The transport and fate of marine plastics in South Africa and adjacent oceans

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South Africa is thought to be one of the worst contributors of plastic into the sea globally. Although some plastic items derive from offshore sources (mainly fishing and other maritime activities, but also long-distance transport), the importance of local, land-based sources is indicated by the composition of beach debris and the concentration of macro-, meso- and microplastics close to urban source areas. Some 60–90% of plastic from land-based sources is expected to strand on beaches, but plastic standing stocks on beaches are much lower than global model predictions of land-based pollution. Burial in beaches and transport into backshore vegetation are significant sinks, although this plastic is likely to be released as the climate crisis leads to rising sea levels and more extreme storms. Most buried items are fairly small, while many larger items, which account for most of the mass of plastic, are removed from beaches by cleaning efforts. However, even daily accumulation rate estimates – which exclude the effects of cleaning – fall well short of model predictions of plastic leakage from land-based sources. Oceanographic models predict that plastics entering the sea from South Africa are exported to the South Atlantic and Indian Oceans, with the proportion depending on source location and item density. At sea, floating macroplastic is concentrated close to urban centres. Farther offshore, plastic items tend to be large and buoyant because biofouling causes small, low buoyancy items to sink. Size-selective removal of plastics by biota might also contribute to the paucity of floating microplastics (<1 mm). The seabed is likely to be the main long-term sink for waste plastics, but the limited data available indicate low levels of plastics on the seabed off South Africa. Only a small proportion of plastic predicted to leak into the sea from South Africa can be accounted for. However, this should not delay the implementation of effective mitigation measures to limit plastic leakage.

Significance:

- High densities of waste plastic around urban centres indicate that most macro- and microplastics come from local, land-based sources and do not disperse far at sea.
- Beach clean-ups remove up to 90% of the mass of stranded plastic, largely found in macroplastic items (>25 mm).
- The seabed is a long-term sink for marine plastics, but densities of plastic on the seabed around South Africa are still modest.
- The global model prediction of plastic leakage from South Africa into the sea probably is a gross overestimate.

Introduction

South Africa is predicted to be the 11th worst global offender in terms of leaking land-based plastic into the ocean, ranking third in Africa after Egypt and Nigeria.[1] Although the projected growth in plastic from South African land-based sources is more modest than most other African countries, without significant interventions South Africa is likely to remain a significant polluter for at least the next decade.[2] Verster and Bouwman[3] report the sources and pathways by which plastics reach the South African marine environment from land-based sources. Here the relative importance of land- and offshore-based plastic sources are assessed and the fate of plastic items once they enter the seas around South Africa is discussed.

Land or sea? Inferring the origins of marine plastics

Most marine plastics are assumed to derive from land-based sources.[4] If this is the case, we might expect the composition of marine debris to be broadly similar to terrestrial litter, at least close to urban sources. There are differences in the proportions of macro-debris types on South African beaches and in urban litter (Table 1), but most of these discrepancies can be explained in terms of differential transport and environmental lifespans. For example, paper and cardboard comprises 25% of street litter, but <1% of beach litter (Table 1), presumably because it is less likely to disperse and is less long-lasting than plastic. Dense materials, such as glass and metal, are also under-represented on beaches, with only floating items made from these materials regularly washing up on beaches (e.g. sealed glass bottles, lightbulbs, aerosols, gas bottles). Amongst plastic categories, cotton bud sticks are disproportionately abundant on beaches as most come from waste-water treatment facilities rather than street litter. Lids and hard plastic fragments are also more common on beaches, probably because they disperse well and have long lifespans (in part because they are small, and thus less likely to be removed by cleaning efforts than larger items such as bottles and bags, and in part because their greater thickness than flexible packaging makes them more resistant to UV and/or mechanical degradation). Bottles have similar properties, but are more common in street litter because of differential cleaning of large items from most South African beaches.[5] Polystyrene trays are the most common macroplastic item on beaches, greatly outnumbering their occurrence in urban litter, largely because they tend to break up in the environment, thus inflating the number (but not mass) of items.[6] Mass is a better currency to track changes in debris composition, and there is a steady increase in the proportion of plastic by mass as one moves away from continental source areas (Figure 1), reflecting the differential dispersal and persistence of plastics compared to other debris types.

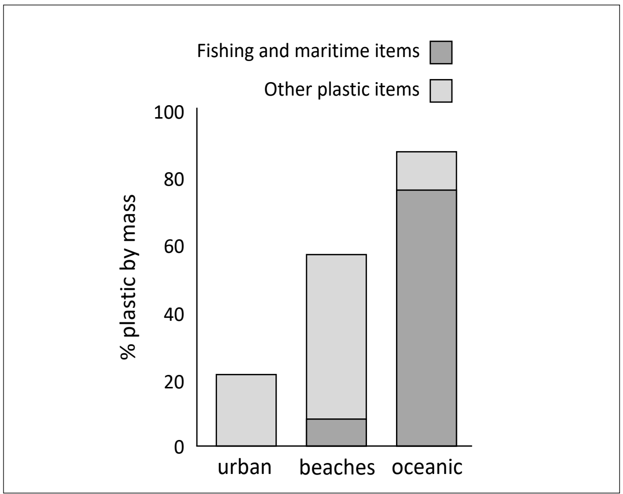

Figure 1: A comparison of the proportion of macro-debris by mass comprising plastic of urban terrestrial litter with that on South African beaches and on a remote oceanic island (Inaccessible Island) in the central South Atlantic Ocean (FitzPatrick Institute unpublished data).

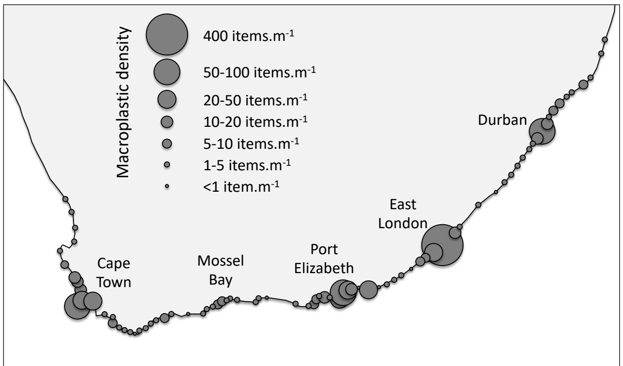

Figure 2: The density of macro-debris (>90% plastic items) at 82 South African beaches in 2015 showing concentrations around urban source areas despite the greater cleaning efforts on urban beaches (FitzPatrick Institute unpublished data).

The dumping of plastic and other persistent wastes at sea was banned in 1989, when Annex V of MARPOL, the International Convention for the Prevention of Pollution from Ships, came into force. However, fishing and other marine activities are still responsible for a substantial amount of marine debris, often accounting for a large proportion of the mass of marine plastic at sites far from land-based sources (Figure 1).[7-9] It is hard to assess how much of this 'maritime' debris is lost at sea accidentally (e.g. as a result of damage to fishing gear or washing overboard during storms) and how much is dumped deliberately. However, in South Africa, fishery-related debris accounts for less than 5% of beach debris by number (12% by mass), much less than food packaging and other single-use plastics typical of street litter (Table 1, Figure 1). Other marine plastics may result from shipping accidents (e.g. 49 tonnes of plastic pellets lost from containers that fell off a ship into Durban harbour in 2017).[10] More problematic to assess, however, is the potential contribution of general waste plastic still dumped at sea in contravention of MARPOL Annex V.[6,11] In this regard, the relative importance of land-based versus offshore sources (fishing, shipping and long-distance drift) can be inferred by examining the distribution and composition of plastic along the coastline.

Table 1: Proportions of macro-debris types at 82 South African beaches sampled in 2015 (n=54 488), in descending order of abundance, compared to Cape Town street and river litter (n=2257). See Figure 2 for the distribution of beaches sampled.

Debris type	Beach	Urban
Polystyrene trays	17.5%	3.5%
Plastic lids and caps (including lid sealing rings)	17.5%	4.0%
Hard plastic fragments	14.4%	1.2%
Cotton buds (earbuds)	8.9%	0.8%
Snack food wrappers (chips, sweets, ice-cream, etc.)	6.6%	12.8%
Plastic straws	5.1%	2.0%
Commercial fishing gear (ropes, netting, floats, light-sticks, etc.)	3.5%	0.0%
Plastic bags (HDPE carrier bags, LDPE bags, mesh bags, etc.)	3.4%	3.9%
Plastic lolly sticks	3.2%	0.2%
Other plastic food wrappers	3.2%	3.9%
Cigarette butts	2.4%	20.5%
Plastic user items (toys, pipes, buckets, etc.)	2.0%	1.8%
Plastic bottles and tubs	1.8%	4.1%
Other packaging (bubble wrap, packing foam, packing strips, etc.)	1.6%	1.3%
Polystyrene lumps	1.6%	0.3%
Disposable plastic items (cutlery, lighters, pens, toothbrushes, etc.)	1.3%	4.2%
Glass items (bottles, lightbulbs, etc.)	1.2%	2.7%
Recreational fishing gear (including monofilament line)	1.2%	<0.1%
Metal items (cans, tins, metal lids, ring pulls, etc.)	0.8%	5.4%
Medical/sewage waste (syringes, condoms, nappies, etc.)	0.6%	0.4%
Shoes, hats, gloves, etc.	0.6%	<0.1%
Paper and cardboard	0.6%	25.5%
Wood (worked timber)	0.5%	0.8%
Other non-plastic items	0.4%	1.7%
All plastic and related synthetic items	**96.5%**	**63.9%**

Regular surveys of debris on sandy beaches around the South African coast, since the 1980s, show that densities of both macro- and mesoplastic items are consistently greater close to urban centres than at more remote beaches (Figure 2).[12,13] This pattern is found among macroplastics even though urban beaches are subject to much greater beach cleaning efforts than remote beaches.[5,14] The distribution of small microplastics (mainly microfibres <1 mm) reported from sandy beaches around the South African coast have differed to some extent between studies[15-17] but the most comprehensive survey to date also found a strong correlation with local urban source areas.[18]

The higher densities of plastics close to urban areas (typically two to three orders of magnitude greater than remote beaches[13,17]; Figure 2) suggest that most plastic on the South African coast derives from local, land-based sources. This is not to say that physical factors do not play a role in the distribution of plastic items along the coast.[19] At a local scale, beach structure and nearshore currents tend to concentrate plastics at some beaches more than at others[10], as evidenced by the correlation between plastic and pumice, a neutral marker of oceanic floating debris[12]. The distribution of plastic standing stocks also is determined by the turnover rate at beaches.[20,21] However, if most plastics were dumped from ships or had drifted from distant sources, we would observe a more uniform distribution of plastic around the coast[13,17] (Figure 2). This conclusion is supported by the greater proportion of locally versus foreign-manufactured items on beaches close to urban source areas than on more remote beaches.[12] Similarly, the proportion of newly stranded plastics carrying bryozoans and goose barnacles (*Lepas* spp.), which is indicative of items that have drifted at sea for some time, increases with distance from urban centres.[22]

All these indicators show that plastics from offshore sources become relatively more abundant with distance from urban centres, which is consistent with land-based litter being responsible for most of the plastic on beaches close to urban centres. Surveys of stranded bottles are currently being conducted to provide a better indication of the relative proportion of land- and ship-based plastics around the South African coast.[6,11] Preliminary results show that most soft-drink bottles derive from local sources, but that many water bottles are from offshore sources, with the proportion of foreign-manufactured water bottles ranging from 15% at urban beaches to nearly 90% at remote beaches (compared to <2% in street litter). The recent manufacture dates and lack of epibionts (organisms that live on the surface of other organisms) on foreign water bottles suggests that they mainly come from shipping passing around the Cape,[6] whereas many of the HDPE bottles manufactured in South East Asia that are found all along the east African coast from Kenya to Cape Agulhas may have drifted across the Indian Ocean because they typically are colonised by bryozoans and often have bite marks from fish (FitzPatrick Institute unpublished data).

Lost at sea – where is all the plastic?

Due to their low density and long lifespan in the environment, plastics can disperse vast distances.[23,24] About two thirds of plastics produced by mass are polymers less dense than seawater[25], and even items made from more dense polymers can float large distances if they contain trapped air pockets (e.g. sealed PET bottles)[6]. Oceanographic models, drifter tracks and observations of debris at sea all indicate that plastic floating at the ocean surface tends to accumulate in the centre of ocean gyres in so-called ‘garbage patches’.[26-29] However, there is a large mismatch between estimates of the amount of plastic entering the sea each year from land-based sources (5–12 million tonnes in 2010)[1] and the amount floating at the sea surface (~250 000 tonnes)[29]. Even allowing for the fact that this estimate of floating plastic is conservative[8] and that Jambeck et al.[1] probably overestimated land-based inputs, the amount of plastic entering the sea each year is at least an order of magnitude greater than the amount floating at sea.[25] This discrepancy adds a new twist to the question ‘Where is all the plastic?’ posed by the seminal paper highlighting concerns about marine microplastics.[30]

Koelmans et al.[31] suggested that rapid fragmentation and sedimentation of floating plastic could account for the relatively small amount of plastic floating at sea. Their model of global plastic flux, fitted by matching known production figures to the observed amount of plastic floating at sea,[29] suggests that more than 99% of plastic that has entered the sea since the 1950s has already sunk to the seabed, with a mean surface retention period of only 3 years. If correct, this means that the sea surface will lose floating plastic fairly rapidly if leakage into the environment ceases.[8] However, only 1 of 50 dated items found in the North Pacific garbage patch in 2015 was less than 5 years old[8], which is consistent with the long travel times predicted from surface drifter models for floating items to reach the accumulation zones in ocean gyres[25,28]. The Koelmans et al.[31] model excludes stranded items from the global mass balance of marine plastics, treating beach plastic as still on land. Lebreton et al.[25] adopted a more realistic three-compartment model for floating macroplastic that tracks items in beaches, as well as floating at sea in coastal and oceanic waters. Using a Lagrangian drift model, with the amount of plastic released from coastal areas related to human population density and waste mismanagement, 96% of particles (or 98% if wind-induced forcing is added to the model) are predicted to strand within 1 year of release.[25] Stranded items can be resuspended and transported offshore, but in order for the model to match observed estimates of floating plastics, only 1% of stranded/seabed macroplastic is resuspended and returned to coastal surface waters each year, and 33% of floating plastic disperses from coastal to oceanic surface waters each year.[25] These estimates appear to be modest, but they depend in part on the assumed degradation rate from macro- to microplastics of 3% per year across all three compartments, which may be slow for plastic on beaches and fast for plastic floating at sea.[24,32] We need better estimates of the fluxes between the main environmental compartments (beaches, sea surface, water column, seabed and biota), as well as plastic degradation rates within each compartment. However, Lebreton et al.’s[25] model predicts that coastlines are important short- to medium-term sinks for marine plastics irrespective of the exact parameter values, which concurs with oceanographic model predictions for the fate of plastics entering the sea from South African urban areas.[19]

Are beaches major sinks for marine plastics?

In a South African context, the fact that plastic densities are greatest close to major urban centres not only indicates that most marine plastic comes from local sources, it also suggests that a large proportion of land-based plastic does not disperse far from source areas. This is consistent with the rapid decrease in the density of floating macroplastic at sea moving away from urban source areas, although sedimentation to the seabed might also contribute to this pattern.[33] Oceanographic models predict that more than 60% of buoyant items entering the sea from South Africa wash up on beaches[19] (Figure 3). The proportion is expected to be much greater for plastic emanating from urban centres along the country’s east coast (>90%) than Cape Town (19%, but all Cape Town litter was simplistically assumed to release into Table Bay; litter entering the semi-enclosed False Bay is less likely to be transported offshore). Fewer plastics with densities greater than seawater are predicted to strand, but even this proportion (35% overall[19]) appears to be rather high given the general paucity of items that sink stranded on South African beaches. Empirical support is needed for these estimates, because the oceanographic model used fails to account for the complex physical dynamics in nearshore environments (waves and tides).[19] In fact, it is likely that the proportion stranding close to major emission points (river mouths and storm drain outfalls) depends on the nature of the receiving environment (e.g. exposure and wave action) as well as the size and buoyancy of the items. Microplastics and low-buoyancy macroplastics (such as bags and flexible packaging, Figure 4a) tend to be transported offshore through surf zones more easily than more buoyant macroplastics (such as bottles and expanded polystyrene, Figure 4b) because they are more prone to be carried offshore in the undertow.[34,35]

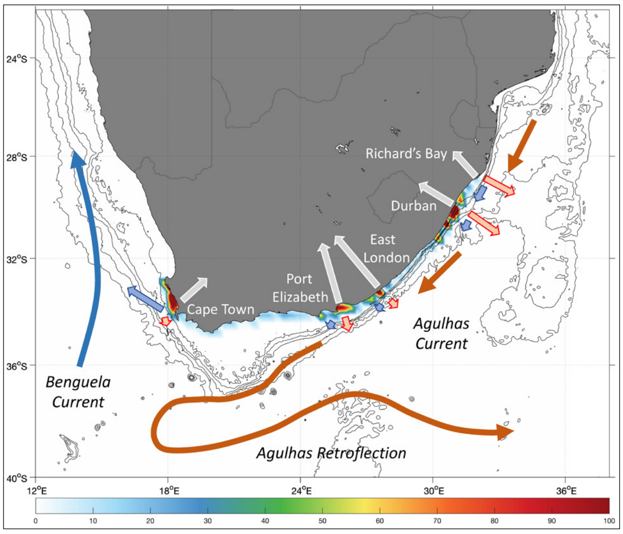

Figure 3: The proportion of plastic items (buoyant and sinking combined) predicted to be exported to the Atlantic or Indian Oceans, or stranded ashore, from the five major urban areas along the South African coast, in relation to ocean currents. Arrow length indicates the relative importance of each pathway. The heat map shading along the coast shows where most debris is predicted to strand (= tracer accumulation factor, adapted from Collins and Hermes[19] with thanks to C. Collins). Cape Town litter was all released off Table Bay (none in False Bay).

Plastic items have been predicted to accumulate along specific areas of the South African coast, mostly downstream from the major urban source areas.[19] However, at a local scale, the predicted zones do not closely match observed hotspots for macro- (Figure 2) or meso/microplastics.[13] These discrepancies probably reflect at least in part differences in shoreline type and associated plastic residence times. For example, concentrations of plastic along the south-central KwaZulu-Natal coast are lower than expected given the high human population densities and large plastic industry in the Durban area[13] (Figure 2). This is not because of reduced plastic input in this area – the amounts of litter stranding on Durban beaches after rain events are quite shocking and regularly attract media attention. A more likely explanation is that the steep, coarse beaches in this area, together with clean-up efforts, result in fast turnover rates for plastic items.[21]

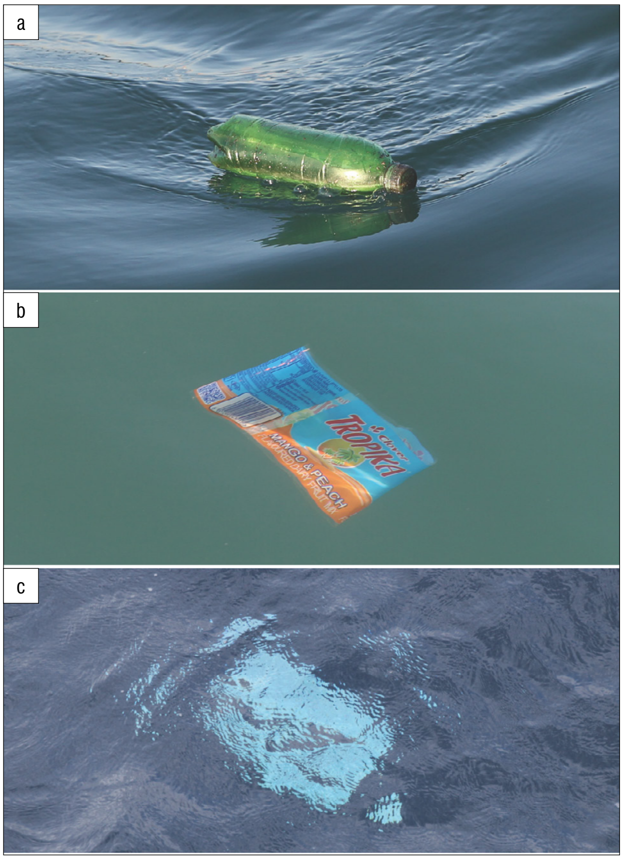

Figure 4: Plastic transport at sea differs between buoyant items with significant windage such as bottles which are blown faster than surface currents even at low wind speeds (a), whereas flexible packaging is close to neutrally buoyant and travels with surface currents (b). After some time at sea, biofouling can cause even large plastic items made from polymers less dense than seawater to sink (c).

One way to test predictions about the proportion of plastic washing ashore is through a mass balance exercise. At least 10^5 tonnes of waste plastic is estimated to reach the sea from land-based sources in South Africa each year.[1-3] How does this figure compare to the amount of plastic stranded on beaches? The average plastic standing stock on South African sandy beaches is <0.1 kg/m, with even the most heavily polluted beaches having 1–2 kg/m (FitzPatrick Institute unpublished data). Extrapolating this estimate along the entire South African coast (3000 km, not all of which is sandy beach) gives a total of $\sim 10^3$ tonnes, appreciably less than the estimated land-based sources. If some 50% of all plastic washes ashore,[19] why do we not see more plastic on our beaches? Several factors might explain this discrepancy: (1) the estimated amount of plastic entering the sea from land-based sources is inflated, (2) the proportion of plastic entering the sea from land-based sources that strands on beaches is lower than expected, and/or (3) turnover rates of plastic items on sandy beaches are rapid, and thus standing stocks underestimate the amount of plastic washing ashore. To resolve the relative importance of these factors, we need direct estimates of the amounts of litter entering the sea,[3] and of the proportion that strands on beaches, but we can make some inferences about how representative standing stocks of beach plastic are of the amount washing ashore.

Burial, export and the impact of beach cleaning

Beaches are dynamic environments, with numerous processes influencing the amount of visible macroplastic.[5,21] Traditional surveys of beach macroplastics only sample superficial items, ignoring buried items.[36,37] In order to estimate the contribution of buried macroplastics, 50-m transects for superficial macroplastics were combined with 1-m wide transects (8-mm sieve) to sample buried macroplastics to a depth of 15 cm. Sampling was conducted at two beaches that are seldom if ever cleaned: a remote beach in the West Coast National Park and at a beach in a restricted area on the False Bay coast. Most macroplastic items were buried at both beaches, but buried items tend to be smaller than surface items because small items are much more readily buried by windblown sand. As a result, buried macroplastics accounted for only 6–34% of the mass of beach plastics (FitzPatrick Institute unpublished data). These estimates suggest that burial is not a major factor in terms of the mass of plastics on beaches. However, they exclude deeply buried plastic items. For example, industrial pellets can occur up to 2 m deep in heavily polluted beaches.[38] Also, sampling did not go far above the storm strand line; substantial amounts of stranded plastic may become trapped particularly on prograding shorelines, which are common locally in southern Africa. Unfortunately, the rapid post-industrial increase in atmospheric greenhouse gases means that we are already committed to substantial sea-level increases (5–10 m) in the near future.[39] Coupled with increasingly severe storm events, it is likely that not only plastic trapped in beaches will be released into the sea through beach erosion, but landfills close to the coast also will be at risk of being washed away (e.g. Coastal Park on the False Bay coast of Cape Town).

There is little information on plastic turnover rates on South African beaches, but they could be fairly rapid, especially for lightweight items given the windy conditions prevalent along the coast. Daily sampling collects 2–5 times more macroplastics by number and 1.3–2.3 times more by mass than weekly sampling, with faster turnover rates for low density items such as expanded polystyrene.[40] The fate of windblown plastic is not well understood; onshore winds blow plastic inland, where much of it is trapped in vegetation along the back shore,[20] whereas offshore winds blow it into the sea. In the surf zone, its fate once again depends on size and buoyancy, with low density items such as sealed bottles and expanded polystyrene being carried back to shore by waves despite their high windage, whereas items such as bags and other flexible packaging, which are much less buoyant, are more likely to be carried offshore.

Beach cleaning efforts likely play a more significant role in removing plastics from marine systems. In South Africa, it is becoming increasingly difficult to find beaches that are not cleaned at least once or twice a year. 'Working for the Coast', part of the government's Expanded Public Works Programme[41], employs teams of people to inter alia clean much of the coastline, augmenting the already substantial municipal cleaning efforts[18] and the ever-growing volunteer cleaning effort. The impact of beach cleaning on plastic standing stocks depends on the frequency and intensity of cleaning, with the intensity largely dependent on the number of cleaners and their level of motivation. There tends to be a strong size bias in cleaning efforts, with larger items more likely to be collected by cleaning teams than small items[5] (Table 2). For example, the beach with the highest macroplastic density sampled along the South African coast in a survey of 82 beaches in 2015 (Figure 2) was an urban beach with daily municipal-funded cleaning. This beach had an average density of 399 items/m of beach, including 66 bottle lids and caps, 52 earbuds, 39 straws and 124 pieces of polystyrene food trays/cups. However, most of the mass of plastic resides in large items. This is illustrated by the comparison of two adjacent beaches on the False Bay coast: one open-access beach that is cleaned regularly by the municipality, and an adjacent beach in a restricted-access area that is seldom, if ever, cleaned. The uncleaned beach has about twice the number of macroplastic items than does the cleaned beach, but the mass of plastic is almost 20 times greater at the uncleaned beach (and 80 times greater if only surface plastic is considered; Table 2). Interestingly, there is more non-plastic debris at the cleaned beach (Table 2), due to littering by beachgoers. This comparison of two adjacent beaches suggests that beach cleaning could account for the removal of over 90% of the mass of plastic stranding

Table 2: The abundance and mass of superficial and buried (to 15 cm deep) macro-debris per metre of beach at two adjacent False Bay beaches with different cleaning histories

Debris type	Uncleaned beach			Cleaned beach			%Cleaned
	Surface	Buried	%Buried	Surface	Buried	%Buried	
All plastic items	35	414	92%	22	268	92%	35%
Bottles	4	7	64%	0	0	–	100%
Lids	9	73	89%	2	21	91%	72%
Straws	3	11	79%	2	6	75%	43%
Bags, wrappers	6	58	91%	4	20	83%	63%
Polystyrene	2	131	98%	3	13	81%	88%
Other packaging	3	15	83%	1	11	92%	33%
User items	5	22	81%	1	5	83%	78%
Plastic fragments	2	69	97%	3	106	97%	**–54%**
Cigarette butts	1	25	96%	6	85	93%	**–250%**
Non-plastic items	2	9	82%	14	118	89%	**–992%**
%Plastic	95%	98%		61%	69%		
Plastic mass (g)	905	472	34%	11	70	86%	94%
Non-plastic mass	41	69	63%	32	126	80%	**–44%**
%Plastic by mass	96%	87%		26%	36%		

%Cleaned shows the proportion removed by regular cleaning, assuming equal inputs.

Debris types which are more abundant at the cleaned beach, despite cleaning effort, presumably due to input from beach users, are shown in bold.

on South African beaches (Table 2). No accurate statistics are kept on the amount of plastic collected; most municipal teams also collect seaweed and other natural marine debris, and even volunteer groups that record the mass of different debris types collected have inflated estimates because they do not clean or dry items prior to weighing. It remains to be answered whether the amount of plastic removed through burial, natural turnover and clean-ups is sufficient to close the gap between the modest superficial standing stocks (~10^3 tonnes) and the amount estimated to strand along the coast (~10^5 tonnes/year), bearing in mind that this latter estimate might be grossly inflated.

Dispersal of floating plastic

What happens to plastic that does not strand on beaches? The drift tracks of plastic items floating at sea can be predicted directly from the trajectories of satellite-tracked weather buoys[26,28] or simulated in oceanographic models[27,42]. The former approach makes no assumptions about oceanographic processes; it simply uses the observed movement of tracked buoys to estimate movement probabilities between grid cells. The website www.plasticadrift.org illustrates global drift patterns and the timescales over which they operate.[28] Plastic items are assumed to have the same drift characteristics as the buoys, which are drogued to track water movements 10–15 m subsurface. Comparisons of drift trajectories of buoys with and without drogues show marked differences due to the effect of Stokes drift (linked to wind and wave action), which decreases rapidly with depth.[43] As a result, these models are best suited for plastics drifting below the water surface (Figure 4c).

Oceanographic circulation models (OCMs) simulate water movements based on forcing mechanisms (wind, Coriolis force, etc.). They can provide a finer-scale prediction of plastic movements than empirical models based on drifter tracks, especially when implemented at a regional[19] rather than a global level.[42] However, even in the open ocean, where OCMs should best simulate water movements, OCM predictions tend to underestimate drifter movements[44] and there are mismatches between distributions of floating microplastics[45]. The models typically do not account for fine-scale features such as drift rows, which result from Langmuir circulation and account for much of the fine-scale heterogeneity in the distribution of floating plastics at sea.[5,21]

OCMs have two advantages compared to drifter-based models. First, drift trajectories can be programmed to account for windage, which typically allows buoyant items to travel faster than prevailing currents (Figure 4b). For example, there was generally good agreement between the observed and predicted dispersal speeds and stranding locations of items with different levels of windage released into the sea by the 2011 Japanese tsunami.[46] Adding windage and stochastic motion improves estimates of stranding probability and the trajectory of objects lost at sea around South Africa.[44] This is particularly important for understanding the dispersal of buoyant items, which dominate floating macroplastics away from land-based source areas.[33] Collins and Hermes[19] did not include windage in their model of plastic dispersal around South Africa because they were interested in microplastics, which generally drift at or just below the water surface.

OCMs also can explore the dispersal of plastics suspended in the water column, and thus simulate the effects of vertical as well as horizontal movement (i.e. accommodate changes in movement trajectories with depth, such as those associated with the thermohaline circulation).[19,47] Elsewhere, suspended plastic has been found to aggregate at the salinity front where large rivers enter the sea,[48] but this is unlikely for the relatively small rivers in South Africa. For plastic items released from the south and east coasts of South Africa, floating items are predicted to be more likely to travel into the Atlantic Ocean, whereas dense plastics which sink towards the seabed are more likely to be entrained in the Agulhas Retroflection and travel into the Indian Ocean.[19] However, like drifter models, OCMs struggle to simulate currents and current-wave interactions in the immediate near-shore environment. For example, the recent study to predict plastic movements around South Africa avoided this issue by releasing tracked particles 8–10 km offshore.[19] We need a better understanding of the movement of plastic items in the surf zone and adjacent nearshore environments to understand the movement of plastic released from South African land-based sources. And although the model produced broadly plausible simulations of currents around South Africa[19], it failed to predict known accumulation zones for plastic drift cards (and oil pollution) along the south coast of South Africa[49].

Drifter-based models and OCMs both predict that most floating plastic items that travel offshore from the South African coast mainly enter the South Atlantic gyre, or drift east into the Indian Ocean.[19,42,44] Only small amounts of plastic from South Africa are predicted to travel south[19], which is consistent with the low densities of plastics observed in the Southern Ocean south of Africa[50]. The accumulation of floating plastic in the South Atlantic gyre has been shown empirically for both micro- and macroplastics.[29,51,52] By comparison, the concentration of floating plastic in the Indian Ocean gyre is less well defined[29,51], with greater leakage predicted to occur into the Pacific Ocean[26,28,53]. However, the absolute amount of plastic entrained in the Indian Ocean is extrapolated to be 4–5 times greater than in the Atlantic Ocean, both in terms of the numbers and mass of items.[29] This difference is driven by greater amounts of macroplastics floating in the Indian Ocean, linked to the much larger input of plastics from South East Asia than from regions bordering the South Atlantic Ocean.[1,53]

Sedimentation of floating plastic and transport by biota

Until recently, models of plastic drifting at sea typically assumed that items less dense than seawater remain at the water surface for protracted periods.[28] However, items drifting at the sea surface tend to lose buoyancy as they become fouled by epibionts, resulting in them sinking.[54] Because fouling occurs on the surface of plastic items, and buoyancy is a function of volume, plastic items with large surface area to volume ratios are expected to sink more quickly.[33] This has been demonstrated experimentally with tethered polyethylene pieces in South African coastal waters, with small (5x5 mm), thin (0.1 mm) pieces sinking within 2–3 weeks, whereas larger (50x50 mm), thicker (4 mm) pieces take more than 2 months to sink.[55] However, it is unclear what impact tethering has on fouling rates and whether fouling in inshore waters is typical of rates experienced farther offshore; fouling rates probably vary seasonally.[56]

Despite these uncertainties, sedimentation probably accounts for the increase in the size and buoyancy of macroplastic items with distance from urban source areas.[33,57] However, there is debate as to the fate of items that sink in this way. In shallow waters, they probably sink to the seabed, where they become fouled by benthic organisms and weighed down by sediment and thus remain trapped on the seabed.[25] This is demonstrated by the fact that most plastic items (77%) collected in trawls on the South African continental shelf are made from polymers less dense than seawater and float once cleaned.[58] Sinking times are of the same order as predicted from the tethered experiments, with a bread bag bearing pelagic goose barnacles (*Lepas anserifera*) trawled up from the seabed within 3 months of being manufactured.[58] In deeper waters, it has been suggested that such items 'yo-yo' up and down in the water column as they start to lose epibionts once they sink below the photic zone.[54,59] Lebreton et al.[25] assumed that this occurred in waters more than 200 m deep. However, the South African trawl survey found a polypropylene margarine tub still bearing pelagic goose barnacles at 685 m.[58] The tub might have travelled down the continental slope after sinking, but it was already colonised by a diverse array of benthic biota, and thus appeared to be unlikely to float again.

Biofouling is not the only process that facilitates the sedimentation of plastics from the sea surface. Microplastics frequently adhere to marine 'snow' (particles of organic detritus[60]), which increases the likelihood of sinking out of surface waters.[61] Sinking is also promoted for microplastics incorporated into zooplankton faecal pellets and larvacean mucous filters[62,63], although microplastics can reduce the sink rate of faecal pellets[64]. Zooplankton may also export plastics directly to deeper waters. Many species forage near the sea surface at night and then migrate vertically to deeper waters during the day, where ingested plastic could be entrained if the zooplankton is eaten in the deep.[65-67] Recent studies suggest that many planktonic organisms now contain ingested microplastics.[65-68] This is particularly true in heavily polluted areas such as the North Pacific 'garbage patch'[68] and near the mouth of the Yangtze River in the Yellow Sea[65], but high incidences of microplastics have been found in mesopelagic fish even in oceanic waters far from the subtropical gyres[66]. Most small pelagic fish off South Africa also contain microfibres (44–80% of individuals of five species contained at least some fibres[69]), but it is not known what proportion of these fibres are synthetic. However, it is questionable whether these items account for a significant proportion of the mass of plastics at sea because they are typically very small fragments and fibres. For example, even in the Yellow Sea, where microplastics are estimated to be almost two orders of magnitude more abundant in zooplankton than in the water column,[65] the mass of ingested plastic is <1 mg/m^2, even if we assume zooplankton occurs to 300 m deep.

Animals might also transport plastics among other environmental compartments. Marine predators, such as seabirds and seals, that come ashore to breed or moult import some plastics to land (e.g. seabirds using plastics collected at sea as nest material).[70] This is probably most significant for ingested plastic in seabirds, which can be released on land through mortality, regurgitation or excretion.[71-73] Off South Africa, petrels in particular often contain large amounts of ingested plastic[74], with adults transferring much of their accumulated plastics to their chicks[75]. However, this is only likely to account for a relatively small amount of plastic, even given the large populations of some species (10^6–10^7 individuals),[76] given average plastic loads of <0.1 g per bird.

The seabed as a long-term sink

The sedimentation of floating plastics, together with the direct sinking of about one third of all polymers that are more dense than seawater, suggests that the seabed is likely to be the ultimate long-term sink for most plastics that enter the marine environment.[77,78] However, very little is published on the composition and abundance of seabed debris in South Africa.[79-81] A recent study of macro-debris in 235 demersal trawls made across the continental shelf (30–900 m deep) between the Orange River and Port Alfred found that plastic was most common in the area north of Cape Town and that densities increased with water depth.[58] Most plastic debris was packaging and other single use items (77%) but these items accounted for only 16% of the mass of plastics.[58] Fishing gear was the next most common category of plastic items (21% by number and 48% by mass). The proportion of fishing gear on the seabed likely increases with distance from land-based sources, particularly on favoured fishing areas such as sea mounts.[82] Overall, the densities of plastics (3 items/km^2 and 0.3 kg/km^2) were markedly lower than in other trawl surveys around the world (typically 20–500 items/km^2 and 2–20 kg/km^2).[58,78] This might be related in part to the nature of the trawl gear used, but examination of remotely operated vehicle camera footage collected for biodiversity surveys across a range of habitats from the continental shelf and slope all suggest very low densities of debris on the seabed around South Africa (Sink K, SANBI, personal communication).

Closer to shore, occasional mass strandings of seabed debris indicate the presence of a pool of plastics on the seabed at least close to urban source areas.[80] For example, monthly spring-low clean-ups of a stretch of rocky intertidal shoreline in False Bay collected an average of 1.65 ± 1.30 plastic items/m (12 ± 10 g/m, $n=36$ months), except one month when more than 65 items (72 g/m) were recorded (FitzPatrick Institute unpublished data). Many items were made of polymers denser than seawater (polyamide cable ties, polystyrene cutlery, etc.). The conditions driving such events have not been studied in South Africa, but probably are related to intense wind-driven upwelling.[83] However, the location of this plastic on the seabed remains unknown, with no plastic items seen in any of 421 images of the False Bay seabed taken to classify benthic communities (FitzPatrick Institute unpublished data).

Current uncertainties and evidence gaps

The gross discrepancy between estimates of the amount of plastic in marine environments around South Africa and the amount thought to be released from local, land-based sources mirrors our inability to produce a plausible mass balance for waste plastics globally.[25,31] Either we are greatly overestimating the amounts of plastic entering the sea, or we are failing to measure a major sink for marine plastics. To solve this dilemma, we need a better understanding of the origins, transport and fates of macroplastics, because they account for almost all of the mass of plastics in marine ecosystems.[8,29]

Although much remains to be learned about the distribution and abundance of plastics on the seabed, all indications are that macroplastic items are scarce on the seabed off South Africa, especially when compared to other densely populated continental margins. As a result, it is unlikely that seabed plastic will fill the deficit in the mass budget. We know even less about plastics suspended in the water column, including how they move vertically with biotic-induced changes in buoyancy.[47,59] Sampling macroplastics in mid-water trawls is perhaps the most practical way to gain useful data in this regard. However, anecdotal reports from fishers and fishery biologists indicate that this compartment is unlikely to explain the thousands of tonnes of 'missing' plastic. Better estimates of plastics removed from beaches might partly explain the deficit, but estimates of daily arrival rates of macroplastics at urban beaches[84-86] are modest relative to the global model prediction. Paradoxically, the biggest knowledge gap pertains to estimates of land-based plastics entering the sea. This should be one of the easiest fluxes to measure, but it is symptomatic of the history of the plastic pollution problem, which started in marine ecosystems and has only recently started to focus on plastics in freshwater and terrestrial ecosystems.[87]

Implications for tackling the plastics problem

The fact that we cannot account for much of the mass of plastic estimated to be leaking from South Africa into the ocean has little bearing on how we go about tackling the plastics problem. Although the exact amounts are poorly known, it is clear that the country is responsible for a significant amount of plastic waste entering the sea, and that this situation needs to be addressed. There are many ways to reduce plastic wastes, including incentives to reuse or recycle plastics; improved product design to reduce plastic use and facilitate recycling; adopting extended producer responsibility for packaging beyond the point of sale; material substitution; and even banning plastics in high-risk applications. However, the ultimate goal is to reduce the amount of plastic and other solid wastes entering the sea. Here, the biggest short-term gains will be made by improving solid waste management on land and intercepting debris in run-off, particularly from urban areas. Installing and servicing effective litter traps in urban rivers will go a long way towards reducing plastic leakage into the sea. However, there is also a need to ensure better compliance with legislation prohibiting the dumping of plastics and other persistent wastes by ships at sea.

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References

1. Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady AL, et al. Plastic waste inputs from land into the ocean. Science. 2015;347:768–771. https://doi.org/10.1126/science.1260352
2. Jambeck J, Hardesty BD, Brooks AL, Friend T, Teleki K, Fabres J, et al. Challenges and emerging solutions to the land-based plastic waste issue in Africa. Mar Policy. 2018;96:256–263. https://doi.org/10.1016/j.marpol.2017.10.041
3. Verster C, Bouwman H. Land-based sources and pathways of marine plastics in a South African context. S Afr J Sci. 2020;116(5/6), Art. #7700, 9 pages. https://doi.org/10.17159/sajs.2020/7700
4. Coe JM, Rogers DB, editors. Marine debris: Sources, impacts, and solutions. New York: Springer-Verlag; 1997. https://doi.org/10.1007/978-1-4613-8486-1
5. Ryan PG, Moore CJ, Van Franeker JA, Moloney CL. Monitoring the abundance of plastic debris in the marine environment. Phil Trans R Soc B. 2009;364:1999–2012. https://doi.org/10.1098/rstb.2008.0207
6. Ryan PG, Dilley BJ, Ronconi RA, Connan M. Rapid increase in Asian bottles in the South Atlantic Ocean indicates major debris inputs from ships. Proc Natl Acad Sci USA. 2019;116:20892–20897. https://doi.org/10.1073/pnas.1909816116
7. Santos IR, Friedrich AC, Barretto FP. Overseas garbage pollution on beaches of northeast Brazil. Mar Pollut Bull. 2005;50:782–786. https://doi.org/10.1016/j.marpolbul.2005.04.044
8. Lebreton L, Slat B, Ferrari F, Sainte-Rose B, Aitken J, Marthouse R, et al. Evidence that the Great Pacific Garbage Patch is rapidly expanding. Sci Rep. 2018;8, Art. #4666, 15 pages. https://doi.org/10.1038/s41598-018-22939-w
9. Monteiro RCP, Ivar do Sul JA, Costa MF. Plastic pollution in islands of the Atlantic Ocean. Environ Pollut. 2018;238:103–110. https://doi.org/10.1016/j.envpol.2018.01.096
10. Schumann EH, MacKay CF, Strydom NA. Nurdle drifters around South Africa as indicators of ocean structures and dispersion. S Afr J Sci. 2019;115(5/6), Art. #5372, 9 pages. https://doi.org/10.17159/sajs.2019/5372
11. Smith SDA, Banister K, Fraser N, Edgar RJ. Tracing the source of marine debris on the beaches of northern New South Wales, Australia: The bottles on beaches program. Mar Pollut Bull. 2018;126:304–307. https://doi.org/10.1016/j.marpolbul.2017.11.022
12. Ryan PG, Moloney CL. Plastic and other artefacts on South African beaches: Temporal trends in abundance and composition. S Afr J Sci. 1990;86:450–452.
13. Ryan PG, Perold V, Osborne A, Moloney CL. Consistent patterns of debris on South African beaches indicate that industrial pellets and other mesoplastic items mostly derive from local sources. Environ Pollut. 2018;238:1008–1016. https://doi.org/10.1016/j.envpol.2018.02.017
14. Ryan PG, Swanepoel D. Cleaning beaches: Sweeping litter under the carpet. S Afr J Sci 1996;92:275–276.
15. Naidoo T, Glassom D, Smit AJ. Plastic pollution in five urban estuaries of KwaZulu-Natal, South Africa. Mar Pollut Bull. 2015;101:473–480. https://doi.org/10.1016/j.marpolbul.2015.09.044
16. Nel HA, Froneman PW. A quantitative analysis of microplastic pollution along the south-eastern coastline of South Africa. Mar Pollut Bull. 2015;101:274–279. https://doi.org/10.1016/j.marpolbul.2015.09.043
17. Nel HA, Hean JW, Noundou XS, Froneman PW. Do microplastic loads reflect the population demographics along the southern African coastline? Mar Pollut Bull. 2017;115:115–119. https://doi.org/10.1016/j.marpolbul.2016.11.056
18. De Villiers S. Quantification of microfibre levels in South Africa's beach sediments, and evaluation of spatial and temporal variability from 2016 to 2017. Mar Pollut Bull. 2018;135:481–489. https://doi.org/10.1016/j.marpolbul.2018.07.058
19. Collins C, Hermes JC. Modelling the accumulation and transport of floating marine micro-plastics around South Africa. Mar Pollut Bull. 2019;139:46–58. https://doi.org/10.1016/j.marpolbul.2018.12.028
20. Brennan E, Wilcox C, Hardesty BD. Connecting flux, deposition and resuspension in coastal debris surveys. Sci Total Environ. 2018;644:1019–1026. https://doi.org/10.1016/j.scitotenv.2018.06.352
21. Ryan PG, Pichegru L, Perold V, Moloney CL. Monitoring marine plastics – will we know if we're making a difference? S Afr J Sci. 2020;116(5/6), Art. #7678, 9 pages. https://doi.org/10.17159/sajs.2020/7678
22. Fazey FMC, Ryan PG. Debris size and buoyancy influence the dispersal distance of stranded litter. Mar Pollut Bull. 2016;110:371–377. https://doi.org/10.1016/j.marpolbul.2016.06.039
23. Ryan PG. The origin and fate of artefacts stranded on islands in the African sector of the Southern Ocean. Environ Conserv. 1987;14:341–346. https://doi.org/10.1017/S0376892900016854
24. Barnes DKA, Galgani F, Thompson RC, Barlaz M. Accumulation and fragmentation of plastic debris in global environments. Phil Trans R Soc B. 2009;364:1985–1998. https://doi.org/10.1098/rstb.2008.0205
25. Lebreton L, Egger M, Slat B. A global mass budget for positively buoyant macroplastic debris in the ocean. Sci Rep. 2019;9, Art. #12922, 10 pages. https://doi.org/10.1038/s41598-019-49413-5
26. Maximenko N, Hafner J, Niiler P. Pathways of marine debris derived from trajectories of Lagrangian drifters. Mar Pollut Bull. 2012;65:51–62. https://doi.org/10.1016/j.marpolbul.2011.04.016
27. Potemra J. Numerical modeling with application to tracking marine debris. Mar Pollut Bull. 2012;65:42–50. https://doi.org/10.1016/j.marpolbul.2011.06.026
28. Van Sebille E, England MH, Froyland G. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environ Res Lett. 2012;7, 044040, 6 pages. https://doi.org/10.1088/1748-9326/7/4/044040

29. Eriksen M, Lebreton LCM, Carson HS, Thiel M, Moore CJ, Borerro JC, et al. Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS ONE. 2014;9(12), e111913, 15 pages. https://doi.org/10.1371/journal.pone.0111913

30. Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AW, et al. Lost at sea: Where is all the plastic? Science. 2004;304:838. https://doi.org/10.1126/science.1094559

31. Koelmans AA, Kooi M, Law KL, Van Sebille E. All is not lost: Deriving a top-down mass budget of plastic at sea. Environ Res Lett. 2017;12:114028. https://doi.org/10.1088/1748-9326/aa9500

32. Andrady AL. Microplastics in the marine environment. Mar Pollut Bull. 2011;62:1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

33. Ryan PG. Does size and buoyancy affect the long-distance transport of floating debris? Environ Res Lett. 2015;10:084019. https://doi.org/10.1088/1748-9326/10/8/084019

34. Isobe A, Kubo K, Tamura Y, Nakashima E, Fujii N. Selective transport of microplastics and mesoplastics by drifting in coastal waters. Mar Pollut Bull. 2014;89:324–330. https://doi.org/10.1016/j.marpolbul.2014.09.041

35. Hinata H, Kataoka T. A belt transect setting strategy for mark-recapture experiments to evaluate the 1D diffusion coefficient of beached litter in the cross-shore direction. Mar Pollut Bull. 2016;109:490–494. https://doi.org/10.1016/j.marpolbul.2016.05.016

36. Williams AT, Tudor DT. Litter burial and exhumation: Spatial and temporal distribution on a cobble pocket beach. Mar Pollut Bull. 2001;42:1031–1039. https://doi.org/10.1016/S0025-326X(01)00058-3

37. Kusui T, Noda M. International survey on the distribution of stranded and buried litter on beaches along the Sea of Japan. Mar Pollut Bull. 2003;47:175–179. https://doi.org/10.1016/S0025-326X(02)00478-2

38. Turra A, Manzano AB, Dias RJS, Mahiques MM, Barbosa L, Balthazar-Silva D, et al. Three-dimensional distribution of plastic pellets in sandy beaches: Shifting paradigms. Sci Rep. 2014;4, Art. #4435, 7 pages. https://doi.org/10.1038/srep04435

39. Dutton A, Carlson AE, Long AJ, Milne GA, Clark PU, De Conto R, et al. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science. 2015;349(6244), aaa4019, 9 pages. https://doi.org/10.1126/science.aaa4019

40. Ryan PG, Lamprecht A, Swanepoel D, Moloney CL. The effect of fine-scale sampling frequency on estimates of beach litter accumulation. Mar Pollut Bull. 2014;88:249–254. https://doi.org/10.1016/j.marpolbul.2014.08.036

41. Glovovic BC, Boonzaaier S. Confronting coastal poverty: Building sustainable coastal livelihoods in South Africa. Ocean Coastal Managem. 2007;50:1–23. https://doi.org/10.1016/j.ocecoaman.2006.07.001

42. Lebreton LCM, Greer SD, Borrero JC. Numerical modelling of floating debris in the world's oceans. Mar Pollut Bull. 2012;64:653–661. https://doi.org/10.1016/j.marpolbul.2011.10.027

43. Fraser CI, Morrison AK, Van Sebille E, Macaya EC, Hogg AM, Ryan PG, et al. Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. Nat Clim Change. 2018;8:704–708. https://doi.org/10.1038/s41558-018-0209-7

44. Hart-Davis MG, Backeberg BC, Halo I, Van Sebille E, Johannessen JA. Assessing the accuracy of satellite derived ocean currents by comparing observed and virtual buoys in the Greater Agulhas Region. Remote Sens Environ. 2018;216:735–746. https://doi.org/10.1016/j.rse.2018.03.040

45. Onink V, Wichmann D, Delandmeter P, Van Sebille E. The role of Ekman currents, geostrophy and Stokes drift in the accumulation of floating microplastic. J Geophys Res Oceans. 2019;124:1474–1490. https://doi.org/10.1029/2018JC014547

46. Maximenko N, Hafner J, Kamachi M, MacFadyen A. Numerical simulations of debris drift from the Great Japan Tsunami of 2011 and their verification with observational reports Mar Pollut Bull. 2018;132:5–25. https://doi.org/10.1016/j.marpolbul.2018.03.056

47. Erni-Cassola G, Zadjelovic V, Gibson MI, Christie-Oleza JA. Distribution of plastic polymer types in the marine environment: A meta-analysis. J Hazard Mater. 2019;369:691–698. https://doi.org/10.1016/j.jhazmat.2019.02.067

48. Acha EM, Mianzan HW, Iribarne O, Gagliardini DA, Lasta C, Daleo P. The role of the Río de la Plata salinity front in accumulating debris. Mar Pollut Bull. 2003;46:197–202. https://doi.org/10.1016/S0025-326X(02)00356-9

49. Shannon LV, Chapman P. Suggested mechanism for the chronic pollution by oil of beaches east of Cape Agulhas, South Africa. S Afr J Mar Sci. 1983;1:231–244. https://doi.org/10.2989/025776183784447520

50. Ryan PG, Musker S, Rink A. Low densities of drifting litter in the African sector of the Southern Ocean. Mar Pollut Bull. 2014;89:16–19. https://doi.org/10.1016/j.marpolbul.2014.10.043

51. Cózar A, Echevarría F, González-Gordillo JI, Irigoien X, Úbeda B, Hernández-León S, et al. Plastic debris in the open ocean. Proc Natl Acad Sci USA. 2014;111:10239–10244. https://doi.org/10.1073/pnas.1314705111

52. Ryan PG. Litter survey detects the South Atlantic 'garbage patch'. Mar Pollut Bull. 2014;79:220–224. https://doi.org/10.1016/j.marpolbul.2013.12.010

53. Van Sebille E, Wilcox C, Lebreton LCM, Maximenko NA, Hardesty BD, Van Franeker JA, et al. A global inventory of small floating plastic debris. Environ Res Lett. 2015;10(12), Art.#124006, 11 pages. https://doi.org/10.1088/1748-9326/10/12/124006

54. Ye S, Andrady AL. Fouling of floating plastic debris under Biscayne Bay exposure conditions. Mar Pollut Bull. 1991;22:608–613. https://doi.org/10.1016/0025-326X(91)90249-R

55. Fazey FMC, Ryan PG. Biofouling on buoyant marine plastics: an experimental study into the effect of size on surface longevity. Environ Pollut 2016;210:354–360. https://doi.org/10.1016/j.envpol.2016.01.026

56. Chen X, Xiong X, Jiang X, Shi H, Wu C. Sinking of floating plastic debris caused by biofilm development in a freshwater lake. Chemosphere. 2019;222:856–864. https://doi.org/10.1016/j.chemosphere.2019.02.015

57. Fazey FMC, Ryan PG. Debris size and buoyancy influence the dispersal distance of stranded litter. Mar Pollut Bull. 2016;110:371–377. https://doi.org/10.1016/j.marpolbul.2016.06.039

58. Ryan PG, Weideman EA, Perold V, Durholz D, Fairweather TP. A trawl survey of seabed macrolitter on the South African continental shelf. Mar Pollut Bull. 2020;150, Art.#110741, 6 pages. https://doi.org/10.1016/j.marpolbul.2019.110741

59. Kooi M, Van Nes E, Scheffer M, Koelmans A. Ups and downs in the ocean: Effects of biofouling on vertical transport of microplastics. Environ Sci Technol. 2017;51:7963–7971. https://doi.org/10.1021/acs.est.6b04702

60. Zhao S, Ward JE, Danley M, Mincer TJ. Field-based evidence for microplastic in marine aggregates and mussels: Implications for trophic transfer. Environ Sci Technol. 2018;52:11038–11048. https://doi.org/10.1021/acs.est.8b03467

61. Ploug H, Iversen MH, Fisher G. Ballast, sinking velocity, and apparent diffusivity within marine snow and zooplankton fecal pellets: Implications for substrate turnover by attached bacteria. Limnol Oceanogr. 2008;53:1878–1886. https://doi.org/10.4319/lo.2008.53.5.1878

62. Cole M, Lindeque PK, Fileman E, Halsband C, Goodhead R, Moger J, et al. Microplastic ingestion by zooplankton. Environ Sci Technol. 2013;47:6646 – 6655. https://doi.org/10.1021/es400663f

63. Katija K, Choy CA, Sherlock RE, Sherman AD, Robison BH. From the surface to the seafloor: How giant larvaceans transport microplastics into the deep sea. Sci Adv. 2017;3, e1700715, 5 pages. https://doi.org/10.1126/sciadv.1700715

64. Cole M, Lindeque PK, Fileman E, Clark J, Lewis C, Halsband C, et al. Microplastics alter the properties and sinking rates of zooplankton faecal pellets. Environ Sci Technol. 2016;50:3239–3246. https://doi.org/10.1021/acs.est.5b05905

65. Sun X, Liang J, Zhu M, Zhao Y, Zhang B. Microplastics in seawater and zooplankton from the Yellow Sea. Environ Pollut. 2018;242:585–595. https://doi.org/10.1016/j.envpol.2018.07.014

66. Wieczorek AM, Morrison L, Croot PL, Allcock AL, MacLoughlin E, Savard O, et al. Frequency of microplastics in mesopelagic fishes from the Northwest Atlantic. Front Mar Sci. 2018;5, Art. #039, 9 pages. https://doi.org/10.3389/fmars.2018.00039

67. Choy CA, Robison BH, Gagne TO, Erwin B, Firl E, Halden RU, et al. The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. Sci Rep. 2019;9, Art.#7843, 9 pages. https://doi.org/10.1038/s41598-019-44117-2

68. Boerger CM, Lattin GL, Moore SL, Moore CJ. Plastic ingestion by planktivorous fishes in the North Pacific central gyre. Mar Pollut Bull. 2010;60:2275–2278. https://doi.org/10.1016/j.marpolbul.2010.08.007

69. Ross KJ. Ingestion of microplastics by epipelagic and mesopelagic fish in South African waters: A species comparison [Hons report]. Cape Town: University of Cape Town; 2017. https://bit.ly/2kbWp64

70. Hartwig E, Clemens T, Heckroth M. Plastic debris as nesting material in a kittiwake (*Rissa tridactyla*) colony at the Jammerbugt, northwest Denmark. Mar Pollut Bull. 2007;54:595–597. https://doi.org/10.1016/j.marpolbul.2007.01.027

71. Ryan PG, Fraser MW. The use of Great Skua pellets as indicators of plastic pollution in seabirds. Emu 1988;88:16–19. https://doi.org/10.1071/MU9880016

72. Buxton RT, Currey CA, Lyver PO, Jones CJ. Incidence of plastic fragments among burrow-nesting seabird colonies on offshore islands in northern New Zealand. Mar Pollut Bull. 2013;74:420424. https://doi.org/10.1016/j.marpolbul.2013.07.011

73. Provencher JF, Vermaire JC, Avery-Gomm S, Braune BM, Mallory ML. Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastic. Sci Tot Environ. 2018;644:1477–1484. https://doi.org/10.1016/j.scitotenv.2018.07.101

74. Ryan PG. The incidence and characteristics of plastic particles ingested by seabirds. Mar Environ Res. 1987;23:175–206. https://doi.org/10.1016/0141-1136(87)90028-6

75. Ryan PG. Intraspecific variation in plastic ingestion by seabirds and the flux of plastic through seabird populations. Condor. 1988;90:446–452. https://doi.org/10.2307/1368572

76. Brooke MDL. The food consumption of the world's seabirds. Proc R Soc Lond B. 2004;271:S246–S248. https://doi.org/10.1098/rsbl.2003.0153

77. Woodall LC, Sanchez-Vidal A, Canals M, Paterson GLJ, Coppock R, Sleight V, et al. The deep sea is a major sink for microplastic debris. R Soc Open Sci. 2014;1:140317. https://doi.org/10.1098/rsos.140317

78. Ioakeimidis C, Galgani F, Papatheodorou G. Occurrence of marine litter in the marine environment: A world panorama of floating and seafloor plastics. In: Takada H, Karapanagioti HK, editors. Hazardous chemicals associated with plastics in the environment. Handbook Environ Chem. 2017;78:93–120. https://doi.org/10.1007/698_2017_22

79. Rundgren CD. Aspects of pollution in False Bay, South Africa (with special reference to subtidal pollution) [MSc thesis]. Cape Town: University of Cape Town; 1992. http://hdl.handle.net/11427/18330

80. Pfaff MC, Logston RC, Raemaekers SJPN, Hermes JC, Blamey LK, Cawthra HC, et al. A synthesis of three decades of socio-ecological change in False Bay, South Africa: Setting the scene for multidisciplinary research and management. Elementa Sci Anthrop. 2019;7, Art.#32, 49 pages. https://doi.org/10.1525/elementa.367

81. Matsuguma Y, Takada H, Kumata H, Kanke H, Sakurai S, Suzuki T, et al. Microplastics in sediment cores from Asia and Africa as indicators of temporal trends in plastic pollution. Arch Environ Contam Toxicol. 2017;73:230–239. https://doi.org/10.1007/s00244-017-0414-9

82. Woodall LC, Robins LF, Rogers AD, Narayanaswamy BE, Paterson GLJ. Deep-sea litter: A comparison of seamounts, banks and a ridge in the Atlantic and Indian Oceans reveals both environmental and anthropogenic factors impact accumulation and composition. Front Mar Sci. 2015;2, Art. #3, 10 pages. https://doi.org/10.3389/fmars.2015.00003

83. Chubarenko I, Stepanovs N. Microplastics in sea coastal zone: Lessons learned from the Baltic amber. Environ Pollut. 2017;224:243–254. https://doi.org/10.1016/j.envpol.2017.01.085

84. Swanepoel D. An analysis of beach debris accumulation in Table Bay, South Africa [MSc thesis]. Cape Town: University of Cape Town; 1995. http://hdl.handle.net/11427/28474

85. Lamprecht A. The abundance, distribution and accumulation of plastic debris in Table Bay, Cape Town, South Africa [MSc thesis]. Cape Town: University of Cape Town; 2013. http://hdl.handle.net/11427/6633

86. Chitaka TY, Von Blottnitz H. Accumulation and characteristics of plastic debris along five beaches in Cape Town. Mar Pollut Bull. 2019;138:451–457. https://doi.org/10.1016/j.marpolbul.2018.11.065

87. Ryan PG. A brief history of marine litter research. In: Bergmann M, Gutow L, Klages M, editors. Marine anthropogenic litter. Cham: Springer International Publishing; 2015. p. 1–25. https://doi.org/10.1007/978-3-319-16510-3_1