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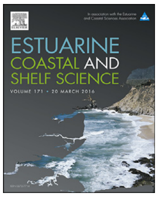

Modelling accumulation of marine plastics in the coastal zone; what are the dominant physical processes?

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ABSTRACT

Anthropogenic marine debris, mainly of plastic origin, is accumulating in estuarine and coastal environments around the world causing damage to fauna, flora and habitats. Plastics also have the potential to accumulate in the food web, as well as causing economic losses to tourism and sea-going industries. If we are to manage this increasing threat, we must first understand where debris is accumulating and why these locations are different to others that do not accumulate large amounts of marine debris. This paper demonstrates an advection-diffusion model that includes beaching, settling, resuspension/re-floating, degradation and topographic effects on the wind in nearshore waters to quantify the relative importance of these physical processes governing plastic debris accumulation. The aim of this paper is to prioritise research that will improve modelling outputs in the future. We have found that the physical characteristic of the source location has by far the largest effect on the fate of the debris. The diffusivity, used to parameterise the sub-grid scale movements, and the relationship between debris resuspension/re-floating from beaches and the wind shadow created by high islands also has a dramatic impact on the modelling results. The rate of degradation of macroplastics into microplastics also have a large influence in the result of the modelling. The other processes presented (settling, wind drift velocity) also help determine the fate of debris, but to a lesser degree. These findings may help prioritise research on physical processes that affect plastic accumulation, leading to more accurate modelling, and subsequently management in the future.

1. Introduction

The input and accumulation of anthropogenic marine debris such as plastics, is regarded in the public domain as an environmental and economic hazard. Macroplastic pollution (items larger than 5 mm) accumulating on the coastline can affect tourism revenue (Jang et al., 2014) and the coastal habitat (Carson et al., 2011). The consumption of plastics, can cause damage to individual animals (Laist, 1997; Gregory, 2009; González Carman et al., 2014; Setälä et al., 2014) and have effects on the food chain (Boerger et al., 2010; Farrell and Nelson, 2013). There is evidence that microplastics (<5 mm diameter) consumed by low trophic level species are transferred up the food chain as they are consumed by other trophic levels (Farrell and Nelson, 2013; Setälä et al., 2014). For these reasons it is important to create management action to prevent plastic waste from entering the environment, as well as devise efficient debris removal schemes. While considering the importance of these factors, there is little data about the way different types of debris move in the ocean, why it accumulates in some locations more than others, and which parameters influence this most.

To maximise effectiveness of plastics debris removal for management and government agencies, geographic prioritisation of removal efforts must be considered. Oceanographic modelling is appropriate as part of a larger strategy to implement prioritisation and management (McElwee et al., 2012). The resolution required to accurately predict areas of accumulation at a beach scale is quite fine, ranging from a few 100 m–1 km. However the recent models of plastic movement in the marine environment focus on models examining much larger scales, for example oceanic scales (Lebreton et al., 2012; Maximenko and Hafner, 2012; Reisser et al., 2013; Ebbesmeyer et al., 2007; also see review by Kubota et al., 2005),

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or within seas (Kako et al., 2011 Pichel et al., 2012) at coarse resolution. The scales and resolution of plastic movement models range from: whole ocean modelling with a coarse resolution of $^1/_2$ degree (Yoon et al., 2010; Maximenko et al., 2012) to a single basin with a finer resolution of $^1/_{12}$ degree i.e. the East China Sea as in Isobe et al. (2009) and the Coral Sea as in Maes and Blanke (2015). The smallest scale of a single coastline, with variable resolution was the Queensland Coast (Australia) in Critchell et al. (2015) and the Gulf of Mexico in Nixon and Barnea (2010). One reason for the large spatial scales is the time over which the simulations are run. The time scales varied from 30 years of simulations as in Lebreton et al. (2012) to a few weeks as in Carson et al. (2013) and Critchell et al. (2015).

Modelling plastics in the ocean can be challenging since plastics range in size, shape, buoyancy, density, etc. To avoid this issue some studies model a specific type of plastic: Ebbesmeyer et al. (2007) modelled a cargo spill (tub toys); Kako et al. (2011) modelled bottle caps; Ebbesmeyer et al. (2011) modelled crab pots; and Isobe et al. (2014) studied different sizes of plastic and how they move in on-shore and off-shore direction. Though many studies continue to model plastics as a general category (Isobe et al., 2009; Martinez et al., 2009; Yoon et al., 2010; Hardesty and Wilcox, 2011; Kako et al., 2011; Lebreton et al., 2012; Maximenko and Hafner, 2012; Maximenko et al., 2012; Reisser et al., 2013; Maes and Blanke, 2015; Critchell et al., 2015).

Specialist large event debris models have also been developed. For example, the NOAA marine debris probability model developed for hurricane debris in the Gulf of Mexico, using 100 m grid cells to compute probability of debris being found after a hurricane. Parameters such as wind speed, storm surge and infrastructure were used to assess the probability (Nixon and Barnea, 2010). A model for the debris from the 2011 Japanese Tsunami has also been developed by Maximenko et al. (2015), they used four different modelling systems with resolution from $^1/_4$ to $^1/_{12}$ of degree grid. The methodology used for oil spills has been found to be effective for modelling floating plastic debris (Le Hénaff et al., 2012), where the floating plastic is assumed to have a velocity equal to the vectoral sum of the water currents and the wind drift velocities. The direct movement of plastics due to the wind (wind drift) is neglected in many studies that model the movements of plastic in the ocean (Isobe et al., 2009; Martinez et al., 2009; Kako et al., 2011; Reisser et al., 2013; Isobe et al., 2014; Maes and Blanke, 2015). In studies that include wind drift, the value of the wind drift coefficient varies from 1% (Ebbesmeyer et al., 2011) to 6% (Maximenko et al., 2015), and in some studies a range of values are used or the value used is not given but instead the empirical formula for calculating the wind drift is given (Kako et al., 2010). In the case of submerged plastic debris, it is spread through the water column, with no exposure to the wind and hence no wind drift is assumed (Reisser et al., 2013).

For a model to become realistic and useful, it not only needs to apply the oil-spill model methodology, like that of the GNOME (Beegle-Krause, 2001), OSCAR (Reed et al., 1995), and other model types reviewed by Potemra (2012), but also needs to include a number of additional processes specific for plastics, which so far appear to have been neglected in marine debris models. These processes are sketched in Fig. 1, and include (1) degradation of macroplastics into secondary microplastics, (2) the different wind drift coefficient for macroplastics (that tend to float) and microplastics (that experience no wind drift as they tend to be in suspension in the water column; Reisser et al., 2013), (3) rates of settling, (4) burial in beaches, (5) resuspension or re-floating from beaches, and (6) the non-uniformity of the wind near the coast especially the dramatically reduced wind velocities behind hills on the land (wind shadow). The incorporation of these parameters into a model should improve the ability to predict the movement and the fate of plastics at coastal scales. This improved and more robust model could be used for plastics in a similar manner to oil-spill models for oil slicks. The oil-spill model methodology is basically advection-diffusion models coupled with chemical sub-models of the weathering of the oil, and are now routinely used by industry management (Chao et al., 2001; Tkalich et al., 2003; Guo and Wang, 2009). Such a model methodology is needed to improve predictions of debris accumulation and thereby improve management strategies for debris removal and mitigation. In addition, the improved model may also be used to backtrack and ultimately help to locate the sources of plastic pollution arriving at a given location, which would also support management goals (Reisser et al., 2013; Thiel et al., 2013). In order to work towards this, true values for the parameters described above must be experimentally determined or found through field observations.

In this study we develop and explain a plastic oceanographic model to study the fate of plastics in estuarine and coastal waters (within 100 km of the coast). We demonstrate the application of this model in the complex case of a rugged coastal region with shallow waters and numerous islands and headlands. The basis of this plastics oceanographic model is a high resolution oceanographic, advection-diffusion model that also includes all the processes identified in Fig. 1. We propose a simple method to assess and rank the relative influence of these various physical processes on the movement of plastics in the coastal zone, using this method to prioritise research of the physical processes influencing plastic movements at sea.

2. Methods

2.1. The oceanographic model

To evaluate the relative importance of coastal processes on the movement of marine debris, we conducted a sensitivity analysis using the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM; www.climate.be/slim). It is a depth-averaged, two dimensional, finite element model with variable resolution developed by Lambrechts et al. (2008). It has been used for a variety of physical and ecological modelling tasks including: fine sediment, fish larvae, floating debris, and turtle hatchling dispersal (e.g. Lambrechts et al., 2008, 2010; Hamann et al., 2011; Andutta et al., 2013; Critchell et al., 2015). The variable resolution (down to 100 m resolution) makes the model particularly useful in shallow coastal zones with complex bathymetry and topography. This model allows for fine scale horizontal resolution and reduces the computational effort necessary to represent the whole model domain. The appropriate use of a depth-average model in shallow, vertically well-mixed waters was previously explored by Critchell et al. (2015). In that study, it was shown that in well-mixed shallow water environments, the diffusion patterns of particles are very similar at the surface, middle and bottom of the water column, and the use of a three dimensional modelling approach, (which computationally very expensive) may be an unnecessary use of computational effort.

The study region used to conduct the sensitivity analyses was the Whitsunday region of the Queensland coast, and is part of the Great Barrier Reef Marine Park (20.2 S, 149.0 E; Fig. 2). This region is made up of approximately 74 coastal islands, coral reefs and other marine and coastal habitats. The coastal waters are primarily shallow with a mean depth <20 m (Fig. 2). This region is also a tourism centre, making it economically important not only for Queensland but Australia as a whole. The area has had a marine debris removal program run by Eco-Barge Clean Seas Inc. since 2009. The islands and reefs create high levels of topographic and hydrodynamic complexity, and create a large variety of unique locations with a rugged coastline, providing an ideal situation to