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Modelling the fate of marine debris along a complex shoreline: Lessons from the Great Barrier Reef

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ABSTRACT

The accumulation of floating anthropogenic debris in marine and coastal areas has environmental, economic, aesthetic, and human health impacts. Until now, modelling the transport of such debris has largely been restricted to the large-scales of open seas. We used oceanographic modelling to identify potential sites of debris accumulation along a rugged coastline with headlands, islands, rocky coasts and beaches. Our study site was the Great Barrier Reef World Heritage Area that has an emerging problem with debris accumulation. We found that the classical techniques of modelling the transport of floating debris models are only moderately successful due to a number of unknowns or assumptions, such as the value of the wind drift coefficient, the variability of the oceanic forcing and of the wind, the resuspension of some floating debris by waves, and the poorly known relative contribution of floating debris from urban rivers and commercial and recreational shipping. Nevertheless the model was successful in reproducing a number of observations such as the existence of hot spots of accumulation. The orientation of beaches to the prevailing wind direction affected the accumulation rate of debris. The wind drift coefficient and the exact timing of the release of the debris at sea affected little the movement of debris originating from rivers but it affected measurably that of debris originating from ships. It was thus possible to produce local hotspot maps for floating debris, especially those originating from rivers. Such modelling can be used to inform local management decisions, and it also identifies likely priority research areas to more reliably predict the trajectory and landing points of floating debris.

1. Introduction

The growing spread and impact of marine debris is regarded as a ubiquitous issue in the world's oceans (Derraik, 2002; Thompson et al., 2009). Marine debris poses a high risk to the global environment (Siung-Chang, 1997), economy (Cho, 2009; Butler et al., 2013) and human health (Thompson et al., 2009). Debris is known to negatively impact marine animals of all tropic levels, by entanglement and through ingestion. Debris also modifies habitats and can be a vector of invasive species transport (Barnes and Milner, 2005). The economic impacts of marine debris are arguably difficult to quantify, however they are likely to be considerable. For example, economic impacts arise when drifting debris causes damage to vessels (Nash, 1992). The negative aesthetic impact of beached marine debris on the coastline can damage tourism by reducing the appeal of a destination (Roehl and Ditton, 1993; Jang et al., 2014). Clearly the economic and environmental impacts of marine debris accumulation require management actions at multiple levels of government and at multiple spatial and temporal scales.

A commonly employed management tool to reduce the environmental and economic costs of marine debris is to remove debris from shorelines, through clean-up activities, yet the cost of these

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shoreline clean-ups relative to their benefits are rarely assessed (Ballance et al., 2000). Clean-up activities are labour intensive and therefore have high costs, leading to reliance on voluntary workers and community groups. Because of this, ease of access often dictates the location of the clean-up activity. Previous studies have found that marine debris accumulates on some beaches more than others, and in most areas the reason(s) for this are poorly known (Convey et al., 2002; Boland and Donohue, 2003). Hence to improve understanding of the costs, benefits and the efficiency of beach clean ups as a mitigation tool requires improving our understanding of source, transport and sink (hotspot) areas (Vegter et al., 2014).

Numerical models have been used for many years to simulate ocean circulation. Hydrodynamic models are used to map water movement, using combinations forcings from *in situ* and remote sensing observations (e.g. current-metres, radar, satellite etc.). Recent approaches to understanding transport of marine debris have used combinations of ocean circulation models such as Lagrangian particle tracking (Potemra, 2012; Carson et al., 2013), direct tracking of ghost nets using aircraft or satellites (Pichel et al., 2012; Wilcox et al., 2013) and physical tracking of cargo lost at sea (e.g. Ebbesmeyer et al., 2007; Robinson, 2009). Studies of marine debris dispersal have primarily occurred over broad spatial scales of an ocean (e.g. see the review by Potemra, 2012; and the modelling of the fate of debris from the 2011 Japanese tsunami by Lebreton and Borrero, 2013) or a regional sea (e.g. the Japan Sea by Yoon et al., 2010). However, the management of marine debris occurs over the smaller spatial scales of government jurisdictions. To be useful, models of marine debris must match the scale of which management can be applied or policy implemented, especially along the coast in order to effectively inform the prioritisation of resources for mitigation (Vegter et al., 2014).

The Great Barrier Reef (GBR) of Queensland, Australia, is a Marine Park and a listed World Heritage Site of exceptional natural beauty and economic importance (Fig. 1). Marine debris is recognised as an emerging threat to the ecological and social value of the GBR, and currently information on sources of debris, how it is transported and where it deposits are largely unknown (Great Barrier Reef Marine Park Authority, 2014). Understanding the source and fate of marine debris in the Great Barrier Reef Marine Park (GBRMP) is both important and possible because there are local scale, high resolution, hydrodynamic models developed for some of the GBR coastline (e.g. Lambrechts et al., 2008) that have been used to track the dispersal of organisms (e.g. Hamann et al., 2011; Andutta et al., 2012, 2013; Thomas et al., 2014) and model physical processes (e.g. Lambrechts et al., 2010; Andutta et al., 2011). A challenge of adapting the model to simulate marine debris transport is that floating objects are strongly influenced by wind as well as currents.

In this study, we utilised hydrodynamic and advection-diffusion modelling to predict the fate of floating marine debris originating from urban rivers and ships, at a scale relevant to management of the GBRMP and in a topographically complex environment. To achieve this we adapted the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM; www.climate.be/slim) developed by Lambrechts et al. (2008), by adding a wind drift coefficient and a beaching factor to simulate the dispersal, and eventual beaching of marine debris (e.g. Andutta et al., 2012; Andutta et al., 2013; Wolanski et al., 2013). We then used the model to simulate the transport routes and beaching areas of debris released from urban rivers and shipping activity within the GBR. We show that the model of the fate of floating debris along a rugged coastline is relatively successful in reproducing the observations. Finally we describe under what conditions the use of the models is most reliable and can probably be used for producing hotspot maps at management-relevant scales. From this study we identify research topics most likely to improve the reliability of models of floating debris.

2. Methods

2.1. Advection-dispersion model

The Great Barrier Reef, on the east coast of Australia (Fig. 1; Latitude $9^{\circ} - 24^{\circ}$ South) has a tropical climate with distinct wet and dry seasons influencing river run off. The GBR system is a shallow and relatively sheltered environment with complex topography, consisting of continental islands, coral cays, coral reefs and shoals. Water movements within the GBR are dominated by the South Equatorial Current that flows from east to west across the Pacific Ocean before dividing, where it meets the continental shelf of Queensland, splitting into a northerly (the North Queensland Coastal Current) and a southerly component (the East Australia Current) (Wolanski et al., 2013). The currents experienced along the coast of Queensland are further influenced by the reefs and islands of the GBR steering the currents and forming the sticky water effect (Andutta et al., 2012). The reefs also create tidal jets, eddies, and slack water areas, which affect the mean flow (Pattiaratchi et al., 1987; Mantovanelli et al., 2012). Hence to step down hydrodynamic models from oceanic to regional scale it is necessary to merge large scales and small scales and incorporate the feedback from small scale to large scales (Wolanski et al., 2003). To investigate marine debris accumulation (i.e., floating debris movement) within the Great Barrier Reef region, we used the SLIM (Lambrechts et al., 2008). This is an unstructured, finite element, two-dimensional hydrodynamic model. The SLIM model is highly versatile and applicable to the GBR region, because it uses triangular elements (Fig. 2). Hence the model has a fine scale resolution in areas of complex oceanography (near the coast, headlands, reefs and islands), and coarser resolution in areas of homogenous water movements (Lambrechts et al., 2008).

There are six different factors that dictate the final destination of floating debris and we use these to set up our model to influence the final destination of simulated buoyant particles in the ocean (Fig. 2). Factors 1 (current speed and direction) and 2 (wind speed and direction) are relatively straight-forward to quantify via standardised physical measurement and publicly available databases. Factor 3 (seeding locations) is the source of debris. The time of drift without wind (Factor 4) only occurs if the wind is light after seeding. During the drift, particles are affected by sub-grid scale diffusion (i.e. at scales smaller than the simulation grid; see a review by Hrycik et al., 2013), often represented in a model by a horizontal diffusivity coefficient. The location of the object when the wind event begins (Factor 5) is dependent on where the object enters the water (Factor 3), the speed and direction of the current (Factor 1) and (if applicable) the time it drifts in low wind conditions (Factor 4). Finally, Factor 6 (the wind drift coefficient) is the magnitude of the winds' effect on the object, which is a function of the buoyancy and shape of the object (Daniel et al., 2002). In the field, there are high levels of complexity due to the combination of these factors (and other small scale forces), making accurate represent difficult in simulations.

The SLIM model has two components, (1) the hydrodynamic component that calculates the currents and sea-level values for each element for each time step (300 s). The hydrodynamic model incorporates the tides, winds and input/output forcing. We used the SLIM hydrodynamic model results of Andutta et al. (2013), which uses field data of wind and hydrodynamics collected from 01/08/06 to 22/01/07 from stations in and adjacent to the GBR and a uniform wind is considered over the whole domain. At the open