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

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Key words:

Marine debris ; modelling; beach orientation; wind drift coefficient; Coastline; Great Barrier Reef;

Marine

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 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-meters, radar, satellite etc.). Recent approaches to understanding transport of marine debris have used combinations of ocean circulation models such as Langrangian 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 (Figure 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 and 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

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 (Figure 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 the 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 Great Barrier Reef, on the east coast of Australia (Figure 1; Latitude 9° – 24° 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 (Figure 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).

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 (300seconds). 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 boundaries, sea level data from TOPEX were used to force tides and the inflow from the Coral Sea, by the East Australian Current, was modelled following Andutta et al. (2011). These field data are a representative sample of long term average wind speeds and directions. The shallow water equations are solved using a second order Discontinuous Galerkin finite element discretisation. The mesh size ranges from 1km near the coast and on the reefs, to 10km in deeper area. More details about the hydrodynamic model can be found in Andutta et al. (2013). (2) The advection-diffusion component uses a Langrangian scheme to track the movement of waterborne particles by advecting the particles over each time step using the predicted currents, and then spreading them laterally using a Markov scheme where the rate of spread is determined by the value of the horizontal diffusion coefficient.

Following Fischer (1979) and Hrycik et al. (2013) horizontal mixing in the SLIM model is parameterised by a horizontal eddy diffusion coefficient which represents mixing in sub-grid scales (i.e. at scales smaller than the model mesh size). This diffusion is strongly enhanced in reef and coastal waters by the shear flows around headlands, reefs and islands. Accordingly, the method of Andutta et al. (2011) was used to account for water movement at scales smaller than the simulation grid. A sub-grid scale eddy diffusion coefficient value of 10 m^2s^{-1} was applied (Andutta et al., 2011; Wolanski and Kingsford, 2014). Due to the nature of the model the coastal boundary was derived from the bathymetry data, not from topographic data and therefore is a simplified coastline.

Like in oil spill models, to track floating debris the advecting phase was modified so that the velocity of a particle $<V_p>$ is,

$$<v_p> = <v_{water}> + W_d<v_{wind}> \qquad (1)$$

where <> is a vector, $<v_{water}>$ is the water velocity for that time step, $<v_{wind}>$ is the wind velocity for that time step from field data and W_d is the wind drift coefficient.

2.2 Wind drift coefficient

The effect of the wind on the speed and direction of particles (the wind drift coefficient) is particularly important for modelling dispersal of floating objects (buoyant marine debris). The wind drift coefficient is directly linked to the buoyancy of the object and the buoyancy of the debris is mostly unknown. Because of the uncertainty in the level of buoyancy the effect of wind is consequently challenging to predict. To acknowledge the variable effect of wind drift is likely to have on the final destination of released particles, we examined the influence of three different wind drift coefficients on beaching location and rates. We used values of wind drift coefficient (W_d) of 0.01, 0.02 and 0.05 following Carson et al. (2013), Beegle-Krause (2001) and Hardesty and Wilcox (2011). These values represent the percentage of the wind vector that is used by the model to compute the particle movement (see Equation 1).

2.3 Seeding parameters

The river simulations were seeded from the mouths of the rivers that run through 5 large urban centres within the model domain: Trinity Inlet (Cairns), Ross River (Townsville), Pioneer River (Mackay), Fitzroy River (Rockhampton), and Calliope River (Gladstone) (Figure 2). We constructed an idealised flood plume around a central point in the mouth of each, mimicking a wet season flood event. Fifteen random points per river were placed within this ‘flood plume’ resembling where the oceanic forces outweighed the fluvial forces (10,000 particles were released at each seeding location). In these simulations the number of particles released from each river mouth was the same however we expect the amount of debris released from each river would differ related to population and management strategies in place. For the shipping lane simulations we digitized shipping lanes from the Maritime Safety Queensland & Australian Maritime Safety Authority User Guide Maps (REEFVTS, 2011) and placed one seeding location (of 5000 particles) every 10km along the known shipping lanes.

The date of release was also varied to understand the role of variable wind events in the accumulation of debris on the coast. The urban river simulations were started on the 1st, 14th and 31st of December 2006 and were run until the particles beached or left the model domain. These dates were chosen as they occur at the start of the tropical wet season. In tropical regions there is very little river flow in the dry season and during this time litter accumulates in urban drainage areas. Once the first rains start the first flush will push the accumulated litter downstream and into the ocean therefore debris is most likely to enter the coastal zone from tropical river systems at this time (Moore et al., 2011). The commercial shipping simulations used three starting dates, approximately one month apart (01/08/06, 01/09/06 and 30/10/06), to encompass many different wind events and to allow maximum time for the particles to reach terminal destinations. The particles in the simulation were designed to imitate domestic, buoyant debris, for example a plastic bottle. As the time periods of these simulation were short (2 weeks for river simulations and 30 days for commercial shipping lanes) and the simulated objects large, it was not necessary to consider the simulated particles changing density.

2.4 Geographic factors

To understand the influence of beach orientation in relation to dominant wind direction we compared the proportion of simulated particles that accumulated on each 1km section of coastline. Doing this enabled us to examine whether sections of the coast with various orientations accumulated debris at different magnitudes. GIS analysis were confined to the coastline within the limits of each simulation, to avoid confounding the results, by comparing segments of coastline that are outside the simulation zone, and therefore would not have particles beach at that location. To determine the influence of beach orientation on the accumulation of particles, we assumed that if the particles were distributed evenly along the coastline, the proportion of particles received by each coastal orientation category would be the same as the proportion of the coastline in that category. To define the orientation categories, the "North facing" category was taken as 337 to 22.5 degrees and then clockwise in equal segments: Northeast, East, Southeast, South, Southwest, West and Northwest.

3. Model validation

Field data suitable to validate the simulations was rare however modelled predictions of debris accumulation were compared to two field data sets on the trajectory floating debris in the GBR, to qualitatively assess the accuracy of the model. Firstly, Walker and Collins (1985) released drift cards at three sites off the coast of Townsville, Queensland, from October 1979 to January 1980. There are no data on the speed of the East Australian Current during that time; we assumed that its speed was the same as in 2006 for which period our model was verified by Andutta et al. (2011). Seeding and recovery data from Walker and Collins (1985) were compared to a simulation seeded in the same locations run in SLIM on days with average wind. The simulated beaching locations were in the lower end of the range reported by Walker and Collins (Figure 3a). However 86% of the drift cards were never found and thus the number of cards received was very small and it is not known if this remaining 14% (n=303) are representative of the mean drift. There is clearly some discrepancy between the observed and predicted landing locations. However some of this discrepancy may be explained by the large inter-annual variability (±50%) of both the wind and the South Equatorial Current (i.e. the inflowing current in the Coral Sea offshore from the Great Barrier Reef) that drives the net currents in coastal waters (Brinkman et al., 2002; Wolanski et al., 2013). It is also likely that some beached cards were resuspended by waves and the wind then advected them further north from their initial landing locations. This may explain some of the difference between the model results and the field data because the model predicts only the location of the initial beaching of the cards while the field data show where the where the floating cards were ultimately recovered.

Secondly, the model was verified qualitatively against data on the drift of a current meter that was lost for a short time (E. Wolanski, pers. com.). The current meter mooring was deployed in early June 1986, on the east side of Bowling Green Bay, south of Townsville, Queensland (Figure 3b). The current meter had 30 kg net buoyancy from two spherical, subsurface buoys. The meter was deployed in calm weather. It broke free from its bottom anchor during strong south easterly winds that started two days after deployment. One week later it was found high up on the rocks on the eastern side of Magnetic Island approximately 57 km away (Figure 3b). The current meter would have floated under the two buoys, one of which would have been almost completely on the surface and the other partially submerged due to the weight of the current meter, resulting in a large wind drift coefficient in the order of 5-10% (Meteo France, 2013). Again we have no data on the speed of the East Australian Current at that time; assuming again that speed was the same as in 2006. The field observation was precisely in the middle of the predicted beaching locations (Figure 3b), from two simulations released on a day with high wind (01 Aug 2006) and one with low wind (12 Sept 2006) using a wind drift of 5% for both release dates.

MOHID (http://www.mohid.com/) is a three dimensional finite volume model with a structured grid. As with SLIM, MOHID consists of a hydrodynamic model and a Lagrangian advection-dispersion model. MOHID was used to model the dispersion of larvae from One Tree Island (23.5075^{0}S 152.0914^{0}E) in the southern Great Barrier Reef in a small scale domain (36 km by 35 km). The rectangular cells ranged in size from 100 × 200 m near reefs to 500 × 500 m in the open water. MOHID was forced with a constant wind of average strength (6.24 ms^{-1}) in the prevailing ESE direction and the dominant M2 tidal component with amplitude of 1 m. A time step of 20 seconds was used. The hydrodynamic model was allowed to spin up for 1 day before passive tracers were seeded. The passive tracers were released at one site on the northern face of the island, and continuously at a rate of 0.25 particles/second for 2 days. Though there were some differences due to the complex 3D flows around an island, generally the passive tracers seeded from One Tree Island in the small scale three dimensional MOHID model had similar dispersal patterns when set to remain near the surface, in mid water, and near the bottom (Figure 3c). Thus the 3D model supports earlier findings that 2D and 3D models predict similar currents in shallow, well vertically-mixed regions such as the GBR (Falconer et al., 1986; Pattiaratchi et al., 1987; Wolanski et al., 1996; Lambrechts et al., 2008; White and Wolanski, 2008). Thus the use of the SLIM 2D model in our study area is justified.

4. Results

4.1 Effect of the wind drift coefficient

In all our simulations where the wind drift coefficient was varied, we found that increasing the wind drift coefficient from 1% to 5% reduced the particles at the extremes of the geographic spread. For example seeding particles at Trinity Inlet with 1% wind drift coefficient resulted in a geographic spread of 0.40^0 latitude whereas with 5% the particles were spread over only 0.17^0. However, the location of the zones of highest accumulation did not vary between wind drift coefficients (Figure 4). For example, for simulations seeded in the mouth of the Pioneer River the peaks in accumulation were at latitudes -21.02, -21.0.5, -21.11, -21.17, -21.20 and -21.25 (Figure 4) regardless of wind drift coefficient applied, however the level of accumulation (height of the peak) varies.

4.2 Effect of release date

Small and inconsistent differences were observed in the location of highest accumulation when the simulation start date was changed (Figures 5 and 6). Overall the modelling demonstrated that releases from each river site over three dates resulted in the same locations consistently accumulating particles, irrespective of when the particles were released, however magnitude of accumulation did change (Figure 5). Contrary to this, in the shipping lane simulations we found small variations in locations of highest accumulation across the release dates (Figure 6). The most even (latitudinal) spread of particles was in the October run and the least from the September run (Figure 6). There was a notable feature at approximately latitude -23, (Figure 6, Southern study area) where a small, but dramatic, change in the orientation of the coastline, corresponds to a consistent low accumulation of particles across all simulation dates.

4.3 Geographic factors

When we released particles from urban river mouths they predominantly accumulated on beaches in east and northeast categories. However, when particles were released from the shipping lanes, beaches in east, southeast and south categories accumulated the highest proportion of particles. There was a significant difference between homogeneous distribution and the observed distribution in both cases (Figure 7). When looking at both river and shipping lane simulations combined: beaches that face to the east and south east accumulate more debris than beaches with other orientations.

4.4 Hotspots of accumulation

All simulations that began in urban river mouths resulted in high accumulation of particles close to the river mouth, with an average geographic spread of 30 km from the river mouth. When simulations were started further offshore (as in the commercial shipping simulations) the distance travelled by particles before landing was further (on average 125km) and thus less predictable. In the field these sources act at the same time, i.e. areas close to river mouths accumulate debris from both offshore (vessel) and from terrestrial (river mouth) sources. Collectively, we predicted that beaches that are most likely to accumulate large amounts of debris if they are facing east to southeast and within close proximity to an urban river mouth (Figure 8). Conversely, beaches are less likely to accumulate large amounts of debris if they are further from an urban river mouth and facing northwest. The caveat here is that this prediction does not consider debris that is left by beach users.

5. Discussion

5.1 The importance of small scales in the dispersion of floating debris

Our study confirms the feasibility and utility of using high resolution, advection-dispersion modelling to understand the fate of floating marine debris along a topographically complex coastline. Modelling at this scale is of particular interest to management agencies. We found that debris sourced from urban rivers has a much smaller and more predictable dispersal range than debris sourced in the commercial shipping lanes (i.e. off shore). Also the spread of debris from sources further offshore had more variability in beaching locations due to the longer time spent under the influence of variable wind (speeds and directions; Figure 2). Different tears of government have responsibility at different spatial scales. The first beaching location of river sourced debris would be of the responsibility of local council or state government, whereas the debris flushed from beaches into Great Barrier Reef Marine Park waters is the responsibility of state or federal government. That being said, the modelling also shows that debris will accumulate preferentially on coastlines that face the dominant wind direction, in our case south/south-easterly. The beaches of highest accumulation seldom changed regardless of changing conditions in the simulations. This knowledge provides the possibility to target sections of coastline for clean-up activities to reduce the economic and ecological impacts of marine debris.

Wind conditions have a large effect on the speed and direction of floating objects. However varying the wind within the range of normal values (changing the start date of simulations) did not influence the physical location of highest accumulation of debris. Although water flows in the coastal zone are constantly changing with the daily tides and changes in wind velocity, this suggests topography plays a strong role in the determination of accumulation areas. Our modelling demonstrates that the dominant wind direction was the main effect on the location of debris accumulation and hence in areas of coastline orientated towards the dominant wind accumulating proportionally most debris. This study does not attempt to predict the locations of accumulation outside of “normal” conditions, for example a large storm (Tropical Cyclone Yasi 2011) or large flood event (Rockhampton Floods

2011). These events are undoubtedly a large source of debris but the field data on the sources of marine debris are unavailable for these events, and the individual conditions would need to be assessed on case by case basis to predict the accumulation areas following such events, in a similar manner to that of oil spill modelling.

The differences in dispersal patterns observed between river source and shipping source is the difference in time spent in the water. River source simulations spend a short time in the ocean and therefor have very localised distributions whereas shipping lane simulations spend much longer in the ocean being affected by the diffusion forces. Mean distance travelled when released from river sources 18.8km and mean distance from shipping sources 249km.

There are two reasons why the diffusion in coastal waters of floating debris that moves under the influence of both currents and wind, is larger than that of particles moving under the influence of currents only. Firstly, the currents reverse at tidal frequency; the wind also varies at time scales of hours to days; these changes are accompanied by enhanced turbulence of both the wind and the currents (Lozovatsky et al., 2010; Korotenko and Senchev, 2011; Korotenko et al., 2012) therefore this results in enhanced turbulent diffusion for floating debris. Secondly, the horizontal shear of the wind around hills (Katurji et al., 2011) and of the currents near headlands and islands (Vermaas et al., 2011) both increase lateral mixing, i.e. mixing perpendicular to the direction of the currents and the wind; because the wind and the currents are generally not parallel with each other, increased horizontal diffusion of floating debris results. The longer marine debris is exposed to this diffusion the less predictable the trajectory will be, as in the case of our shipping lane simulations.

5.2 Needs for future research

Our study identified a number of research topics to improve the reliability of modelling the fate of floating debris. We wish to point out what we believe to be the most important ones in term of helping to produce more reliable models. In our study once debris was beached we classed that as its final destination. In reality coastal processes such as tides and waves may resuspend some of the landed debris while not moving the remaining debris, some of which may become buried in the sediment. Also once beached, and if not resuspended, the plastics will begin to degrade forming smaller pieces with different physical properties. Research on these processes is practically non-existent in the scientific literature and is very much needed (Vegter et al., 2014; Eriksson et al., 2013).

Hills on islands and headlands may create calm water areas downwind of such islands and thus change the trajectory of debris and the deposition onto beaches. To include this effect would necessitate coupling small-scale atmospheric models with small-scale coastal oceanography models; such coupling of models are exceedingly complex and rare in the scientific literature (e.g. Myksvoll et al., 2012) but are needed to improve the accuracy of prediction of debris deposition on beaches. This is likely to increase the variance of beach surveys, and alter the ability to accurately quantify beached marine debris from rare visits. Collection of debris each day may provide improved estimates of debris (Eriksson et al., 2013).

While data exist on floating debris flows from several rivers, there are virtually no quantitative data on the rate of debris discharge from commercial and recreational vessels. Without such data, models of debris accumulation on beaches will remain qualitative and the identification and quantification of the source of the debris will remain problematic. It must also be considered that the types of debris in the ocean are wide and variable, the modelling we have presented is only one type of medium sized buoyant objects (e.g. a plastic water bottle).

Finally it is important to consider the degradation rate of floating plastics and other degradable material. Degraded plastics may lose their positive buoyancy and either disperse as a waterborne particle or sink to the bottom. Scientific literature on such processes is scant but is urgently needed because of the increasing threat posed by discarded plastics to the marine environment.

5.3 Conclusions

Our results demonstrate the utility of advection-dispersion modelling in understanding movements and accumulation of marine debris at management relevant scales. As a World Heritage Site, with an increasingly prominent marine debris issue, the GBR is a valuable study location for possible management initiatives. The management of marine debris in the GBR region is currently limited to Non-Government Organisations (such as Tangaroa Blue, Eco Barge Clean Seas Inc. and community groups) working to remove debris and raise awareness, often funded by government grants and company donations. However these organisations frequently rely on volunteers to collect and sort debris, raise awareness and even work administratively. Due to reduction in interest, volunteer labour as a resource, wains over time. To maintain interest it is important for volunteers to have a sense of achievement after the activity, for beach clean-ups, this often comes from removing a large amount of debris. To achieve maximum debris removal in the (often limited) time available, the location of the clean-up is important. Locations that will have a large amount of debris should be prioritised for clean-ups. Our model provides a tool to prioritise beach clean-ups, which is the first step for decision makers to increase ‘bang for your buck’ out of these activities.

6. Acknowledgements

The development of the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM, www.climate.be/slim) has been supported by the Communauté Française de Belgique under contract ARC 10/15-028. Jonathan Lambrechts is a postdoctoral researcher with the Belgian Fund for Research (F.R.S.-FNRS). Christine Wildermann created Figure 2. Mia Hoogenboom gave valuable advice on an earlier draft of this manuscript. Flavio Martins advised Jodie Schlaefer during the 3D modelling used in this manuscript.

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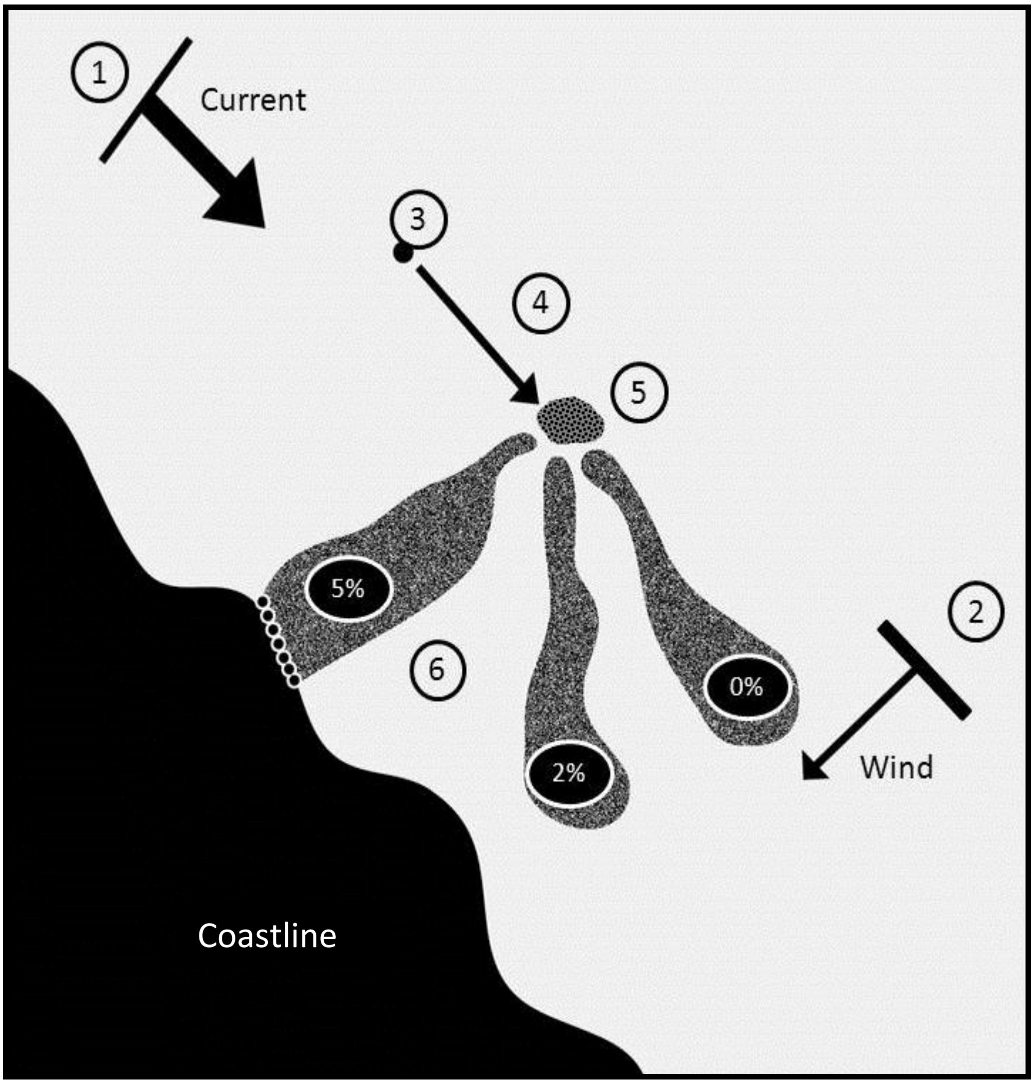

Figure 2: Schematic drawing of the dominant factors affecting the dispersal at sea and ultimate landing of floating marine debris. 1. Mean current speed and direction. 2. Wind speed and direction. 3. Location of the object entering the water. 4. The time that the object would drift with the currents and disperse under oceanic mixing in the absence of a shoreward wind event. 5. The location of the object when a wind event begins. 6. The wind drift acting on the object, parameterised as a wind drift velocity of the floating object that is a fraction of the wind velocity, during which time the object still drifts with the currents also.

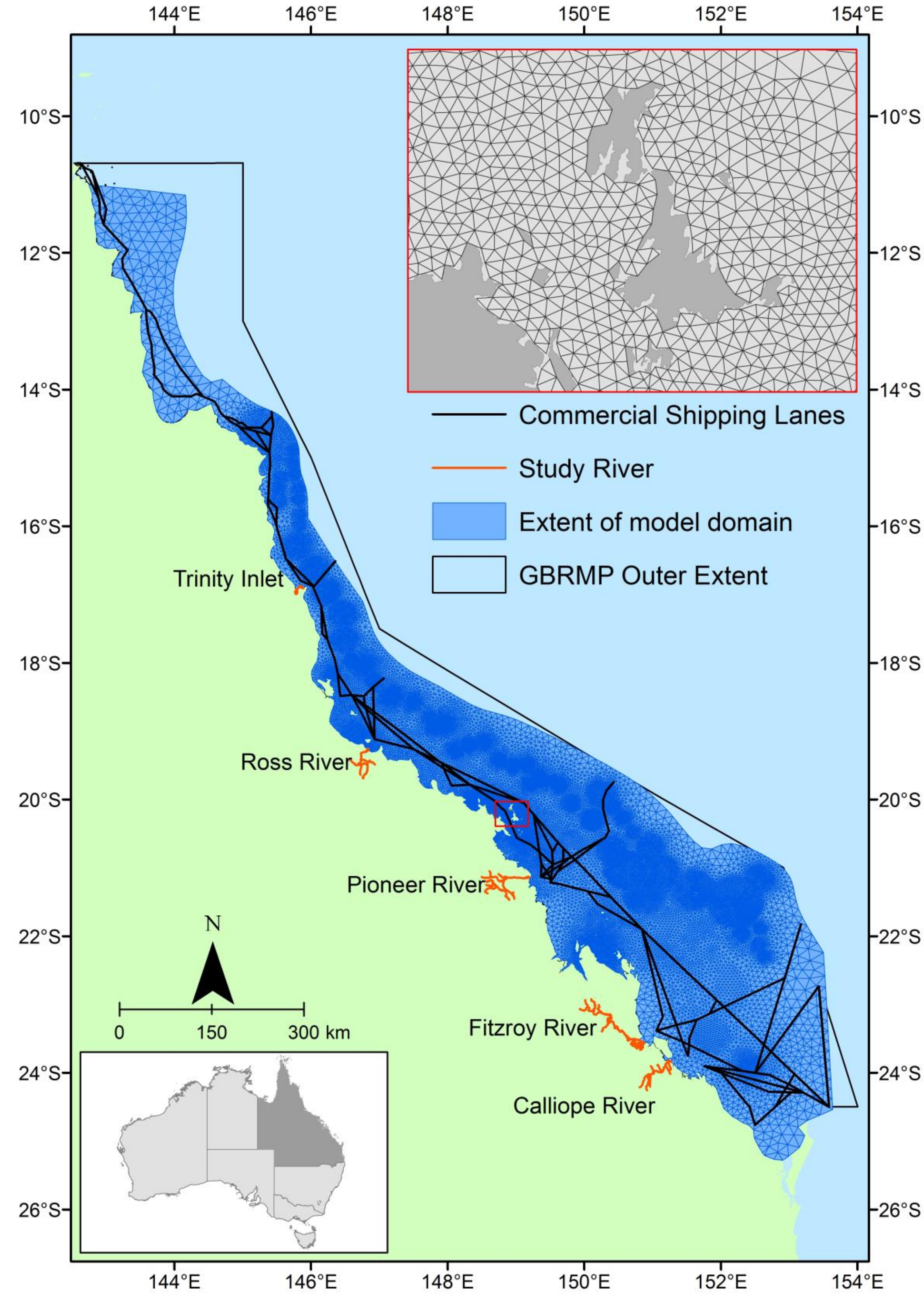

Figure 1: Map of the study region and the oceanographic model mesh. The Great Barrier Reef Marine Park, designated shipping routes and the urban rivers used in the study are indicated. The red extent indicator shows the physical location of the insert showing a more detailed view of the triangular element mesh of the SLIM.

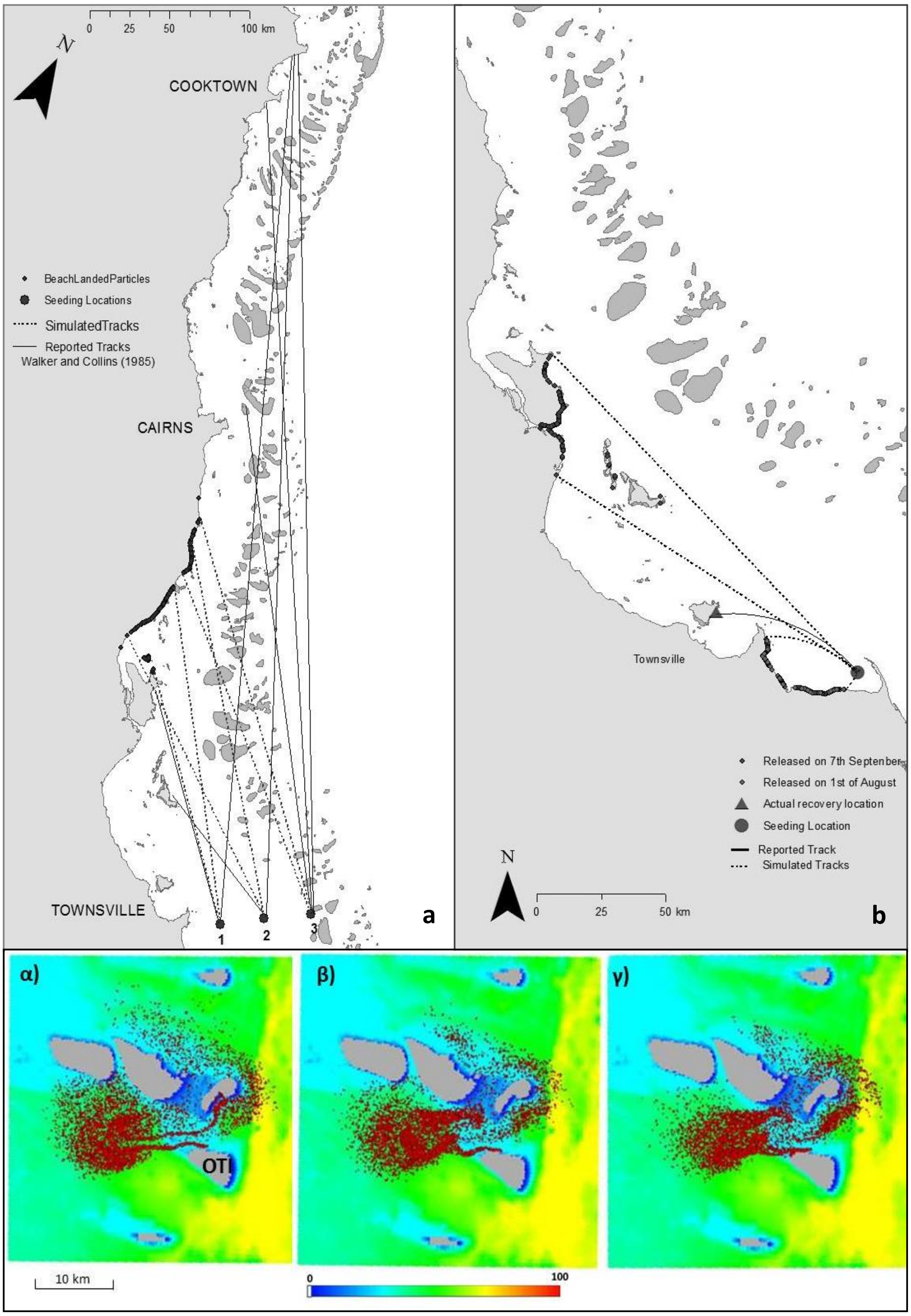

Figure 3: Model validation. (a) The range of drift card retrieval locations from field data redrawn from Walker and Collins (1985). (b) The loss and recovery of a current meter. In (a) and (b) the solid lines represent the range of beaching locations from source to recovery locations observed in the field, and the dashed lines represent the predicted tracks, created by the model. (c) The tracer plumes predicted by the MOHID 3D model after 2 days when the tracers were released continuously at One Tree Island (OTI), were set to remain α) near the top of the water column, β) at mid-depth and γ) near the bottom of the water column. In (c) the colour bar indicates the bathymetry.

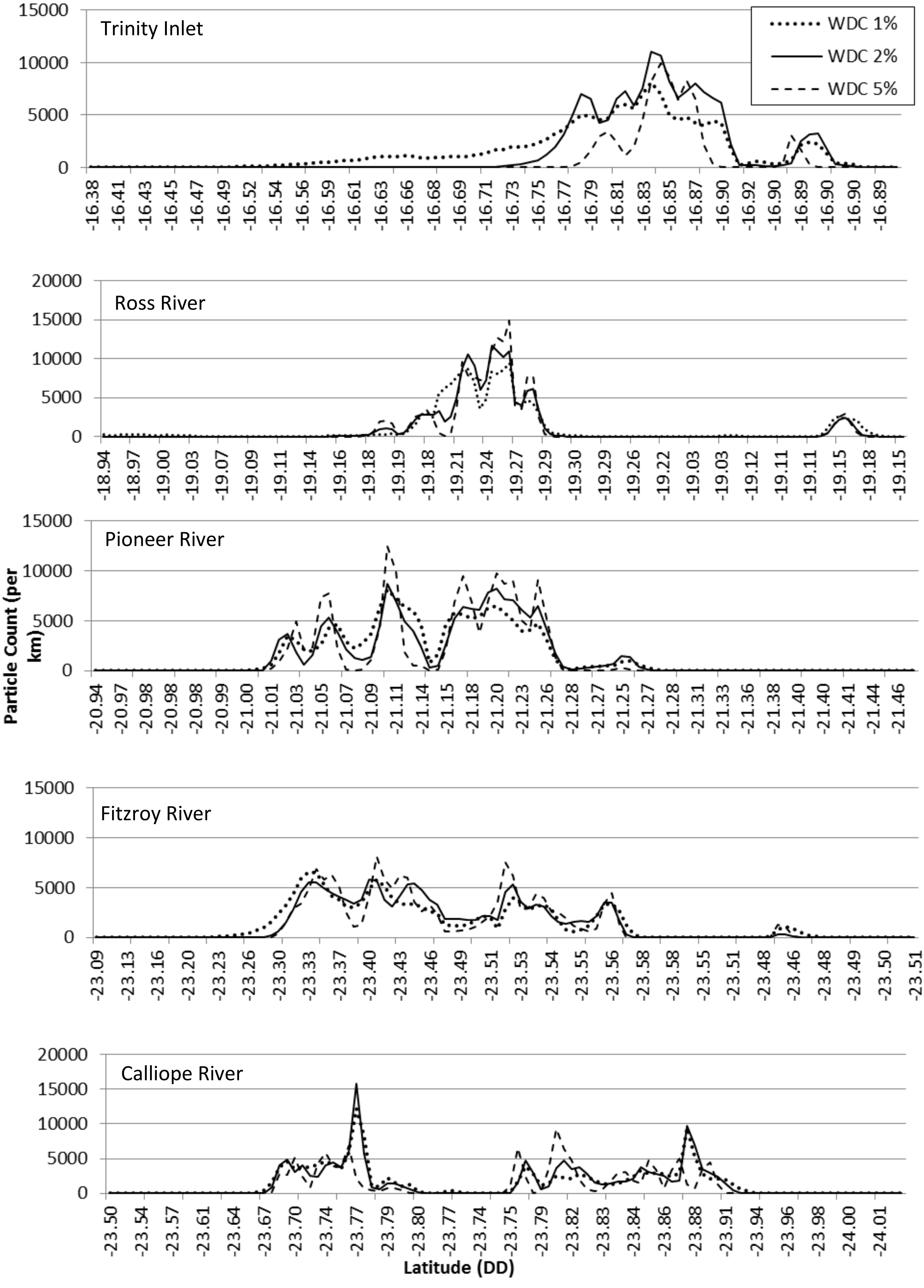

Figure 4: Distribution of landed particles across latitudes for particles released from river simulations under wind drift coefficients (WDC). The x-axis is not continuous due to the complexity of the coastline.

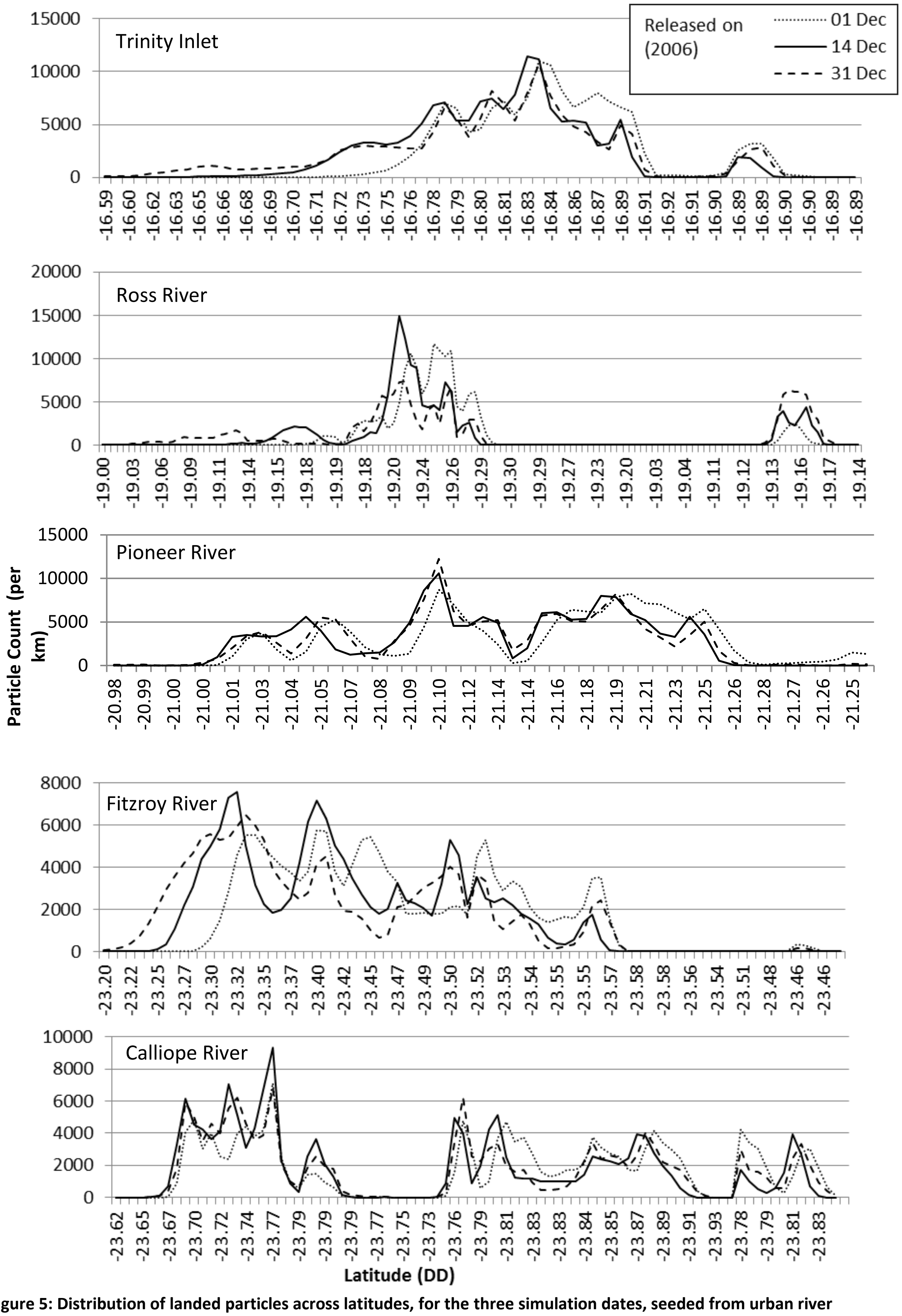

Figure 5: Distribution of landed particles across latitudes, for the three simulation dates, seeded from urban river mouths. The x-axis is not continuous due to the complexity of the coastline.

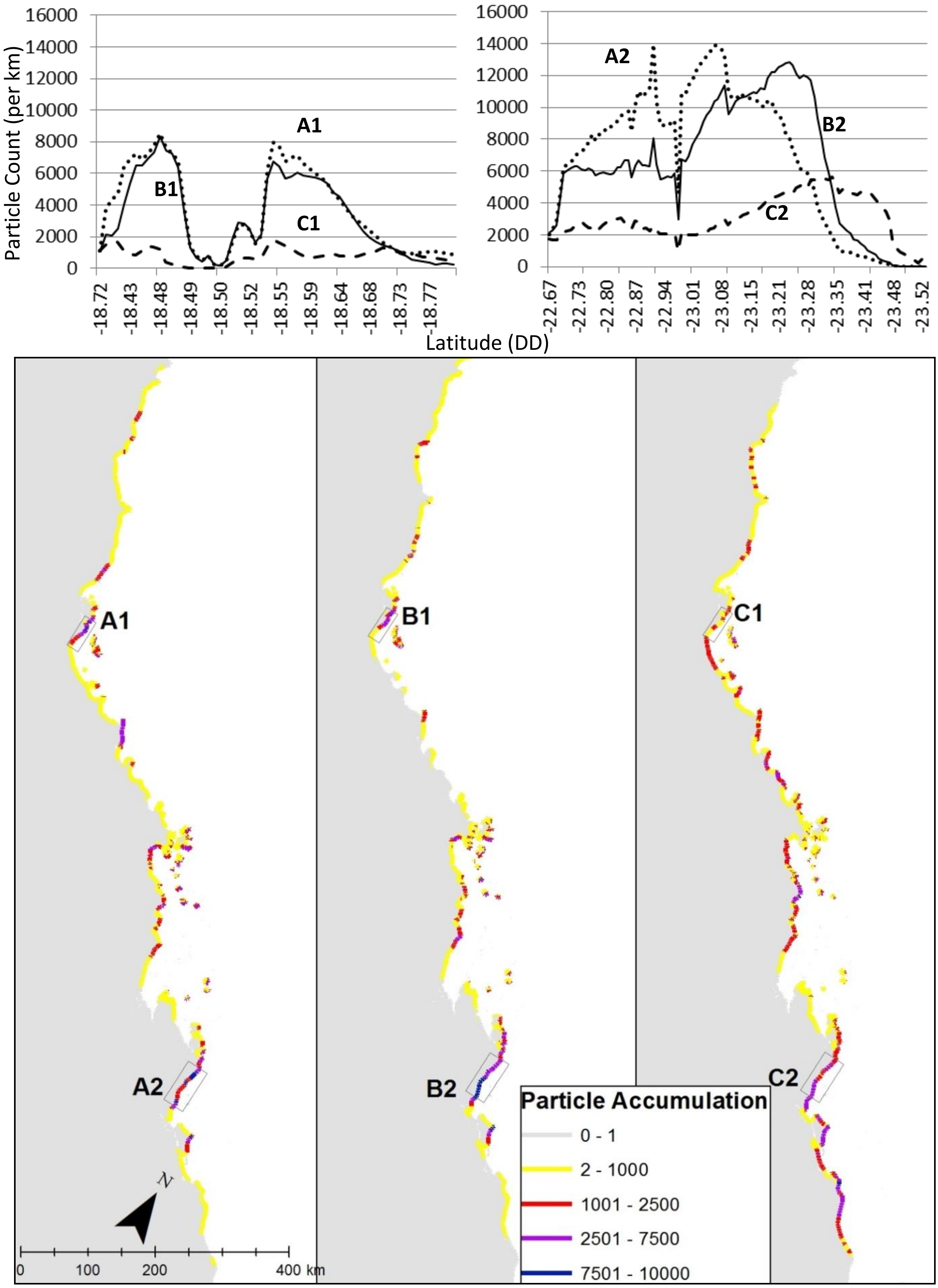

Figure 6: Distribution of landed particles across latitudes for the three simulation dates (A) 01/08/06, (B) 01/09/06 and (C) 30/01/06, seeded from the commercial shipping lanes. The inset graphs show the accumulation across the three dates at the two sites indicated on the maps.

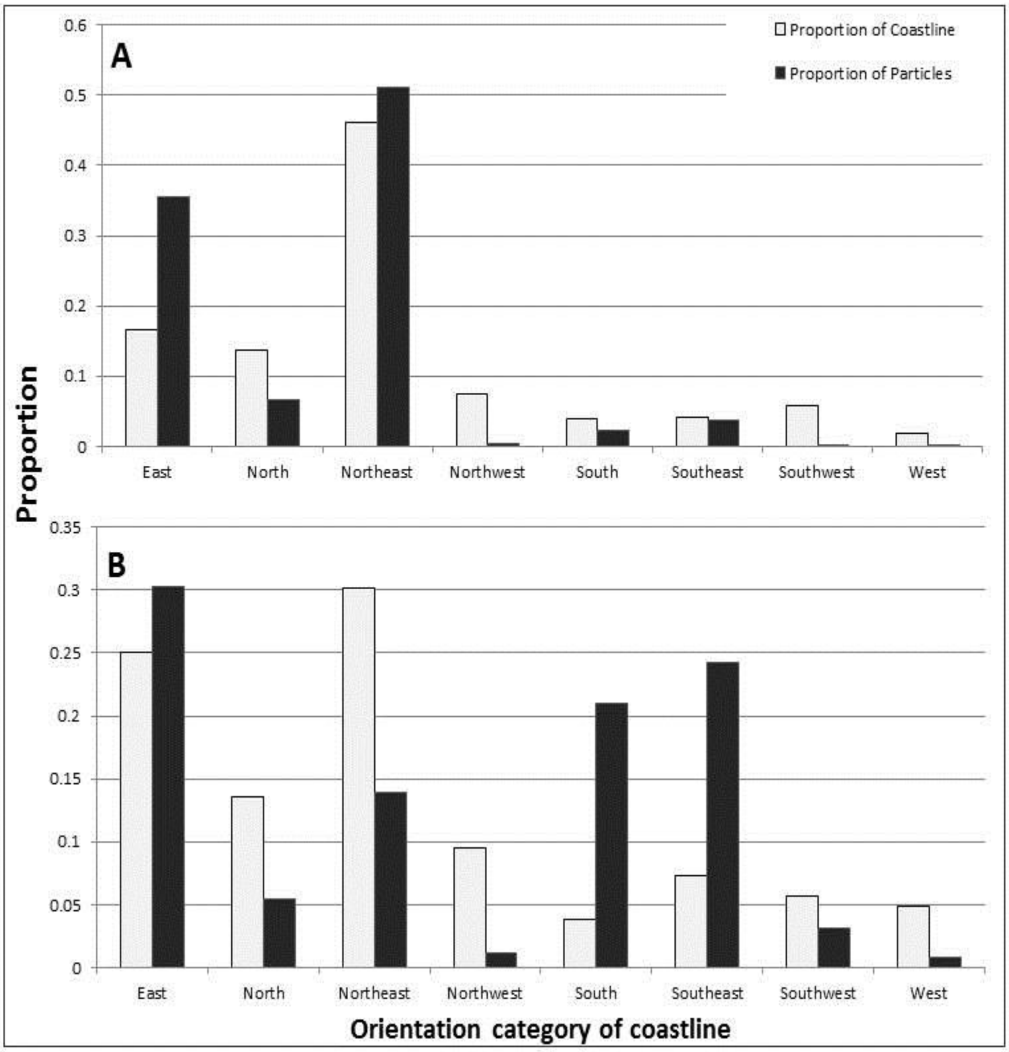

Figure 7: The proportion of coastline in each orientation category compared with the proportion of the particles accumulated by each orientation category during the simulations seeded in (A) urban rivers and (B) commercial shipping lanes.

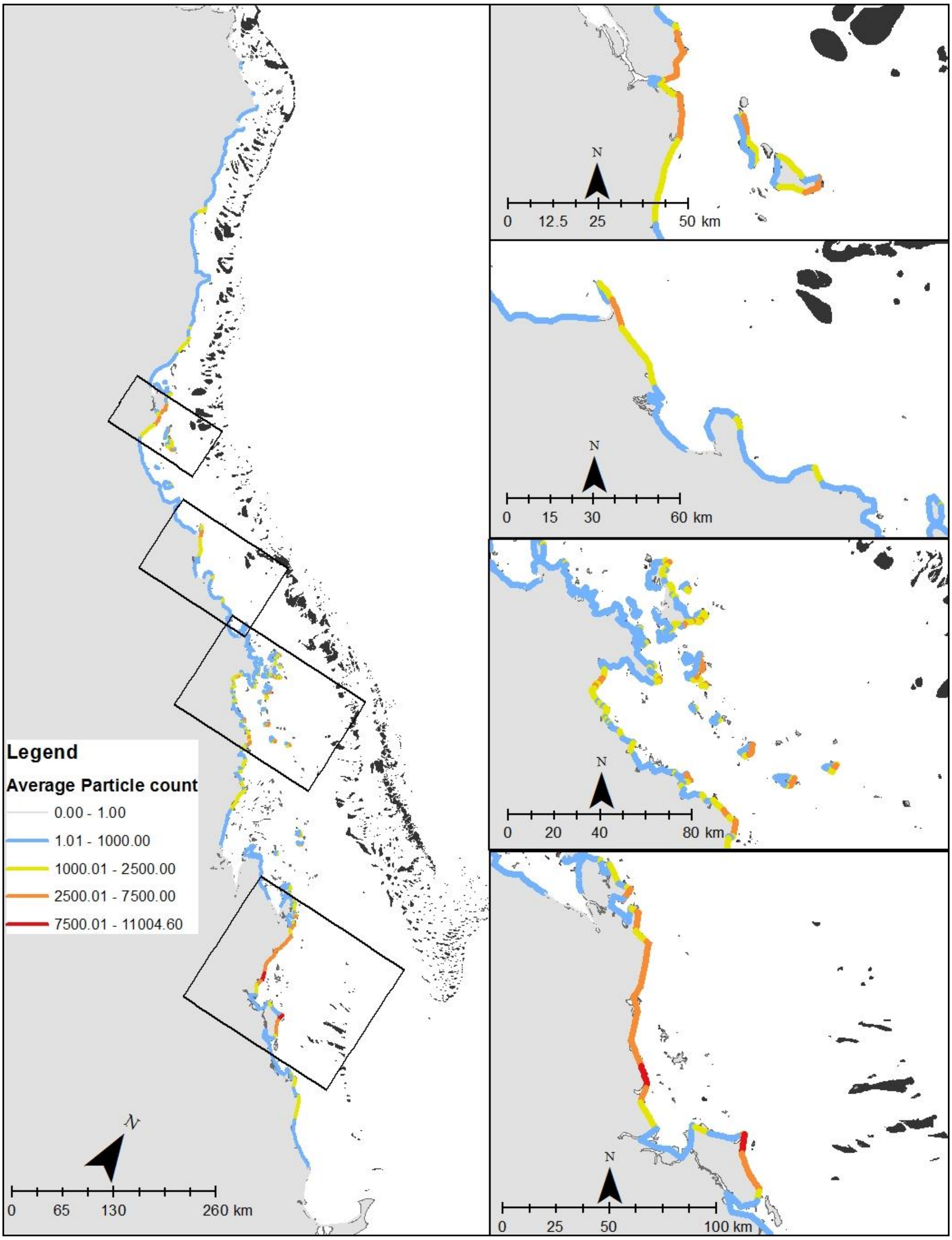

Figure 8: Average accumulation of particles across all simulations. Insets show detail case studies outlined in main map.