditions and changes in debris densities, some areas of the ocean, such as the western tropical Pacific Ocean, retain significant amounts of unexplained variation with some bias in the corrected values. Finally, when an oceanographic model is used to interpolate the corrected observations to make global estimates of the distribution of debris or its total amount, there are areas of poor underestimation in the centres of the gyres.

These uncertainties are driven to some extent by the underlying character of the data. The data was collected across 27 different studies, potentially involving multiple vessels, over more than a 40 year period. In our analysis we noted a number of possible drivers of variation in the sampling process. First, there appears to be a difference between day and night samples, which we detected in the subset of data with time. Vertical migration of the planktonic community could lead to variation in sampling efficiency, due to additional material in the nets used for collecting debris. We explored the relationship with daylight, the proximity to dawn and dusk, and a number of other hypotheses. However, we were not able to detect a strong enough signal to establish whether vertical migration might be causing this effect. We also noted a strong effect of the 27 studies on the debris sampled. However, this effect is confounded with the distribution of debris as studies do not generally overlap in space and time with each other. Thus, there is an inherent trade-off in examining the differences among vessels and estimating the spatial distribution of the debris from the samples. Clearly a range of factors related to the studies could affect their detection rates, including configuration of the net deployment (e.g. tow angle, tow height, vessel wake proximity), sample processing facilities and methods, and competing work demands for the research team, to name a few.

One clear source of uncertainty in the data arises due to the sampling effort in the data collection process. The mean area trawled across the 11,854 samples is 1769 square meters, suggesting an average lower detection limit of 565 items per square kilometre. Examining the raw data, there do appear to be missing observations between 0 and 500 items per square kilometre. There are 4247 trawls with debris densities of zero and 6,829 trawls with densities greater than 500 pieces per square km, but only 241 surveys with densities in the interval 0 to 500. Given that densities are continuously distributed, and otherwise right skewed (smaller values are more frequent), this suggests a large portion of low density locations are recorded as zeros.

This is known as right censored data in the statistical literature (). Censored data, including right censored data, can be used in statistical modelling, however, it requires specialized approaches to account for the uncertainty in the censored region. These methods could potentially improve the estimates we present, however, many of the statistical tools we utilized, in particular spherical smooths and the Tweedie error structure, are not readily available together with tools for censored data. Censoring is one likely explanation for the area of poor fit observed in the standardization model in the tropical Pacific. This area is predicted to have low densities, and there are many zero observations, but also some non-zero ones, making it difficult for the statistical model to fit this bimodal distribution.

Local heterogeneity at fine scales may also be a significant factor in generating additional variation in the data. Marine debris accumulates in surface circulation patterns, creating narrow linear features with significantly elevated levels of debris in them. Sample estimates of densities in this environment will vary widely, depending on the angle of sampling relative to the feature. If a trawl is parallel to the direction of the surface features, it will either underestimate or overestimate the density, depending on whether it intersects the feature or not.

We found that the global surface predicted for marine debris, based on coastal inputs provided a reasonable fit, with the exception of the high concentration zones at the eastern edge of the north Atlantic gyre, in the north Pacific gyre, and off the coast of Japan. Recent analysis by van Sebille *et al.* (2015) also noted this pattern, which suggests that there is an issue with the underlying dynamics used to generate the debris surface. Researchers have divided their models into basins to allow more flexibility in fitting, using this as a method to address this issue (e.g. Cozar *et al.* 2014, Van Sebille *et al.* 2015). However, this is only an approximation, as the lack of fit implies either a miss-specified error term, or incorrect dynamics in the underlying physical model.

We also found that the regression fit showed evidence of heteroskedasticity, in this case larger variance in the observation data in areas with high density. This is presumably due to surface circulation concentrating debris at small scales, which would make sampling increasingly variable as debris concentrations increase.

There are a number of practical steps that could be taken to improve both the underlying data, and the modelling approaches used to predict the distribution and abundance of plastic drifting in the sea. Future at-sea sampling could be improved by using replicate trawls at each sampling station, allowing within sampling station variation to be estimated. This would assist with removing effects of small scale spatial heterogeneity in the samples. Sampling strategies could also be structured in an adaptive manner, with increasing effort in low density areas to reduce issues with censoring. Future analysis of debris data should address censoring, using appropriate statistical modelling of the data in the standardization process. Consideration should also be given to the error distribution used in fitting predicted debris distributions to empirical data. The increase in the variance in samples in areas with high average values is typical of counting type processes, where variance frequently increases with the mean of the distribution (Hilborn and Mangel 1993). This could be addressed in future work by using an error distribution where the variance scales with the mean for the fitting, or explicitly modelling the variance in addition to the mean.

4.2 Changes in debris with time

4.2.1 Fragmentation and degradation of plastic

Plastic debris is expected to slowly degrade in the ocean through photo-oxidation due to ultraviolet radiation, thermo-oxidation, biodegradation and physical shearing (e.g. through waves, friction with sand, or consumption and excretion by animals), leaching of additives (see GESAMP, 2015). Consequently these processes will result in the breakdown of macro debris into micro and eventually nano-sized particles. Fragmentation also affects plastic litter transport through marine systems. Smaller particles have a larger surface area: volume ratio, decreasing their sinking rate. The surface area is also important for biofouling, causing changes to the density and hydrodynamics of plastic litter.

Fragmentation rates of marine plastic litter have only been roughly estimated, with rare attempts to determine loss of tensile strength or surface area (Andrady 2011, O'Brine & Thompson 2010). In fact, it is currently unknown to what extent plastic litter in the ocean is converted into micro and nano-sized plastic particles, and how long it takes under ambient marine environmental conditions for plastic to be mineralized into harmless carbon dioxide (CO_2) and water. Recently, it was suggested that there appears to be a fast removal of plastic fragments smaller than a millimeter from the ocean surface water (Cozar *et al.* 2014). Hypothetical explanations for this observation include sampling and analytical artefacts, selective ingestion of the size category by zooplankton, abrupt fragmentation of micro into nano-plastics, sinking due to biofouling increasing the specific gravity of small particles, or high speed mineralization of plastic particles <1 mm.

Fragmentation increases surface: volume ratios of produced plastic particles, creating a larger contact area for further physical, chemical and biological transformations and reactions. Model calculations from Deltares suggest that smaller plastic particles might indeed degrade and split into smaller fragments at faster rates, but experimental evidence for this is needed (Gerritse *et al.* 2015). There is also some suggestion based on observational data that this fragmentation is driven by beaching of larger material, fragmentation in the surf zone and foreshore (Isobe *et al.* 2014).

In the framework of the European FP7 CleanSea, new methods to measure plastics degradation and fragmentation have been tested (Gerritse *et al.* 2015). A marine mesocosm experiment in the laboratory containing a variety of conventional 'durable' and compostable plastic materials was set up to see if electrical resistance measurements can be used to assess plastic degradation in seawater. First results indicate that the plastics in the mesocosm showed a decrease of electrical resistance over time, indicating polymer degradation and/or absorption of seawater. Further research within CleanSea is currently underway to determine if such measurements can provide a simple, cheap and easy to use alternative method to determine degradation rates of plastics in seawater.

4.2.2 Influences of fragmentation on plastic litter movement in the marine environment

Vertical motion

The quantities of small plastic fragments after fragmentation decrease exponentially into deeper layers (Kukulka *et al.* 2012; Reisser *et al.* 2015), and thus, the vertical distribution of the concentration (N) of such microplastics can be expressed as follows:

$N = N_0 \, e^{wz/A0}$,

where N_0 denotes the concentration of microplastics collected using a neuston net, w is the plastic rise velocity proportional to fragment sizes (⍰) as w [m/s] = 0.002×⍰⍰[mm] for hard plastics and sheets (Reisser *et al.* 2015), and z is the vertical axis looking upward from the sea surface. The dependency of the rise velocity on fragment sizes suggests that tiny microplastics with a large surface: volume ratio are likely to intrude into deeper layers by friction exerted on plastic surface. The parameter A_0 is computed as:

$A_0 = 1.5\, u_* \, k \, H_S$,

where u_* represents the frictional velocity of water (=0.0012 W_{10}), k is the von Karman coefficient (0.4), H_S is the significant wave height, and W_{10} is the 10-m wind speed (Kukulka *et al.* 2012). Therefore, marine plastic debris after fragmentation is likely to sink into deeper layers as the fragmentation proceeds, especially under stormy (wavy) conditions.

Horizontal motion

The transport process in coastal waters favors the fragmentation (degradation) of mesoplastics (Isobe *et al.* 2014). The field surveys, in conjunction with a numerical model, demonstrated the near-shore trapping of mesoplastics by a combination of the Stokes drift onto beaches and high ascending velocities of relatively large fragments. The mesoplastics drifting close to the coast are likely to be washed ashore on beaches, and easily return to the ocean by tides and waves. This selective onshore transport of mesoplastics works persistently until they degrade on beaches into microplastics. Once mesoplastics degrade into fragments smaller than a few millimeters, these microplastics are free of the near-shore trapping, and thus able to spread offshore.

Biofouling***

Biofouling however makes the above motion more complicated. Biofouling can increase the density of small plastic fragments to the point where they sink. Buoyancy is related to item volume, whereas fouling is related to surface area, so small items (which have high surface area to volume ratios) should start to sink sooner than large items (Ryan *et al.* 2015). In sampling small plastic fragments in the oceans, it is found that concentrations of tiny microplastics (<1mm) decrease rapidly, while a similar rapid decrease in small-sized fragments never occurred for non-plastic particles (Cózar *et al.* 2014). This might suggest that a major fate of marine plastic debris is deep oceans (Woodall *et al.* 2014; Ryan, 2015), although we need further examinations for uncovering the budget of marine plastic debris.

4.3 Sources

4.3.1 Evaluating coastal source drivers

The significant mismatch between recent estimates of inputs from land and the standing stock of plastics in the ocean raises questions around coastal sources of debris, and the relationship between these sources and the standing stock in the open ocean (Jambeck *et al.* 2015, Cozar *et al.* 2014). Recent efforts to create a detailed mass balance between plastic production and fate also find that significant portions of plastic (e.g. 60% of production) cannot be accounted for in terms of disposal, and thus is likely to be lost into the environment (Kim *et al.* 2015). However, these losses overestimate observations on the standing stock, and thus point to unaccounted for factors in the connection between land-based sources and the stock of plastic in the ocean.

4.3.2 Plumes and extreme events

Many authors have noted the presence of higher levels in coastal regions near river outflows, particularly those that pass through urbanized areas. There is long-term evidence of increased transport of land-based pollutants due to extreme events such as hurricanes or typhoons (Kuo *et al.* 2014, Osborne *et al.* 2008, Nixon and Barnea 2010). Research in Korea estimated that deposition rates of marine debris in coastal regions was 14 times higher than normal, with the passage of a typhoon (Baksun; Yunhansam). Work by NOAA researchers after a major hurricane in the Gulf of Mexico found that the majority of the larger debris transported offshore was deposited within a few kilometres of the coastline in areas close to heavy damage of infrastructure on land (Nixon and Barnea 2010). Studies of solid waste losses into the ocean have also noted the effect of smaller events, such as the substantial effect of the first rainfall of the year (Armitage and Rooseboom 2000, Allen *et al.* 2015, Guneroglu 2010, Marais *et al.* 2004). However, research on transport of land-based solid waste into drainage systems, and its impact on plastic transport to the ocean remains relatively understudied.

4.3.3 Connection to land-based littering and dumping

There is strong evidence of increased debris densities in coastal and offshore areas that are close to urban populations (e.g. Hardesty *et al.* in press). While the connection between land based littering and transport of debris to marine systems has long been appreciated (e.g. Armitage and Rooseboom 2000), there is less appreciation of the link to illegal dumping, particularly in developed countries where waste management is well regulated. Coastal debris have been linked to illegal dumping in large scale empirical analyses (Hardesty *et al.* in press). Similarly, waste management in coastal regions, and unregulated dumping in particular, have been assumed to be a major driver of solid waste input into marine systems (Jambeck *et al.* 2015). In developed countries with strong waste management regulation, illegal dumping appears to be a major problem in waste management (Baird and Cruz 2014). For instance, there were an estimated 5,000 illegal dump sites of commercial scale in southern Italy in 2010, with organized crime and a an increasing trend making it a pressing priority (). Illegal disposal on public lands, which frequently include waterways, wetlands, and other locations in the coastal zone is a common problem globally across the range of development levels (Vieira *et al.* 2013, Glanville and Chang 2015, Njue j*et al.* 2012, Hettiarachchi *et al.* 2011).

4.3.4 At sea losses and dumping

Approximately 20 percent of the plastic load in the ocean is assumed to come from marine sources, including shipping, fishing, and oil and gas platforms (Watkins *et al*. 2015). There are an accumulating number of studies linking debris, including plastic, on the seafloor to vessel based activities and areas of high vessel density (). This data suggests that marine sources of plastic can be quite significant in some areas, in particular on fishing grounds and in navigation channels (NOAA Technical Report 2011). This variation is reflected in debris washing up in coastal areas, with regions of high fishing and/or low coastal populations frequently showing a preponderance of fishing and general vessel related waste (Reisser *et al.* 2014?, others?). In some areas, such as the North Sea, this source has been estimated to make up as much as 90% of the waste stranded along the coastline (Van Franeker 2010).

It is very difficult to get data on the waste disposed of by vessels. A recent study of port reception facilities in the EU provided an estimate of 150,000 to 220,000 tons of waste disposed in port facilities across the EU per year between 2004 and 2010 (Øhlenschlæger *et al.* 2013). The study authors also noted significant variation among years in the waste, yet could not find definitive explanations for the variation (Øhlenschlæger *et al.* 2013). They noted a number of potential drivers for the variation, including development of private disposal arrangements, issues related to reporting structures, and the potential for illegal disposal, driven by cost in time and money, level of supervision, and provision of facilities (Øhlenschlæger *et al.* 2013). A recent study of solid waste disposal behaviour on large fishing vessels operating in the Western Pacific was able to estimate dumping rates of shipboard waste, oil discharges and leaks, and loss of fishing gear covering 8,000 incidents between 2004 and 2013 (Richardson *et al.* 2015). Discharge of solid waste accounted for 69% of the incidents observed, while losses of fishing gear accounted for only 13%. Of the solid waste discharges, the largest fraction (36%) were plastic (Richardson *et al.* 2015). Nearly all of these discharge events are prohibited under the MARPOL convention, an international treaty regulating waste disposal at sea (Richardson *et al.* 2015). While the researchers were able to estimate frequencies and spatial distribution of disposal, they did not provide estimates of volume.

Loss of fishing gear at sea is another substantial source of plastic materials in marine systems, at least with respect to at-sea sources. As in other cases, estimates of the rates of loss and the volumes are difficult to come by, largely due to limited monitoring efforts and little synthesis at the global scale to date (Gilman 2015). Globally it is estimated that approximately 6.4 million tons of fishing gear is lost into the sea annually (MacFayden *et al.* 2009). Loss rates vary by fisheries, with a range of causes including gear design, conflicts between fisheries, overcrowding, weather, and other drivers. Studies suggest gear loss rates on the order of 10 to 20 percent per year for trap fisheries, with losses spatially correlated with fishing effort and catch (Maselko *et al.* 2013). Loss rates exceeding 70% have been reported in some contexts, particularly in cases where gear is in contact with the bottom (Ayaz 2010). Evidence from coastal net removal operations suggests that loss rates are particularly high in some regions. For instance, Wilcox *et al.* (2015) report densities of derelict nets as high as 3 tons per km of coast in northern Australia, in this case due to a complex of illegal fishing, overcrowding, and low awareness or capacity among operators and crew.

4.4 Sinks

4.4.1 Coastal deposition

It is clear that there is a substantial load of plastic items along the world's coastlines. However, there has been little analysis to date of the role of the coast as a sink for plastic transported in the ocean. In particular, there is a significant challenge in parsing out terrestrial and marine sources of plastic along coastal margins. There is a clear pattern of fishing gear being more prevalent in remote locations, while consumer items and other non-fisheries waste is more common in more heavily populated coastal regions, as found in Australia (Hardesty *et al*. 2014) and other regions around the world. While it is relatively clear that the fisheries component of this waste is marine in origin, it is less clear what the relative terrestrial and marine component of the non-fisheries waste is.

4.4.2 Biota

Marine organisms have been suggested as one of the potential reservoirs for plastics in the marine environment, particularly in light of the mismatch between estimated inputs from land and the estimated standing stock of plastic in the ocean (Cozar et al. 2014, Erikson et al. 2014, van Sebille et al. 2015 in press, Derraik 2002). While there have been a number of reviews of plastic interactions with species, most recently by Gall et al (2015), there have been few efforts to document ingestion rates across a species, taxon, community or ecosystem.

There are an exploding number of studies of plastic ingestion, focused on single species, locations, or other limited contexts. A few recent studies have estimated debris loads globally for whole taxa, such as seabirds (Wilcox *et al.* 2015), marine turtles (Schuyler *et al.* 2015), and cetaceans (Baulch and Perry 2014). However, these studies are primarily focused on estimating exposure and potential ecological impacts, as opposed to total load as a component of marine plastic. While the estimated loads in these taxa could be used as a component in an estimate of the total load of marine plastics in the biota, they only cover a tiny proportion of the total number of taxa and biomass that would need estimates in order to evaluate the role of marine biota as a sink for plastics.

4.4.3 Seabed and sediments

A recent review of the literature on plastics debris in the benthos attributed the patterns to 5 major drivers: urban proximity, hydrology, geomorphology, vessel based activities, and river inputs (Corcoran 2015. While there are scattered reports of debris densities, there is to date no system wide estimate of plastic load in the benthos analogous to that in the ocean's surface waters. Plastic concentrations range widely, but typically reach on the order of hundreds to thousands of items per square meter of benthic habitat (Table 5).

Small scale heterogeneity due to the drivers listed above appears to produce much more complex patterns than in surface waters, and probably inhibits any reliable basin scale estimates at this point. For instance, river outflows result in higher concentrations of plastic in the benthos, particularly near urban centres (Corcoran 2015). This effect is increased by the concentration of fishing near urban areas, and particularly near bottom features that both concentrate fish and result in snagging of gear (Corcoran 2015). Similarly, bathymetry and submarine features interact with transport mechanisms, resulting in local retention in canyons (Corcoran 2015).

Critically, many of the sampling methods used to date also introduce biases, either due to sampling location, size selectivity or response to material type, among other sources. Developing a synthetic dataset on plastics in the benthos will require not only robust sampling that can address the complexity of deposition rates and transport mechanisms, but will also require methods to address the bias in the various sampling methods used.

4.4.4 Water column

There has been relatively little sampling in the water column. However, the existing empirical studies document some plastic in the water column below the surface layer (Reisser *et al.* 2015, Deforges *et al.* 2014) A number of surface sampling efforts have noted the short-term effect of downward mixing by winds on plastic densities at the surface (e.g. Collingon 2012). However, the most detailed survey of the water column to date (Reisser *et al.* 2015) suggests that presence of debris in the water column is largely a result of downward mixing by wind, and occurs during periods of strong wind. This implies that the water column is unlikely to be a major sink for plastic particles, as negative or positive buoyancy will likely drive the particles to the surface or bethos, with elevated levels in the water column only during mixing events.

5 Future directions and priority actions

5.1 Focus

The central focus of this report is on modelling and monitoring of plastic in the ocean. This section focuses on priorities for addressing uncertainties and key actions in this context. While we touch on broader issues, such as the relevance of policy, it is primary with respect to its impact on key uncertainties identified with reference to monitoring and modelling.

5.2 Understanding drivers and dynamics of sources

The connection between production, use, and disposal of plastics on land and its losses into the ocean remains a key uncertainty. Critical questions in this area fall into two categories:

Drivers for sources

- How does government policy affect losses of plastic into the ocean?
- What is the relative impact of facilities, incentives, social marketing, and other types of interventions in relation to their cost?
- Are there lessons from particular contexts where plastics losses have been reduced, or have increased, that could be transferred to other regions?
- How do drivers and dynamics differ across the range of economic development and income levels in different countries?
- How can local changes in inputs be monitored cost-effectively to provide feedback to government and non-government actors on the scale of the problem and the impact of their actions?

Source Dynamics

- What is the conceptual model for losses of plastic into the environment generally, and subsequently into marine systems?
- What are the key processes determining these flows in this conceptual model?
- How are the rates of inputs from land and ocean based sources changing with time?
- Do changes in other variables, such as changes in wealth, product design, or economic activity, affect inputs of plastic into marine systems?
- Are there predictable source dynamics that can assist with identifying hotspots for inputs or intervention?

In targeting research and investment in this area, it will be important to link activities to clear outcomes. For instance, a potential outcome could be the design of cost-effective government policies to reduce inputs of plastic to marine systems. This target will define the relative importance of the key uncertainties listed above, and may also suggest additional ones. One of the key uncertainties discussed in the scientific literature, and noted in our expert workshops, was the link between predicted inputs from land and the estimated standing stock of plastics in the ocean. Resolving the substantial mismatch between these estimates requires a more nuanced understanding of the key processes, and estimates of flows given those processes.

5.3 Transport processes

Transport processes in the open ocean, particularly in the surface layer of the ocean, are relatively well understood. Most of the other transport process, and the resulting fluxes between sinks, are much less well understood. For instance, large negatively buoyant items transported by extreme events have been well studied in some contexts. But transport of debris less than 10 cm in dimension is much less well known, with little understanding of movement out from urban areas through waterways and into the ocean. There is a significant body of sediment transport research that could provide a basis for work in this topic, but little has been done to date.

The largest flux identified in our expert workshops was that between the nearshore environment and the coast, both input from the coastline to the ocean, and return of material from the ocean back to the coast. The transport processes governing this flux have received a small amount of study, however, they are complicated by dynamic forcing from winds, tides, and wave action along with heterogeneity in coastal landforms, currents and plastic inputs. This is a key research area, and given the impact of transport at this interface on both inputs to the ocean and loss of materials back to the coast as a sink, this area should be prioritized above the other fluxes and transport processes (Figure 1).

A key research activity in this area would be to use existing transport models to predict transport from coastal sources into the nearshore region, and subsequent transport back to the coast. These predictions could be compared against empirical data, both on at sea distributions of plastic and plastic densities deposited on the coastline.

5.4 Changes in particles with time

Changes in particles with time, in particular processes related to fragmentation and colonization by marine life are key to understanding transport and deposition. If fragmentation processes could be understood, there is some possibility for using these processes in inverse modelling of sources and other key variables. Fragmentation is also very important for estimating potential impacts on marine ecosystems and wildlife.

There are currently several efforts ongoing to look at fragmentation processes, incorporating mechanical action, exposure to ultraviolet radiation, and degradation by marine life (K. Law pers. Comm., W.J. Shim pers. comm). There have not been any publications to date in the marine debris literature focused on breakdown rates of materials, although there are a variety of observational data from debris surveys.

Key uncertainties with respect to fragmentation include the rate of breakdown with time, the influence of exposure to oxidation, ultraviolet radiation, and physical stresses in both open water and coastal contexts, particularly in contact with coastal sediments in the wave zone. These processes are almost certainly affected by polymer type, and may interact with colonization by marine organisms.

It may be prudent to await preliminary results from existing experimental studies prior to identifying priority actions in this area. One key priority that can be identified at this point is extending these experiments into field conditions, as the rates estimated in laboratory studies may not translate directly to field conditions. Replicating natural processes in a field context may require significant time, implying it would be prudent to initiate studies in this area in the near term.

5.5 Deposition processes and sinks

The current mismatch between predicted inputs of plastic to the ocean and the predicted standing stock in the ocean may be explained by rapid throughput of plastic into one of the potential sinks. There has been some work done estimating the flux from the ocean to the various sinks, however, these fluxes remain a fundamental uncertainty. At present, the research on fluxes to the seafloor does not appear to be able to account for the missing material. Similarly, while many species ranging from zooplankton to top predators have been documented as ingesting plastic, it seems unlikely that this mechanism can account for the imbalance between predicted inputs and standing stock. The conclusion from the expert workshops was that the likely sink for the material is the coastline, and potentially coastal sediments.

Understanding the deposition and resuspension process for plastic at coastal margins is likely the top priority for understanding and monitoring plastic in the ocean. In particular, it would be very useful to understand the flux rates and the interaction between debris characteristics (e.g. size, shape, density, buoyancy) and deposition and resuspension. These processes will be affected by environmental conditions, such as prevailing wind speed and direction, wave action, and other transport related variables. Similarly, the characteristics of the coastal region will be important to account for, including geology, topography, vegetation, and other variables that will affect the balance between deposition and resuspension.

Tackling these uncertainties in an efficient manner will require a mix of experimental work, inference from observational studies in the field, and comparison between model predictions and field observations. In order to control for the variation in these processes at local scales, it will be critical to implement studies at a large enough spatial scale to draw inference across local patterns and use robust statistical designs and analyses to control for confounding factors.

5.6 Integrating Sources, Transport, and Deposition in Coastal Regions

The key overall priority, discussed in 5.2, 5.3, and 5.5 above, is the need to a better understanding of the dynamics in the coastal region, in particular the link between coastal sources, transport, and coastal deposition. This key set of processes governs the balance between inputs from sources and deposition in what suspected to be the primary sink. In addition, debris in coastal and continental shelf regions likely has the greatest ecological impact, due to high biodiversity in these regions, and the greatest economic impact due to interactions with tourism, fisheries, transport, and solid waste management.

While this process has been discussed in three separate sections, the most efficient approach is likely to be tackling this system in an integrated fashion, using focal areas to understand sources and drivers, locally relevant transport models to represent movement of plastics, and statistically robust sampling in coastal regions to look at deposition and resuspension. There have been some efforts in this respect, in particular recent work by Isobe *et al.* (2015) along the Japanese coastline and Hardesty *et al.* (in press) in Australia. However, there remains a need for a study that can link land based sources, transport to the marine system and along continental shelves and coastal margins, and deposition and resuspension from coastlines.

This study would need to integrate:

- land-based sampling of wastes and loss rates to the environment;
- flow modelling for wind, water, and human transport to the marine system;
- modelling of transport processes in the marine system, particularly at coastal margins and including deposition/resuspension; and
- robust sampling and analysis of debris in the coastal zone.

This effort would require higher resolution numerical models than have been used for transport to date, along with investigation of transport processes on land, and connection of both sets of transport processes to system scale sampling in the terrestrial system. It is likely to be most productive if conducted using a limited number of case study regions, covering different socio-economic aspects and physical systems.

5.7 Progressing our knowledge

Modelling efforts have greatly improved in recent years, and as computing power increases, so too does our ability to incorporate additional parameters into marine debris modelling. There are presently a variety of modelling approaches available, including circulation models, risk models and bioaccumulation models (ecosystem scale modelling). Each has a relevant role to play in increasing our knowledge and understanding of marine litter transport, and the development and employment of different modelling approaches depends upon the question asked, the region studied, and the overall aim of the research.

One of the advantages of applying modelling approaches to the marine litter issue is that modelling can allow us to apply a variety of approaches at a multitude of scales. With models we can focus on major drivers at a global scale that can scale down to consider local processes. There currently exist global data on wind, tides, waves, pressure and other processes that are identified as critically important. These global data can be scaled down to achieve model solutions at more local scales. While there may be some loss in resolution through such scaling, these approaches will nevertheless improve our ability to map risk – and impact - to marine biota, regions, and ecosystems.

Where possible, researchers should aim to validate models with independent data. Independent validation of models can be used to not only increase model utility and confidence in results, but also increases our understanding of uncertainty. Quantifying, and indeed, acknowledging uncertainty in model solutions can help identify research opportunities and key knowledge gaps. Validating models against empirical data may also yield greater insights to processes, highlight regions or taxa of greater (or less than) predicted risk, provide additional opportunities for policy impact, as well as improve model calibration.

It is generally recognized that coastal areas are especially important due to much higher space and time variability of atmospheric and oceanic conditions, frequent erosion and sedimentation processes, anthropogenic activities (especially fishing), sewage discharge, use of beaches for recreation, presence of industries that manufacture plastics, transport of materials by large vessels, boats maintenance and cleaning, and several engineering operations, like dredging and marine building. Preferably, coastal models will have very high spatial resolution (e.g. 10 m in the horizontal and less than 1 m in the vertical) and include the parametrizations of several bio-geo-chemical processes (such as fragmentation and beaches deposition). Ideally, the time scale would consider short-term effects (periods of few minutes) up to seasonal and decadal variabilities.

Interactions with atmosphere, rivers, land and deep ocean areas would all ideally also be included (as highlighted previously). While the general view is that the greater the resolution the better, the importance of acknowledging the significant contributions to be made with poorer resolution (both vertically and horizontally) cannot be overstated.

Tracing plastics to their sources is often highlighted as critical. This can be difficult in part due to variability between and within regions, which is often greater than realized. Models can, however, be tuned to consider empirical data collected in various regions (e.g. incorporating country, region or basin specific inputs, waste mismanagement and other covariates). Even in the absence of complete data (e.g. from all regions), including sparse or incomplete data can still prove valuable.

Overlapping spatial mapping (for example, with accumulation models) with species distributions facilitates our ability to quantify the risk of plastics to biodiversity and marine ecosystems. Dynamically modelling of the risk or impacts becomes critically important not only for individuals and populations, but also for marine species that are exposed to multiple threats to survival and persistence. Identifying key geographic regions and taxa at higher or lower threat from marine plastics (e.g. Wilcox *et al.* 2015; Schuyler *et al.* 2015) can provide a useful lever to drive policy.

6 Ocean circulation models and oceanographic datasets used for marine debris modelling and particle tracking

There are a number of factors to consider when selecting available ocean circulation models and the environmental drivers that are available for them. Some of the specific questions to consider include:

1) What is the time frame over which you want to model the movement?
2) What is the geographic region or extent which you want to consider?
3) What is your specific zone of interest (nearshore or offshore)?
4) What level of detail do you require (e.g. tides, waves, wind)?
5) What is the uncertainty in the windage, currents and other processes you aim to consider?

Table 7. Available data sets containing environmental drivers for off-line trajectory models.

[1] Can be observation (O), empirical estimate based on observations (EE) or dynamical simulation (M)

Data Set	Description	Type[1]	Environmental Drivers	Spatial resolution/domain Temporal resolution/range	Limitations	Availability
OSCAR	based on satellite sea level and surface winds	EE	surface currents	1/3 degree, global 5-day, 1992-present	satellite-based, limited near-coastlines	NOAA, NASA PO.DAAC
Argo	autonomous profiling floats that drift in the ocean	O/EE	surface currents	1-degree, global monthly, 2003-present	based on surface drift; marginal seas/southern ocean gaps; near shore limitations	APDRC IFremer
Surface Drifters	NOAA's Global Drifter Program (GDP) maintains about 1,000 surface drifters throughout the globe	O/EE	surface currents	½ degree, global monthly climatology	based on drouged drifting buoys; somewhat sparse coverage	NOAA
AVISO	satellite measured sea surface height	EE	surface currents	¼ degree, global daily, 1993-2014		
SCUD	diagnostic model based on satellite winds and sea level	EE	surface currents	¼ degree, global/Pacific daily, 1999-2009 (global) 1999-present (Pacific)		APDRC
SODA	long-integration of data-assimilating model	M	surface currents, surface winds	½ degree, global monthly 1871-2010		APDRC SODA/TAMU SODA/UMD
ECMWF	ocean reanalysis (ORA-S3, ORA-S4)	M	surface currents, winds	1 degree, global monthly 1958-2014		APDRC ECMWF
WW3	Operational wave forecast	M	surface winds, surface waves	1 degree, global hourly, weekly (hindcast and forecast)		NCEP
SWAN	operational wave forecast	M	surface waves	not sure if there is an archive; model is available		

Table 7. Continued

Data Set	Description	Type[1]	Environmental Drivers	Spatial resolution/domain Temporal resolution/range	Limitations	Availability
GFS	Operational weather forecast	M	surface winds	¼ degree, global hourly for past month		NCEP
NCOM	Operational data-assimilating ocean model	M	surface currents, surface winds	1/8 degree, global daily, 2003-2013		
NLOM	Operational data-assimilating model	M	surface currents, surface winds	1/16 degree, global daily 2002-2006 1/32 degree, global daily 2005-2013		
HYCOM	Operational data-assimilating ocean model	M	surface currents, surface winds	1/12 degree, global daily, 2009-present		
BlueLink	Operational data-assimilating ocean model	M	surface currents, surface winds	1/10 degree (variable), regional (90-180, to 20N) daily, weekly forecast		
OFES	hindcast ocean model	M	surface currents, surface winds	1/10 degree, global daily/monthly, 1950-2011		
IPCC	coupled climate models	M	surface currents, surface winds	typically 1-degree global monthly output from decadal runs		
ECCO	data-assimilating GODAE-era model	M	surface currents, surface winds			
ROMS	high-resolution, regional operational model	M	surface currents, surface winds	variable resolution, different regional implementation, e.g., IOOS		
SLIM		M				
Delft-3D FLOW	hydrodynamic near-shore model	M	Produces 2D or 3D dynamic flow fields	Is generic software. Spatial and temporal resolution depends on specific implementation, can be very flexible		Deltares, Open source http://oss.deltares.nl/web/delft3d
Delft-3D WAQ	sediment transport and water quality software	M	Sediment and water quality substances	Is generic software. Spatial and temporal resolution depends on specific implementation, can be very flexible		Deltares, Open source http://oss.deltares.nl/web/delft3d
Delft-3D BLOOM	phytoplankton model	M	Algae concentrations, limiting factors (nutrients, light)	Is generic software. Spatial and temporal resolution depends on specific implementation, very flexible		Deltares, Open source http://oss.deltares.nl/web/delft3d
Delft-3D PART	Particle tracking software	M	Trajectories of particles	Is generic software. Spatial and temporal resolution depends on specific implementation. can be very flexible		Deltares, Open source http://oss.deltares.nl/web/delft3d

Table 7. continued

Data Set	Description	Type^1	Environmental Drivers	Spatial resolution/domain Temporal resolution/range	Limitations	Availability
SIMONA	2D/3D hydrodynamic software	M	Produces 2D or 3D dynamic flow fields	Is generic software. Spatial and temporal resolution depends on specific implementation. can be very flexible		http://simona.deltares.nl/
WFLOW	distributed hydrological (catchment) software	M	1D flow velocity, currents, discharge	Is generic software. Spatial and temporal resolution depends on specific implementation. can be very flexible		Deltares https://publicwiki.deltares.nl/display/OpenS/WFlow+rainfall-runoff+model
SOBEK	1D hydrology software	M	1D flow velocity, currents, discharge	Is generic software. Spatial and temporal resolution depends on specific implementation. can be very flexible		Deltares: https://www.deltares.nl/en/software/sobek/
DFLOW - Flexible MESH	1D/2D/3D hydrodynamic software	M	Produces 1D/2D/3D dynamic flow fields	Is generic software. Spatial and temporal resolution depends on specific implementation. can be very flexible		http://oss.deltares.nl/web/delft3d/d-flow-flexible-mesh

Table 8. Some of the available particle tracking models, with information on their capability and limitations.

Trajectory Code	Description	Highlights	Limitations	Availability	Example Applications
Arianne					
trackmass	U. Stockholm				
CMS	Particle tracking code	written in FORTRAN, source code available, memory efficient, relatively fast, includes forward and backward trajectories, sources/sinks can be digitally available; can read via OPeNDAP			
GNOME	NOAA Oil spill response and restoration model; users can input source/sink and forcing fields and see advection in real time	easy to use; includes terms for uncertainties, weathering, amount of spill; can specify forcing; forward/backward tracking	Digital output (e.g., data file) are difficult (screen output only); source code not available; simulations can be limited by system memory (need to load entire forcing fields)	NOAA ORR	
Pol3DD					
OSCURS	Old NOAA web application	easy to use	very limited for long integrations; web application so digital I/O not possible		
PELLET-2D					
Connie2		User friendly	Updated through 2014	Open source: http://www.csiro.au/connie2/	
Adrift.org.au		User friendly; educational tool	Large-scale resolution	Open source: www.adrift.org.au	

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