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Understanding the types, sources and at-sea distribution of marine debris in Australian waters

Final Report to the Department of Sustainability, Environment Water, Population and Communities

Britta Denise Hardesty and Chris Wilcox
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Enquiries should be addressed to:

Dr Denise Hardesty
Wealth from Oceans Flagship
CSIRO Ecosystem Sciences
Phone 07 4091 8814
Email denise.hardesty@csiro.au

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1 Acknowledgements

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2 Abstract

Marine Debris is an increasing issue for the integrity of marine ecosystems in Australia, with reports of impacts on wildlife ranging from entanglement and drowning to increased transport of pollutants into food chains. Researchers have identified some animal populations that are heavily impacted by marine debris, including several species of turtles in the northern and eastern marine bioregions and seabirds nesting on some offshore islands. Impacts may range result from either ingestion or entanglement, and may result in reduced health, decreased reproductive output and mortality.

However, it has remained difficult to develop a synoptic description of the overall threat to ecological systems. This uncertainty is due to three causes: an absence of a national map of the distribution of marine debris, comparative information on exposure of wildlife across taxa and regions, and a clear understanding of the effects of exposure to debris. This project provided an initial step in addressing this uncertainty by identifying available information on debris and developing preliminary analysis of its sources and distribution at a national scale.

This project has four major outputs. First, we collated information from various marine debris monitoring sites across the country in order to identify and understand the available data, and then to use it to describe the types of marine debris that wash up on shore at selected sites. Second, we chose four sites that would be geographically representative and which had good quality monitoring data. For each of these sites we used ocean drift models to predict the likely paths of debris arriving at these sites to understand the potential sources of the debris. Third, we investigated the likely domestic versus foreign contribution to debris in the Australia marine estate by modelling the likely paths of debris emanating from major domestic population centres and from selected locations at the boundary of the Australian Exclusive Economic Zone. Fourth, to understand how the characteristics of debris might affect their movement and distribution we analysed the effect of wind and surface currents in the movement of debris, and the variation in these effects among years and seasons. This analysis provides some information on how sources different types of debris might vary.

3 Introduction

Human activities can result in an abrupt decline in the world's biological diversity, and marine debris in particular has become a major hazard to marine life (Derraik 2002). Marine debris leads not only to aesthetic degradation, economic losses and human health hazards (Islam and Tanaka 2004), but also to entanglement and ingestion that can result in health risks, decreased productivity and mortality to wildlife. The increase in amounts of marine debris over the past decades can be attributed to at least three factors: (1) synthetic materials, which tend to degrade slowly in seawater and which have increasingly replaced natural fibres in the manufacture of everyday items; (2) synthetic materials are often less expensive than the natural fibres they replace, which decreases incentives to reuse or recycle items; (3) there are simply more ships and coastal residents that can lose or discard materials (Ribic *et al.* 1992). Marine debris consists mainly of two types: particles that immediately sink to the seafloor and items with a high capacity to float for extended periods which are commonly transported by currents and wind before being cast ashore or being pushed offshore and persisting in regions of convergences. Overall, the distribution, abundance and composition of floating marine debris (FMD) are poorly known. While shore-based studies may provide some first approximation of the composition and abundance of FMD in adjacent seas, they nevertheless represent only the fraction of marine debris that has been cast ashore. A more comprehensive understanding of the dynamics of FMD can be obtained by incorporating at-sea surveys (i.e. Thiel *et al.* 2003, Law *et al.* 2010, Browne *et al.* 2010, Hinojosa *et al.* in press) and computer models that chart the likely paths of FMD (i.e. Wakata and Sugimori 1990, Maximenko 2008, Isobe *et al.* 2009, Martinez *et al.* 2009, Kako *et al.* 2010a, Kako *et al.* 2010b).

To evaluate the role of FMD in the marine environment, it is important to first understand the factors that drive their abundance and distribution, which may vary substantially throughout the world's oceans. Sources of FMD are often highly localized, such as rivers and human population centres. Hinojosa (2010) suggested that most FMD introduced by human activities persists for only a short time in coastal waters and most likely contaminates local beaches. This suggestion is supported by sighting surveys and beach clean-ups in which the highest FMD densities were reported on beaches near potential sources of FMD, i.e. human population centres and at the mouths of large rivers. However, some FMD (e.g. plastics, Styrofoam, buoys with high floating potential) may escape the local supply-sink dynamics and has the potential to travel very long distances as it is carried by ambient currents and wind. The post-supply distribution of floating items depends to a large degree on the characteristics of floating objects, with buoyancy and exposure to winds or surface currents exerting a strong effect on the observed distribution of floating objects (Kako *et al.* 2010).

4 Methods

4.1 Data compilation

We compiled data from a number of organizations including Surfrider Foundation Australia, Tangaroa Blue Ocean Care Society, local Coastcare groups, and other groups involved in beach cleanups across Australia (Appendix 1). We also contacted various state agencies that are or have operating marine debris monitoring programs. After initial assessment of the types of data collected and the frequency of clean ups, we identified sites around the country for further analyses. We selected sites with consistent data collection procedures, those that had carried out regular clean ups for multiple years, and that had data on volume or weight of different types of marine debris, as well as sampling effort per unit area.

4.2 Drift modelling

We adapted an existing particle tracking model to simulate the dynamics of marine debris. The model is based on one developed for the Australian Connectivity Interface or Aus-Connie (Condie *et al.* 2005, http://www.csiro.au/connie2/). This open-access online application allows the user to explore historical marine connectivity patterns by simulating the dispersal of particles in the Asian-Australian oceanic region. It can be used to find likely destinations (or probable origins) of materials suspended in the ocean such as plankton, larvae, sediments or dissolved chemicals (or, in the case of this study, marine debris). This particle tracking model is 'forced' by the currents as simulated by an eddy-resolving and data-assimilating ocean general circulation model (sensu Schiller *et al.* 2008; Figure 1). We used this model as marine debris can be influenced by currents and wind, known as leeway drift or windage. This can be modelled by balancing the hydrodynamic and aerodynamic drags (see formula in Figure 2). Although the Aus-Connie interface does not permit the user to specify windage values, the particle tracking code developed by its creators does permit this feature (appropriate .m files can be found at http://www.svnserv.csiro.au/svn/Connie2/ tracking/trunk/matlab/). The wind fields used to force the models were extracted from the ERA interim 10 metre wind (http://www.data-portal.ecmwf.int/data/d/interim_daily/). The model tracked the location of particles on a daily basis, which we aggregated up to a 0.5 degree grid for display purposes.

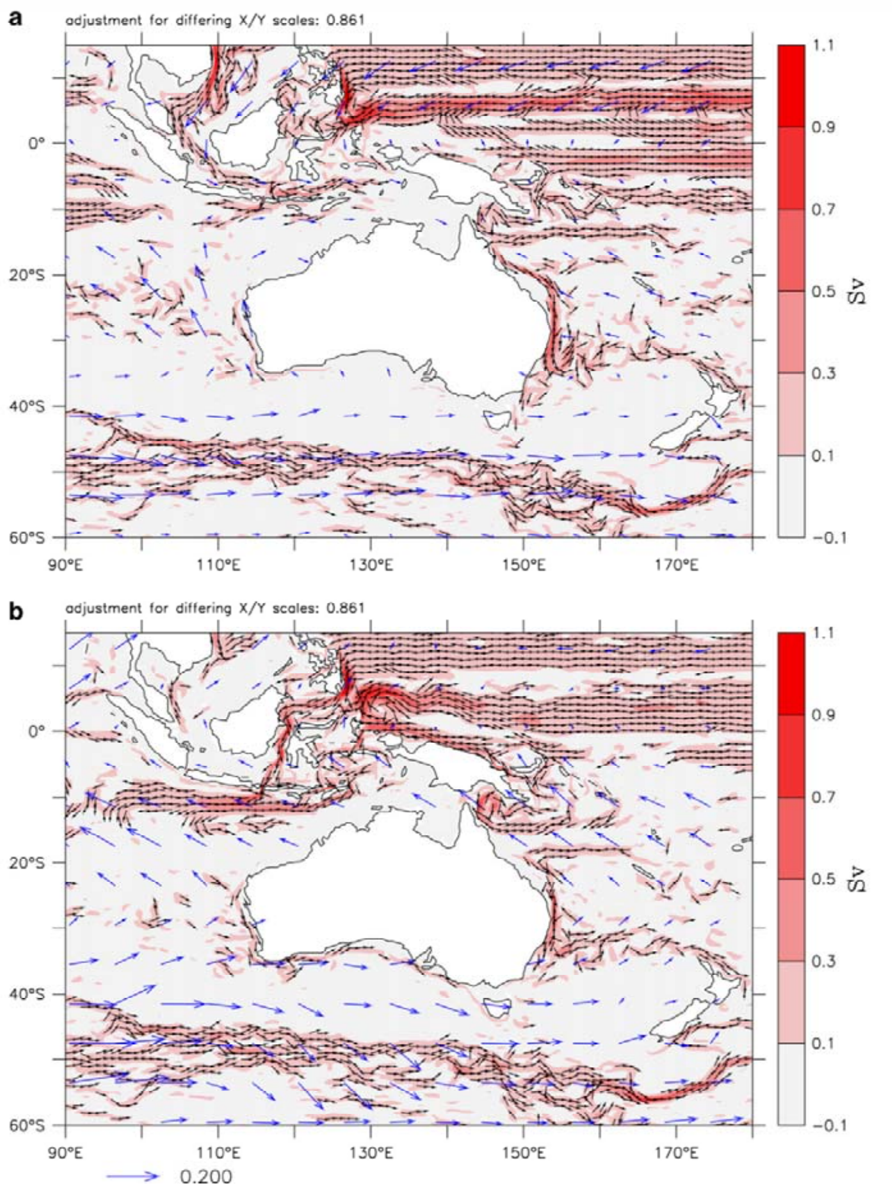

Figure 1. Volume transports (black arrows for direction, red colour for amplitude) in each 1° box integrated over top 100 m from the Bluelink oceanographic model reanalysis (BRAN, http://www.marine.csiro.au/ofam1/) for (a) January and (b) July. Unit vectors show direction of transport >0.1 Sv. Superimposed in blue are climatological surface wind stresses. Wind stress vector scale is shown at bottom (N/m2) (sensu Schiller *et al.* 2008).

w = influence of the drag force exerced directly by winds

$$w = \sqrt{\frac{\rho_a}{\rho_w}\frac{Cd_a}{Cd_w}\frac{A_a}{A_w}}$$

ρ_a (ρ_w) = air (water) density

Cd_a (Cd_w) = drag coefficient in the air (seawater)

A_a (A_w) = horizontally projected area

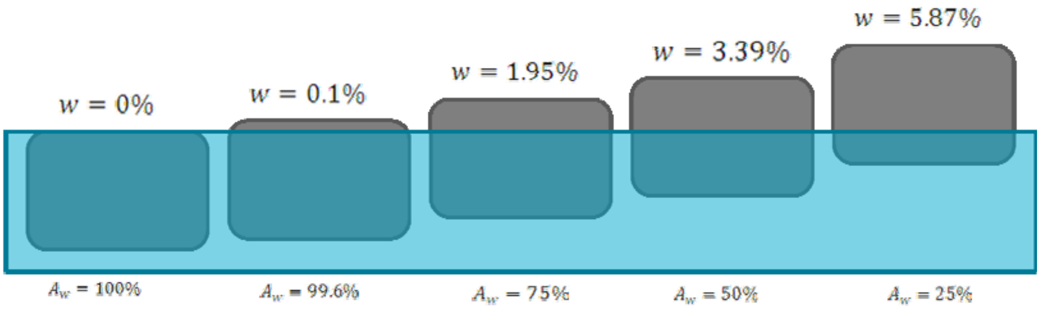

Figure 2. Windage (w) formula and schematic drawing of potential marine debris positions (gray squares) on the water surface. We tested each of the 5 values shown in particle tracking model runs.

4.3 Release areas and space/time scale used

We used data from volunteer groups and agencies to identify sink sites for which to make source predictions. The data we compiled from various volunteer groups and agencies had several sites with a reasonable number of clean-up events (Figure 3a). However, for the purposes of this pilot study, the particle tracking code was applied to just four beach clean-up sites around Australia: Cape Arnhem (NT), Port Douglas (QLD), Quarry Bay (WA) and Spain Bay (TAS) (Figure 3b). Beaches can be considered sink regions into which marine debris arrives, and from that viewpoint, the particle tracking model was run backwards (back-projected) to find the sources of the particles rather than their destination. We included paths for up to 80 days in duration to evaluate the extent of possible sources.

We evaluated the relative contribution from domestic and foreign sources, along with the effects of windage and ocean currents on the accumulation of debris in a single large analysis. The rationale behind this choice is that the relative magnitude of wind and current forcing vary by location and time, and thus can have a strong effect on the relative influx of debris from international sources versus the retention of debris from local ones. To elucidate the regions where the currents and winds could allow an influx of international marine debris, particles were released at 12 points equally spaced on the Australian Exclusive Economic Zone (EEZ) (Figure 3c). For all these release points, the release area was 0.5° longitude X 0.5° latitude, with 1000 particles were released at random locations within this area over a 30 day period. Particles were tracked over a period of 80 days in the surface layer (<5 meters depth). To consider potential influence of seasonal variation in ocean currents on marine debris sources and sinks, for each release, the model was run twice (January and July) each year (1994–2007).

In addition to the twelve release sites at the EEZ boundary, we also released particles at several of the major cities across the country: Adelaide, Brisbane, Hobart, Melbourne, Perth and Sydney – each of which can be considered a potential domestic source of marine debris (Figure 3d). Releases were conducted as per the EEZ releases, with 1000 particles released in January and July over the years 1994 to 2007.

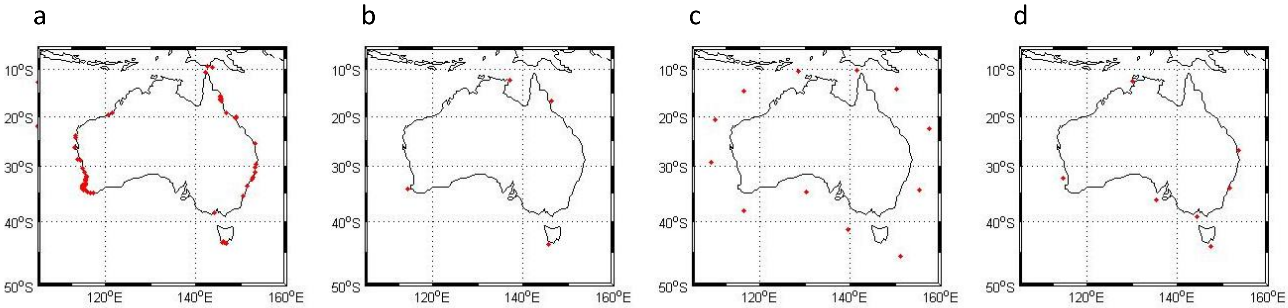

Figure 3. (a) Beach clean-up locations, (b) Beach clean-up locations where virtual particles were released, (c) EEZ release points and (d) and release points at cities.

We ran the particle tracking code using five different windage values which are associated with different potential positions of an object in the water column (Figure 2). The windage values were estimated using the formula developed by Richardson 1997. This approach has previously been used to simulate the drift of marine debris in the East China Sea Shelf (Isobe & Kako 2009, Kako *et al.* 2010a, Kako *et al.* 2010b). Using these five windage values, and running the particle tracking model twice a year during Austral summer and winter (1994– 2007), we produced 140 outputs for each release area (6 cities, 4 beaches, 12 EEZ points, see Figure 2). Outputs included the number of virtual particles that passed through each model grid cell (0.5° latitude X 0.5° longitude) during the 80 days of dispersion. After running the particle tracking models, we computed the mean of the number of virtual particles that pass through each grid cell using the outputs of the 28 models for each windage value and location.

5 Results

5.1 Beach clean-up sites

Since the project's inception we have compiled data from beach clean-ups at 43 sites in Queensland (Figure 4a), a single site in Victoria and eight sites in New South Wales (Figure 4b) clean ups, 172 sites in Western Australia (Figure 4c) and 21 sites in Tasmania (Figure 4d). The Northern Territory's Department of Natural Resources, Environment, the Arts and Sport also provided data, but because these data were not received until April 2011, we were unable to include them in our analyses. Data from Queensland, Western Australia and Tasmania are summarized in Table 1, as representative states with high-quality data sites. While we were not able to obtain data from the region, we understand that Victoria has historic and possibly ongoing clean up data from a number of sites.

Table 1. The number of clean ups conducted at sites for which we were able to compile data in Queensland, Western Australia and Tasmania.

NUMBER OF REPEATED CLEAN-UPS AT A SITE	QLD	WA	TAS
1	28	113	14
2	6	24	2
3	1	14	3
4	0	2	0
5	0	1	0
6	0	3	2
7	0	0	0
8	0	4	0
9	0	2	0
10	0	1	0
20	5	1	0
30	3	0	0
40	0	3	0
50	0	3	0
60	0	0	0
70	0	0	0
80	0	0	0
90	0	0	0
100	0	0	0
250	0	1	0

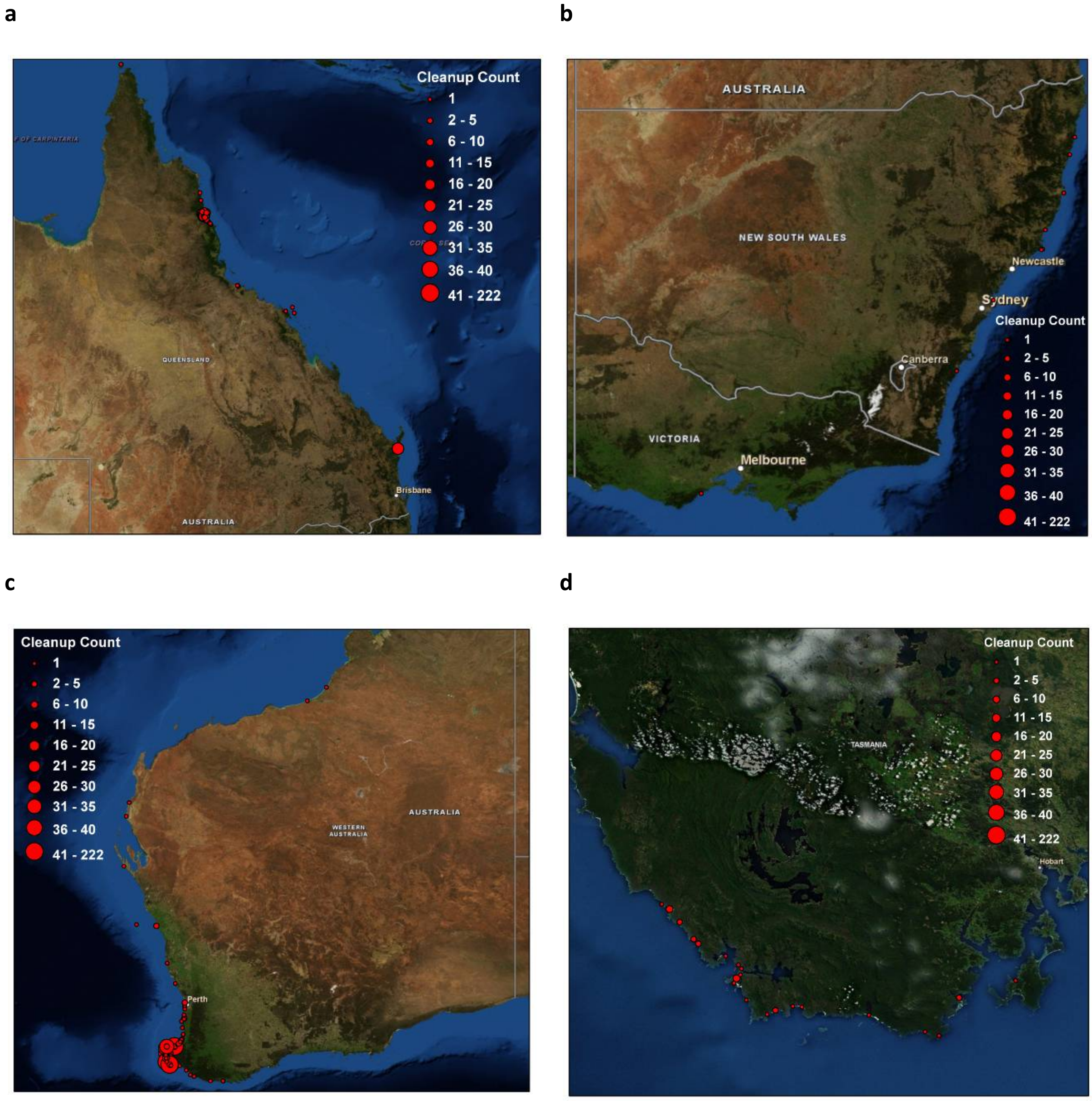

Figure 4. Clean-up site locations in (a) Queensland, (b) Victoria and New South Wales, (c) Western Australia and (d) Tasmania.

Upon collating beach survey data from various sources, we summarized the records by state from those sites for which data has been collected for a minimum of two years (Queensland, Western Australia and Tasmania; Appendix 2a, b and c respectively). To create a time series of data we summarized those sites with a higher frequency of clean up visits each year (a minimum of two visits per year) for Queensland (Table 2) and Western Australia (Table 3), as they were identified as the states for which the best data was presently available. Tasmanian clean-up sites were visited only once a year between January and April, and hence are not presented in tabular form.

Table 2. Queensland sites with more than two monthly clean up records

Site	J	F	M	A	M	J	J	A	S	O	N	D	Total Clean-ups
Fraser Island South East	4	6	6	7	1								24
Port Douglas 4MB Mid HT	2	1	3	2	2	2	1	3	2	1	2	2	23
Port Douglas 4MB North1	1	2	1	1	1	2	2	2	3	2	3	3	23
Port Douglas 4MB South2	2	1	2	1	1	1	2	2	2	2	2	2	20
Newell Beach	1	1	1	1	1	1	1	2	1	2	2	2	16
Low Isles	1	1	1	1	2	1	1	1	1	1	1	1	13
Cooya Beach	1	1	2		1	2		1		1	1	1	11
Port Douglas 4MB South1		1	1			1	2	2	2	1	1		11

Table 3. Western Australian sites with more than two monthly clean up records

Site	J	F	M	A	M	J	J	A	S	O	N	D	Total Clean-ups
Busselton Jetty	29	25	49	26	17	9	1	2	6	19	19	20	222
Quarry Bay	4	5	5	3	3	4	4	4	4	5	3	3	47
Foul Bay South	4	5	5	3	3	4	4	4	4	4	2	2	44
Foul Bay North	3	4	4	3	3	4	4	4	4	4	2	2	41
Ellensbrook	3	4	3	3	3	3	3	2	2	3	2	2	33
Yallingup	3	2	2	3	3	2	3	2	4	3	1	5	33
Injidup	3	3	3	3	3	2	2	3	2	1	3	3	31
Skippy Rock Beach	1	1	1	1		3	2	1	1	4	1		16
Cosy Corner		2	1	1		1	1	1	1	2			10
Augusta Rivermth to Lookout	1	1	1			1	1	1	1	2			9
Hillview	1	2	1		1	1	1		1	1			9
Augusta Cliffs	1	1	1	1			1	1	1	1			8
Augusta Lookout to Lighthouse	1	1	1			1	1		1	2			8
Conto Spring					2		1	1		4			8
South Beach		2			1			2		2	1		8
Foul Bay	1	1	1							1	1	1	6
Prevelly	1	2	1		1							1	6
Redgate Beach		1				1	1			3			6
Augusta Waterwheel		1		1	1	1	1						5
Deepdene South		2								2			4
Sarge Bay	1		1		1						1		4
Augusta Flind to Albany Terr		1			1		1						3

Augusta Flinders to Jays Bch		1	1	1		3
Redgate N to Boodjidup Cr	1		1		1	3

The high quality sites identified and results of which are compiled here included Pt. Douglas, QLD; Quarry Bay, WA; and Spain Bay, TAS (Figure 5). For these sites (and as part of the process of identifying those with best data available), we compared quantity and type of debris recorded at the beach clean up locations. This enables us to 'fine tune' the particle tracking model if different types of debris may exhibit different characteristics or profiles at sea. The most abundant items at each of these three sites included plastic pieces, end user items, remnants and industrial commercial fishing and farming products (Figure 6).

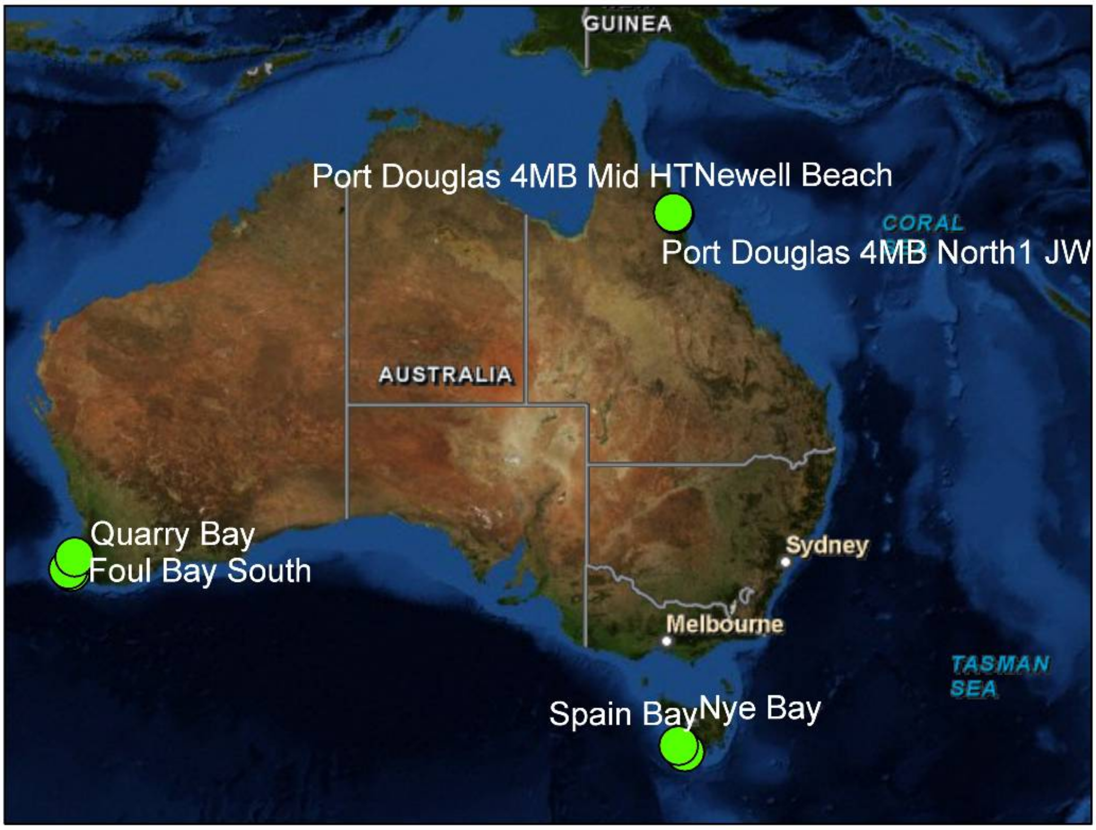

Figure 5. Identified clean-up sites for further analysis.

The main categories consistently recorded across sites included end user items, industrial commercial fishing and farming debris, linear items, oil and tar, packaging items, remnant bits of plastic/debris and sundry items (all data combined, Figure 6). In identifying debris at Pt. Douglas (Figure 7a), Quarry Bay (Figure 7b) and Spain Bay (Figure 7c) we see that while some items are present at all sites, they occur in different frequencies. For example, remnants are in higher density at Quarry Bay than at Port Douglas or Spain Bay (Figure 6) and at Quarry Bay fishing line and oil globules comprise part of the top 10 types of marine debris across all clean ups. In contrast, cigarettes and polystyrene foam occurs at two of the top ten items at Port Douglas, and bait box straps are abundant at Spain Bay.

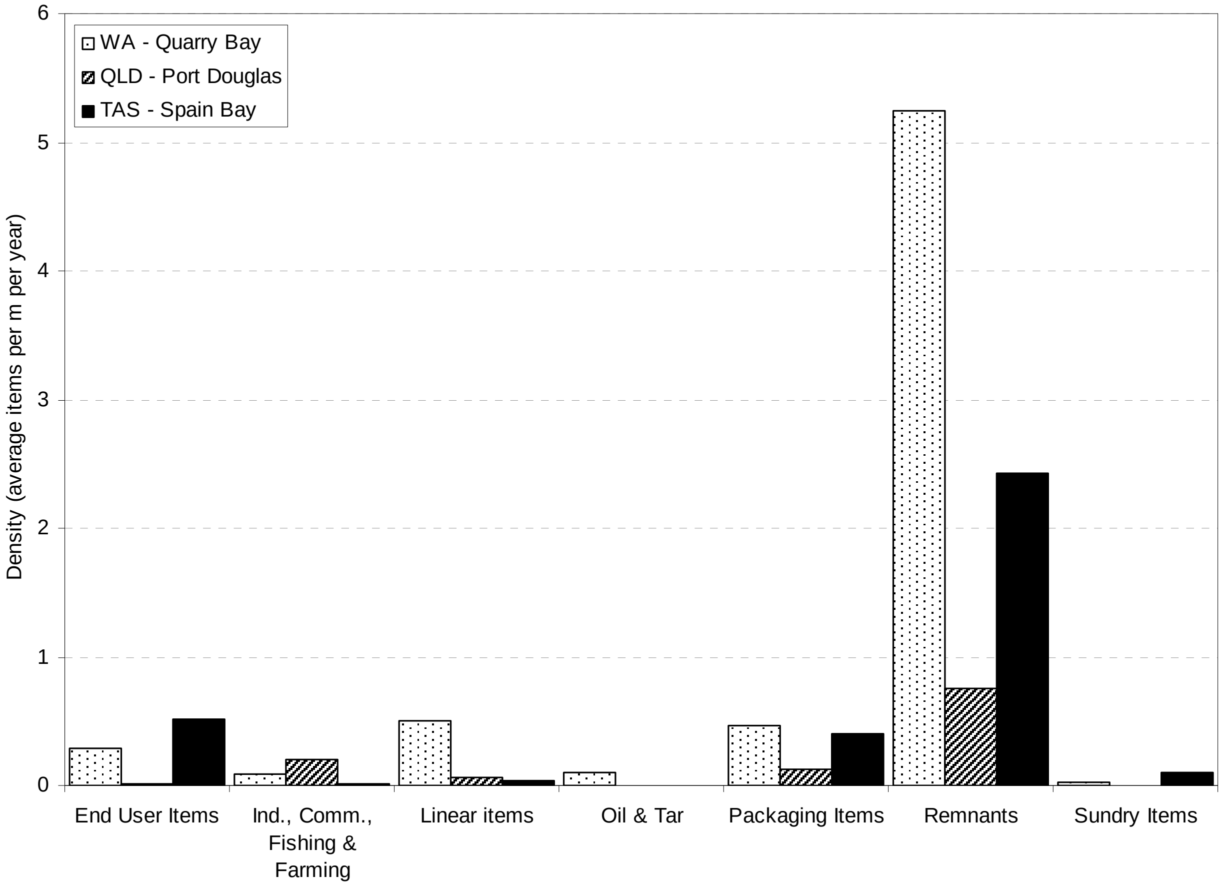

Figure 6. Average annual density of marine debris at Quarry Bay, Pt. Douglas and Spain Bay by category.

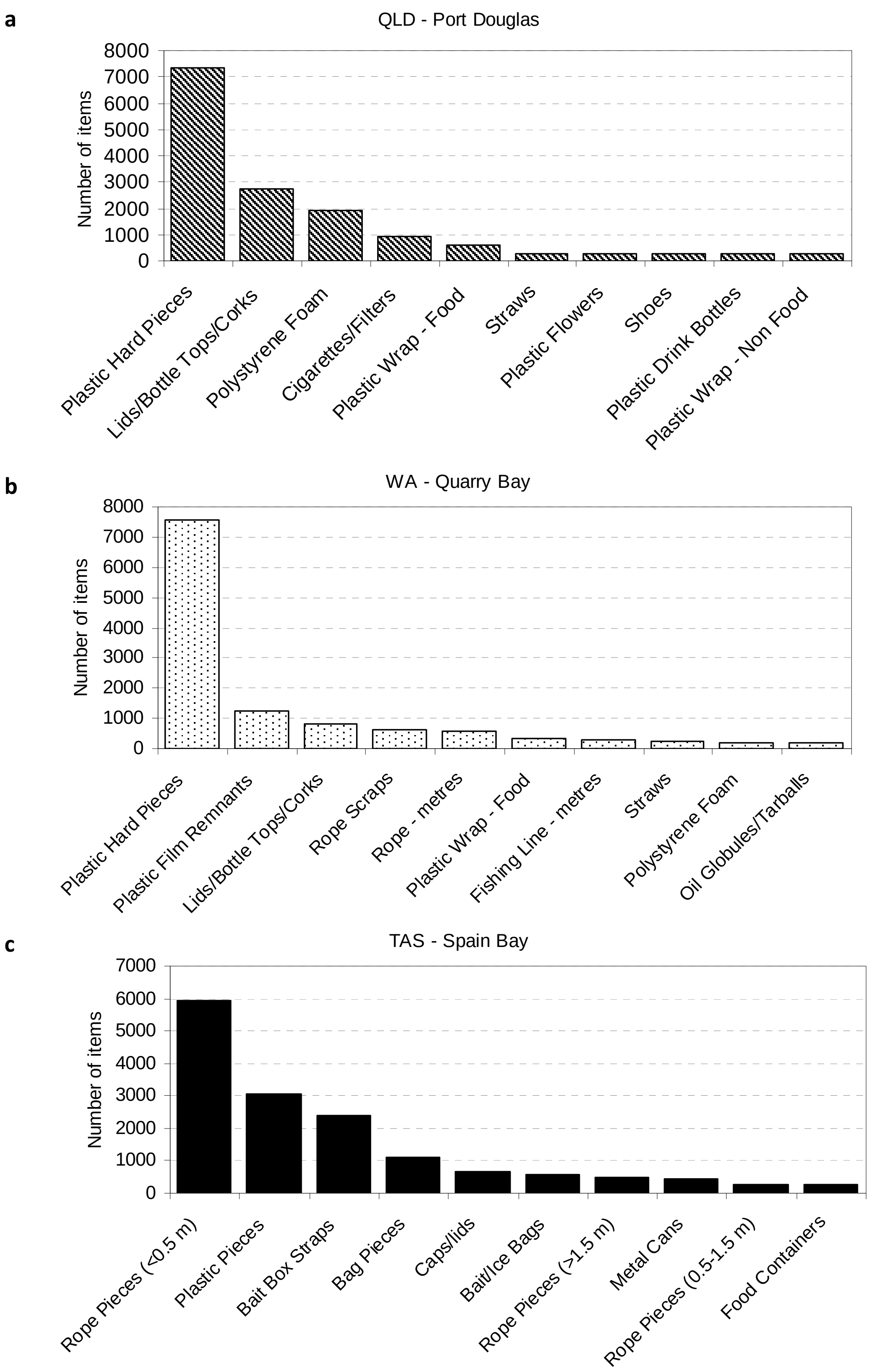

Figure 7. Top 10 types of marine debris found at all clean ups at (a) Port Douglas QLD, (b) Quarry Bay WA, (c) Spain Bay TAS.

5.2 Release sites and seasonality in model outputs

We applied the ocean-tracking model to create likely paths that the debris could have taken to arrive at clean-up and monitoring sites. Although we applied five windage values (see methods) and ran the particle tracking model twice for each year to identify potential seasonal difference (Austral summer and winter), we only show results from minimum and maximum windage values. By integrating across many paths that all terminate at a given monitoring site we built an expected at-sea distribution of the beached marine debris at each of the focal sites (Figure 8).

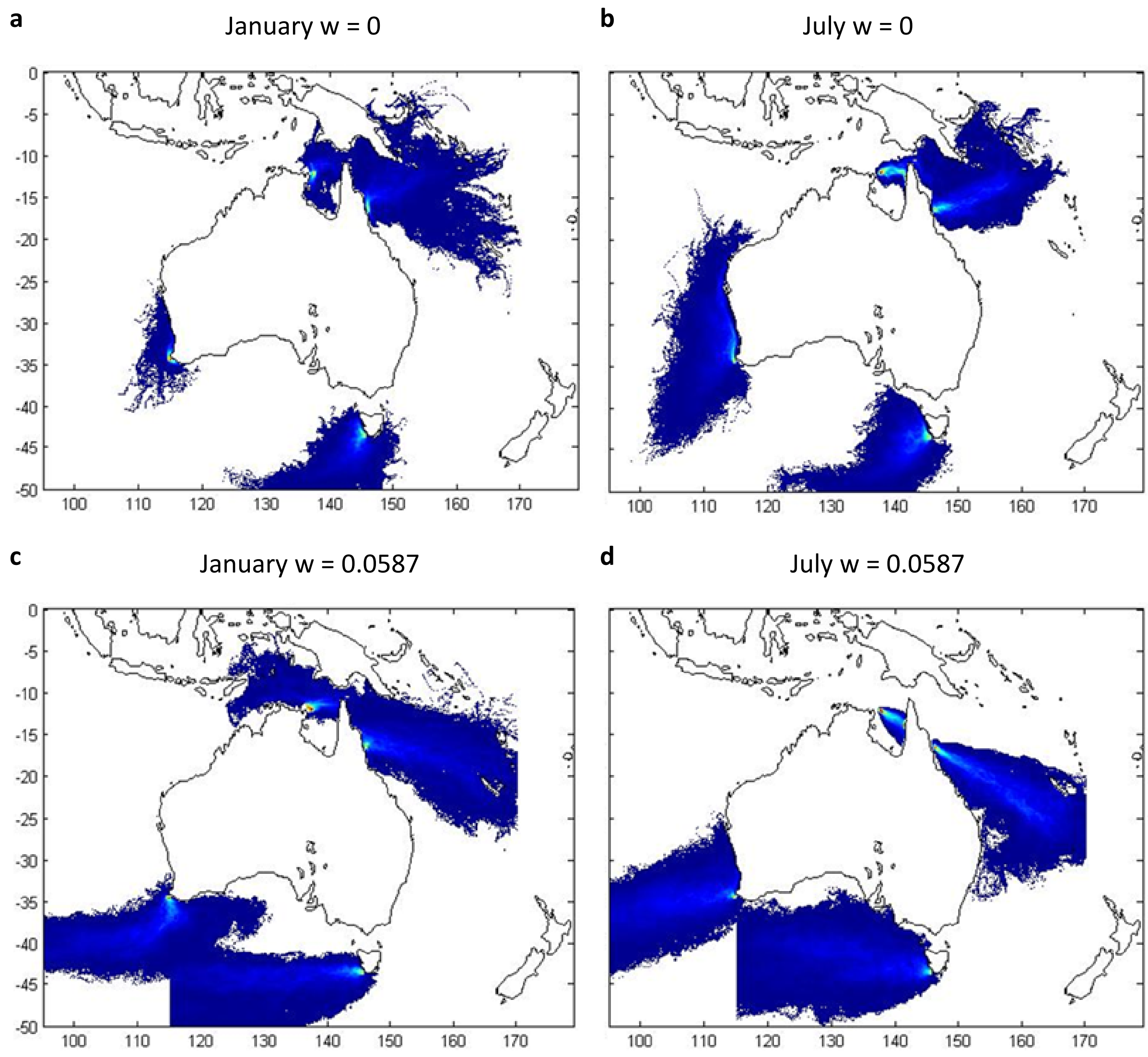

Figure 8. Particle tracking results for the four selected sites (Cape Arnham, Port Douglas, Spain Bay and Quarry Bay for both January and July with windage values = 0 and windage = 0.0587.

Comparing across seasons for debris that is not affected by windage, drift patterns are relatively consistent (Figure 8a and b). Debris arriving at Port Douglas and Cape Arnham appears to emanate from the Solomon Islands, Papua New Guinea, and West Papua, Indonesia and the marine zone in between these regions and Cape Arnham. Importantly though, the Gulf of Carpentaria is a potential source for debris during the winter season, as there is a strong circulation pattern affecting the debris paths in that region. Debris at the Quarry Bay (WA) and Spain Bay (TAS) sites appears to have a significant contribution from offshore. However, Quarry Bay does appear to receive significant inputs from the coastal region to the north during the winter. Interestingly, this coincides with a pattern observed in the WA clean-up data in which the density of plastic bags slowly declines with distance from Perth.

Turning to results for debris with high windage values, all of the sites receive data from a much larger spatial area (Figure 8c and d). While the contribution from domestic coastal locations is still significant for Port Douglas in both seasons and from Spain Bay in the winter, in general much more of the debris is predicted to come from either the offshore regions of the EEZ or from areas outside the EEZ. The prevailing southeasterly winds off the east coast and westerly winds off the west coast clearly influence the predicted patterns.

Moving from looking at the distribution of debris based on sink locations to evaluating the contribution from sources we ran the particle tracking model making forward projections of paths from locations at the boundary of the EEZ and major population centres along the Australian coast. As with the sink analysis, there are strong differences predicted fates for debris from the various urban centres depending on season and windage (Figure 9). For debris not strongly affected by windage, there is a strong coastal contribution predicted for both east and west coast cities (Figure 9a and b). Darwin is expected to make a contribution to both the coastal region in its vicinity, with debris spreading to the Gulf of Carpentaria and across to Indonesia. Debris spreads eastward from the east coast cities into the Tasman Sea, driven by the influence of the East Australian Current and Tasman Front.

For debris strongly affected by windage, again the spatial extent of the debris emanating from Australian cities is much larger (Figure 9c and d). There is a strong contribution from Perth to the coastal region to the north in WA in summer, but also a predicted export of debris northwestward out of the EEZ. Similarly, in winter, debris from Darwin appears to rapidly leave the EEZ moving northwestward along the Indonesian coastline. Winter also brings significant amounts of debris to the coastal zone from north of Perth all the way around to the east coast of the continent, with little loss of debris from the EEZ apparent.

Debris from the east coast follows a different and somewhat more consistent pattern. There is a consistent prediction for debris from eastern seaboard cities to reach coastal locations all along the east coast of the continent, from Townsville southward. A second consistent pattern for wind affected debris is rapid movement southeastward, with an increasing southerly component in summer. This suggests that debris from the east coast of Australia likely reaches New Zealand on a fairly consistent basis.

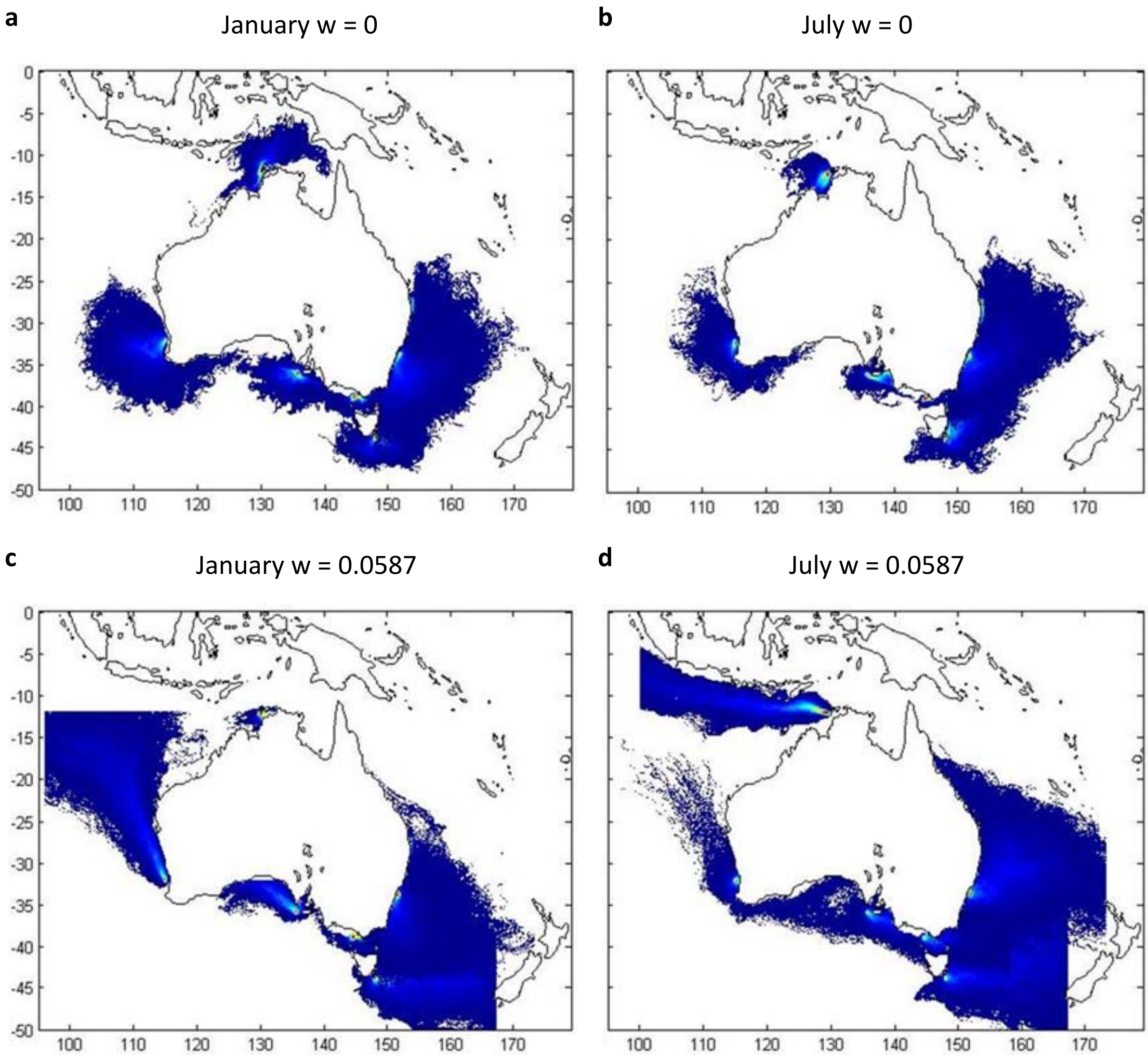

Figure 9. Back-projection of likely particle tracks from oceanographic model with end points at major cities in Australia. Here we present results from model runs for January and July and for windage = 0 and windage = 0.0587.

The complement to the analysis of the fate of debris from Australian cities is that for debris emanating from locations along the EEZ. The general pattern of drift from the 12 evenly spaced points along the EEZ gives an indication of the potential for input into the Australian marine estate from outside its boundaries. Taking debris that has little windage first, in general it appears that debris from locations along the EEZ largely just diffuse out evenly from their starting point (Figure 10a and b). This is particularly true for the summer season, implying that there is not a strong foreign component to debris in the Australian marine estate during this period. There are a few expectations however, with sources in the Arafura Sea, Northern Coral Sea, and along the southern portion of the EEZ all showing a significant pattern of drifting coastward.

For debris affected by wind, the effects of the trade winds and the prevailing westerlies, both of which are the strongest in winter, are apparent (Figure 10c and d). During winter Australia is a strong net exporter of debris with releases along the north and northwestern regions of the EEZ boundary being rapidly swept offshore toward the northeastern Indian Ocean and along the coast of Indonesia. Similarly, releases at points along the south and southeast boundary of the EEZ are rapidly swept eastward with some contribution along the coastline but rapid transport out into the Tasman Sea. Again, debris emanating from the southern boundary of the EEZ and the northern Coral Sea regions are the only ones predicted to make a major contribution to debris in the Australian marine estate.

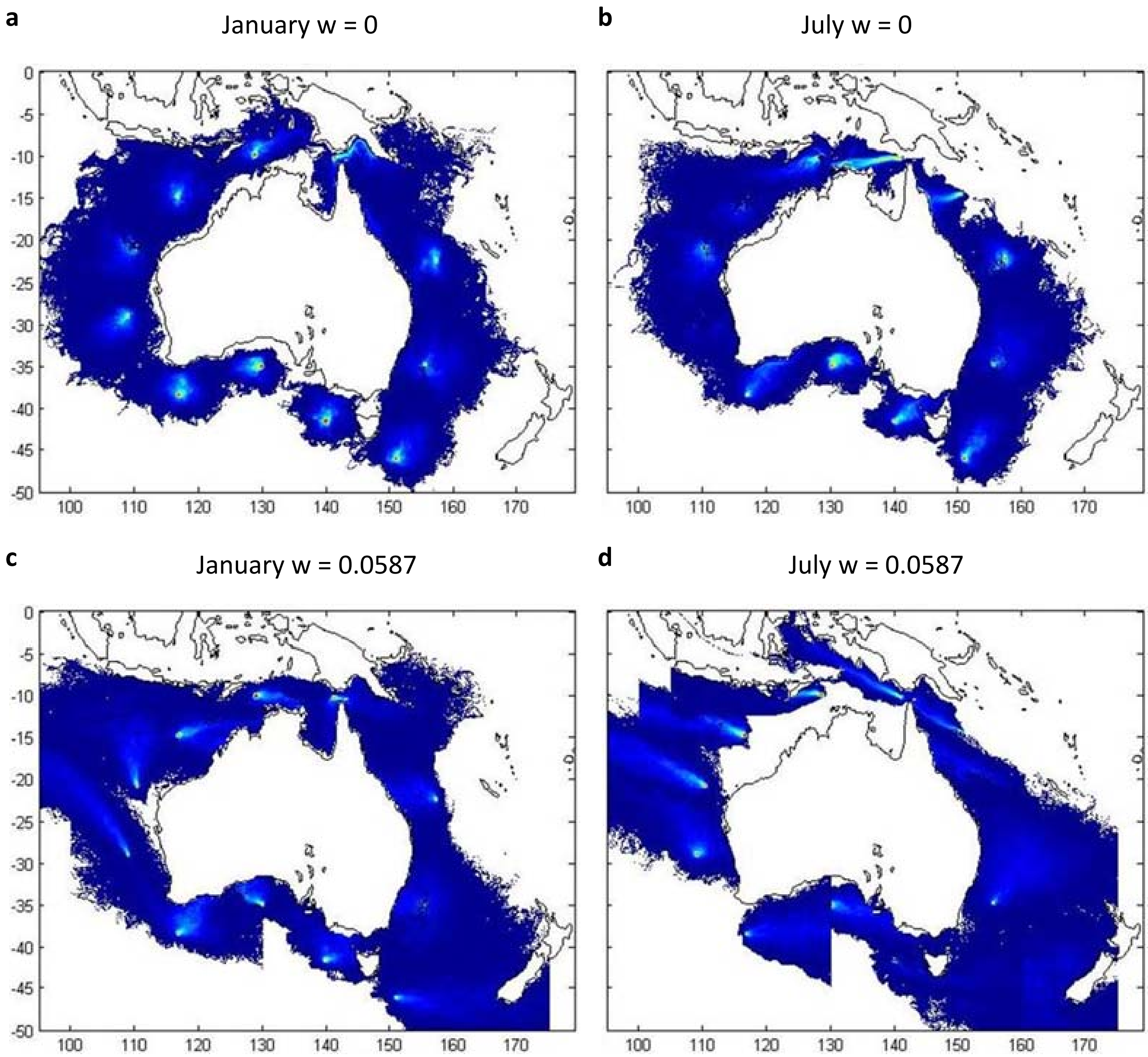

Figure 10. Hypothetical releases at twelve sites along the EEZ with time series initiation in January and July and windage = 0 and windage = 0.0587.

6 Discussion

There is a significant amount of data from coastal clean-ups around Australia. In some cases the data is quite detailed and collected in a standardized and rigorous manner. Interestingly, data from volunteer clean-up groups in some cases is of a quality equivalent or even superior to data from state agencies and other publicly funded groups. However, based on conversations with nongovernmental organizations involved in cleanups, such as Tangaroa Blue, maintaining high quality data from volunteers requires frequent interaction. Particularly important is use of the data and feedback to volunteers in regard to the utility of the data they collect (H. Taylor, Tangaroa Blue, pers. comm.).

In this project we identified data from several regions that is of a quality adequate to allow spatial and temporal analysis. Most of the data, including the high quality data, is currently being collected by volunteers. Surfrider Foundation and Tangaroa Blue in particular are very active in this effort. Clean Up Australia and other local Coast care groups may also be able to provide data, and in some cases are willing although we were not able to obtain information from all potential data sources in time to incorporate it in this project. While not a focus in this project, data in the select regions presented in the results would support analysis of time and space trends, types of sources, and effects of local site characteristics on accumulation of debris. A central issue in the use of these data however is standardization of the categories used for classifying the data and types of ancillary data collected. For instance, although most of the common items collected from surveys in Tasmania result from fishing (Figure 7c), the aggregated data shown in Figure 6 indicates that other sites have more fishing debris and that remnants are the most common type of debris in Tasmania. These sorts of issues in classification and standardization limit the utility of the data available at the moment, or at least require significant reprocessing to make it useful for regional, national or international comparisons.

In general, based on our preliminary analysis of data from three of the focal sites with high quality data, remote areas tend to have debris that result from commercial fishing and to some extent shipping, while areas closer to urban centres may have a higher frequency of consumer items. Marine debris identified from these clean-ups included some rubbish types that have been shown to have significant impacts on wildlife in other regions. For instance, plastic bands that are used on boxes of fishing bait have been implicated in declines in pinniped populations (Raum-Suryan *et al.* 2009, Steward and Yochem 1987). It is unclear if there if this is a current issue for pinnipeds in Australia, however, the potential certainly exists.

One of the largest issues arising in our audit of the available data on marine debris is the need for a national database that is centrally housed. If this database incorporated two additional functionalities for interacting with users it could significantly increase the utility of the data from both past and future clean-up and monitoring efforts. First, the database could have a standardized data sheet for data entry that is available online. The advantage of this facility is that it would provide a basis for standardizing the information groups collect. Providing a downloadable version of the document, along with a matching web interface for data entry would significantly facilitate incorporation of volunteer data. Secondly, incorporating some basic mapping functionality that could be delivered over the web would allow users to put their data in context, comparing it over time and to other locations. This functionality would provide vital feedback to volunteer groups and a basis for interaction among groups. Given the size of the marine debris problem and the difficulty in collecting synoptic data on the state of the problem, providing the infrastructure for standardization, capture and reporting of volunteer data is an essential component of understanding and managing the threat.

Our analysis of the sources of debris at four clean-up sites highlighted the complexity in understanding where debris at a site originates. In general, debris with greater windage relative to current effects was predicted to travel further and thus could potentially come from a much larger area. Wind and current forcing is also not necessarily in the same direction, indicating that different sorts of debris at a site may have quite different sources. For instance, debris at the site in southwestern WA likely comes from coastal

WA if it is not strongly affected by wind, but from the central Indian Ocean if it is. Thus, a plastic bag may be from a local source, while an empty drink container found next to it may travel thousands of kilometres to reach its final location. The model does provide some suggestions as to sources however. For instance, debris at the site in the Northern Territory does appear to emanate from the region shared with countries to the north, and coastal WA likely contributes much of the low windage debris appearing in the southwest of the state. Debris in the Port Douglas region might well come from offshore in the Coral Sea.

The model results around Pt Douglas points out an important caveat. Debris from coastal areas near Pt Douglas would likely be washed back on shore due to the general direction of both the currents and the wind in that region. Thus, one would expect both a local domestic contribution (as local debris would not be able to escape) and input of debris from offshore. Given that we do not consider the intensity of the source, i.e. how many items go in the water locally versus offshore, it is difficult to scale these two sources against each other. Thus all the debris at the Pt Douglas site could be washed onshore from the high seas, or it could all be locally lost and just never leave the area due to strong currents and wind retaining it there, or it could be a mixture of the two sources. Given the frequency of consumer items in surveys in the local area (Figure 7a), it is likely that they are lost locally and retained. In any event, it is important to keep in mind in using the model to interpret sources that the model results assume that the amount of material entering the water is equivalent everywhere.

The analysis of fates of debris from domestic and offshore sources also illustrates the differences across space and time in how debris moves. Domestic sources could account for a significant amount of the debris washing ashore along the eastern and southern coasts of the nation. However, items that are strongly affected by wind appear to be largely carried offshore, either to the southeast toward New Zealand or to the northwest toward Indonesia and into the northeastern Indian Ocean. While there is some coastal retention of debris, particularly for items that float at or below the water surface, Australian cities appear to be net exporters of debris to areas outside the EEZ in many cases.

Modelling of sources at the EEZ boundary tells much the same story. Items that are not strongly affected by wind largely diffuse evenly from their starting points, with an equal chance of drifting toward the coast or away from it. There are a few exceptions during the winter, when surface currents move items along the northern and southern EEZ boundaries either toward the coast or parallel to it. This suggests that in general there is some contribution from foreign sources, with hotspots along the northern and southern coasts. Items more affected by wind follow a similar but more extreme pattern. Winter trade winds and westerlies rapidly move debris from starting positions at the EEZ away from the Australian continent. The only exceptions are along the northern and southern boundaries of the EEZ, where in some cases transport is generally toward or parallel to the coastline.

In using the results from the model analyses presented here there are a few important caveats to keep in mind. First, the model was only run for 80 days for each particle release. Thus the distributions illustrated are not the final distribution, but are indicative of where particles are going to go or come from. If a distribution has a strong pattern to it, one can assume that in general that trend will continue in the short term. If it is evenly spreading, that would also likely continue and expand in the short term. Second, we do not consider the frequency with which items are introduced into the ocean in any of the analyses, instead assuming that they are introduced equally in all locations. So, for instance we release the same number of particles in Sydney and Hobart to estimate the distribution of debris from those two sources. However, it is likely that many more items would enter the marine system around Sydney due to the larger population, thus the actual distribution would be much larger than the Hobart distribution as with more particles one would expect some particles to reach longer distances in a fixed amount of time. Using a constant number of particles allows one to compare between sites, but it does not give the most representative picture of what the distribution of debris would look like from a particular site. This issue appears in other contexts, for instance in the predicted distribution of starting locations for debris at the Port Douglas site discussed above. Since we do not consider the input rates of debris into the marine system in different locations, our modelling provides information on the possible starting locations not the actual ones. One potential extension to our analysis is to address this using data on population density by location along the coast, along with information on density and type activity in the offshore zone including fishing and shipping.

7 Conclusion

Overall domestic sources are probably an important contributor to marine debris in Australia, with debris released in areas of intense human activity reach even distant locations along our coastline and in offshore areas. Some international areas do appear to have the potential to contribute debris into the Australian marine estate, particularly the northeastern Coral Sea, Arafura Sea, southern Indian Ocean and Southern Ocean. Australia is probably a net exporter of debris to some neighbouring marine regions and surrounding countries. In particular debris from the densely populated east coast is likely transported toward New Zealand and into the southwestern Pacific. Debris from the north and west coasts is likely transported northwestward toward Indonesia and into the northeastern Indian Ocean. In terms of composition, debris appears to have a higher proportion of refuse from marine industries such as shipping and fishing in remote areas, with more from coastal inputs in regions near urban areas. Overall, the results from this study suggest that control of domestic inputs may be the critical issue, whether they are from economic activities offshore or from coastal sources, as our modelling indicates that this is potentially a very important source of debris in the Australian marine estate.

7.1 Future Directions

This analysis gives a rough picture of the distribution and source of the marine debris threat. Refining the analysis using a more systematic data set and a more thorough modelling analysis could provide a synoptic picture of the marine debris threat. Additional analysis can build on tools developed in this project, in particular it can utilize the particle tracking model that has already been developed for making more complete predictions. The primary issue to be addressed in terms of the modelling is to incorporate the source density when predicting the distribution of debris, either through inclusion of information on population density or other economic activities such as commercial and recreational fishing. The necessary datasets for this analysis are available, either through a recent risk analysis conducted by CSIRO for SEWPAC or via existing geographic information systems in the public domain.

A second useful elaboration of the analysis presented here would be to compare the predicted composition of debris washing onshore at different locations with clean-up data observed at those locations. For instance, if we combine predictions based on commercial fishing and shipping with those from coastal populations and make predictions about the relative contribution from these two sources at point along the coastline we could compare this to the compositions observed at those sites as presented in Figure 7. This would provide some validation of the models and allow us to ensure we are making realistic predictions at large scales.

Third, we could overlay the predicted marine debris distributions with distributions of marine biodiversity, in particular threatened, endangered, and protected species. The department commissioned CSIRO to produce distribution maps for these species from the ERIN database, and final maps are now available. Overlay of the debris and species distributions would allow the department to identify species and locations for which there may be a significant threat. This would provide a basis for allocating further resources toward investigation or regulation of these threats. This basis for decision-making is currently lacking, making targeting of resources in implementing the marine debris threat abatement plan difficult.

Finally, development of a national database for marine debris data, and volunteer data more broadly, is a critical step in improving the understanding, and eventually management, of threats in the marine zone. Data on marine systems is notoriously difficult to collect, however, in the case of marine debris there is a significant opportunity to utilize data from volunteer clean-up and monitoring operations at very little cost. The primary requirement is the provision of some infrastructure for capturing the data and providing feedback to users based on the accumulated information. The atlas of living Australia has developed an excellent platform for this purpose, designed for interacting with citizen science initiatives. This platform is readily adaptable and would meet the needs described here. Maximizing the utility of this initiative would mean incorporating the existing data into this format and liaising with exiting clean-up groups to promote its use. However, this piece of infrastructure could significantly assist in a variety of contexts including state of the environment reporting, implementation of the marine debris threat abatement plan, and evaluation of marine debris control activities if successfully implemented.

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9 Appendices

Appendix 1: Data Sources and Groups contacted

ORGANISATION	CONTACT	WEBSITE	INFORMATION
Tangaroa Blue	Heidi Taylor/Wally Smith	http://www.oceancare.org.au/site/	National Marine Debris Database (NMDD), number of sites nationally, some with annual clean ups some with year round monthly
World Wildlife Fund	Head Office	http://wwf.org.au/ourwork/oceans/debrismap/	Data 2001-2003. Linked with NT government, see below.
Project Aware	Joanne Marston	www.projectaware.org	Marine debris underwater (dive) cleanups
SurfRider Foundation	Jim or Matt Dell/ Kristy Theissling	http://www.surfrider.org.au/	Beach litter surveys, multiple sites, states, cleanups
Clean Up Australia	Head Office	http://www.cleanup.org.au/	Annual data collection Repeat locations? No fine scale data collated. Report is the level of detail recorded.
Coast Care	Melissa Whitelaw	www.coastcare.com.au	They do not collect data, forwarded to coastcare group that does collect marine debris data
NT government	Shane Penny/Scott Whiting	http://www.nt.gov.au/nreta/wildlife/marine/research.html#debris	Joint data with WWF; multiple ranger groups across the top end, multiple years of data
SARDI	Jason Tanner	http://www.sardi.sa.gov.au/ http://www.sardi.sa.gov.au/research_sectors/aquatic_sciences/education__and__extension/ocaen_litter_surveys	Ocean litter and beach litter surveys
Keep Australia Beautiful	Scott Lyall	http://www.kab.org.au/	'Beach' data referred to on their website is actually more land based sites at beaches such as car parks or shopping centres so not really marine debris

Appendix 2: Queensland annual beach clean-up sites with records for two or more years

SITE NAME	2008	2009	TOTAL CLEAN-UPS
Fraser Island South East Coast		24	24
Port Douglas 4MB South2 JB	6	14	20
Port Douglas 4MB North1 JW	10	13	23
Port Douglas 4MB Mid HT	10	13	23
Low Isles		13	13
Newell Beach	4	12	16
Cooya Beach		11	11
Port Douglas 4MB South1 AM	4	7	11

Appendix 3: Western Australian annual clean up sites with records for two or more years

SITE NAME	2006	2007	2008	2009	2010	TOTAL CLEAN-UPS
Busselton Jetty			138	84		222
Quarry Bay	8	12	12	12	3	47
Foul Bay South	8	14	13	9		44
Foul Bay North	8	11	13	9		41
Ellensbrook		12	10	9	2	33
Yallingup		9	13	11		33
Injidup		11	8	12		31
Skippy Rock Beach	7	3	4	2		16
Cosy Corner	5		3	1	1	10
Augusta Rivermouth to Lookout	8			1		9
Hillview				6	3	9
Augusta Lookout to Lighthouse	7			1		8
Augusta Cliffs	7		1			8
South Beach		3	3	1	1	8
Conto Spring		5	2	1		8
Redgate Beach		1	4	1		6
Foul Bay				3	3	6
Prevelly				4	2	6
Augusta Waterwheel				5		5
Sarge Bay		2	2			4
Deepdene South		1	2	1		4
Deepdene North			2	1		3
Boranup Beach		1	1	1		3
Boodjidup Beach		1	1	1		3
Redgate North to Boodjidup Creek		1	1	1		3
Quinninup Beach		1	1	1		3
Moses Rock		1	1	1		3
Gallows		1	1	1		3
Smiths Beach		1	1	1		3
Bunker Bay		1	1	1		3
Dunsborough Town Beach		1	1	1		3
Busselton Jetty Foreshore		1	1	1		3
Capel Dalyellup Beach		1	1	1		3

Augusta Flinders Bay to Albany Terrace			3	3
Augusta Flinders Bay to Jays Beach			3	3
Augusta Colour Patch to Flinders Bay	1	1		2
Knobby Head		2		2
Hamelin Bay South End	1		1	2

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

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FOR FURTHER INFORMATION

CSIRO Ecosystem Sciences
Dr Denise Hardesty
t +61 7 4091 8814
e denise.hardesty@csiro.au
w www.ces.csiro.au/