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RESEARCH ARTICLE

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Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean

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Abstract Organisms have travelled the Atlantic Ocean as neuston and have rafted on natural marine debris for millions of years. Shipping increased opportunities for marine organism travel mere thousands of years ago but in just decades floating plastic debris is transforming marine rafting. Here we present a combined open-ocean and remote coasts marine debris survey of the Atlantic (from 68°S–78°N). Daily shipboard observations were made from the Southern Ocean to the high Arctic and the shores of 16 remote islands were surveyed. We report (1) anthropogenic debris from the most northerly and southerly latitudes to date, (2) the first record of marine biota colonising debris at latitudes >68°, and (3) the finding of exotic species (the barnacle *Elminius modestus*) on northern plastic debris. Plastic pieces dominated both open-ocean and stranding marine debris. The highest densities of oceanic debris were found around northwest Europe, whereas the highest stranding levels were equatorial. Our findings of high east-Arctic debris colonisation by fauna contrast with low values from west Arctic (though only two samples) and south Atlantic shores. Colonisation rates of debris differed between hemispheres, previously considered to be similar. Our two South Atlantic mega-debris shipboard surveys (10 years apart) found no changes in open-ocean debris densities but resurvey of a UK and an Arctic island both found increases. We put our findings in the context of the Atlantic literature to interpret spatial and temporal trends in marine debris accumulation and its organismal consequences.

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Introduction

Prior to the colonisation of the land by plants beginning in the Ordovician there was probably little flotsam on ocean surfaces except algae and localised and periodic bursts of pumice from volcanic activity (though this may have been more common and ubiquitous millions of years ago). For hundreds of millions of years since then organisms have had limited travel on floating marine algae, plant trunks, pods, or other floating parts as well as on neustic animals or gas-filled shells of dead cephalopods. Sometimes, however, natural debris can travel for years and between oceans (Barber et al. 1959; Coombs and Landis 1966; Smith 1985). The onset of human travels at sea, particularly with respect to commercial shipping, marked the onset of drastically increased dispersal for many marine organisms (Carlton 1987). In the latter half of the last century a new persistent traveller invaded the global marine environment—anthropogenic rubbish. Plastic became a major marine problem for exactly the same reasons that had made it a commercial success. Plastic was so cheap to make, it was disposable. The resistance of plastic to degradation made it highly persistent, even with long exposures to UV light in haline environments (see Gregory 1999). At first this seemed merely a nuisance in terms of spoiling the coastline, but wide-scale poisoning and choking of wildlife quickly emerged (Croxall et al. 1990; Bjorndal et al. 1994; Gregory 1999). In the 1970s plastic particles were discovered in offshore Atlantic waters both in the cool north (Colton et al. 1974) and in the tropical south (Carpenter and Smith 1972). A decade later mega- and macro-plastics began to accumulate on remote mid-ocean islands (Ryan 1987; Benton 1991), increasing at alarming rates (Ryan and Moloney 1993).

Organisms ranging from dinoflagellate algae (Masó et al. 2003) to iguanas (Censky et al. 1998) have now been observed to raft rubbish in Atlantic waters. Stranded debris on island shores has revealed a considerable biota, which in many cases would normally have been highly restricted in dispersal (Winston et al. 1997). The global extent and levels of colonisation of marine debris clearly represent a massive and historically unparalleled opportunity for dispersal for marine organisms (Barnes 2002). Introduction of non-native animals to new environments is widely accepted to be one of the greatest causes of loss of species (e.g. see Carlton and Geller 1993). The avian, small mammal, and other island extinctions following accidental and deliberate transport of rats, cats, and goats (amongst other animals; Elton 1958; Simberloff and Boecklen 1991; Vitousek et al. 1997) around the globe has provided only some insight into the potential problems facing marine exotic introductions.

In the sea, removal or even control of pest species is not practical nor probably even feasible (unlike on small islands). It has been estimated that plastics have doubled organisms' opportunities for dispersal in the tropics but humans have most increased potential dispersal at sub-polar latitudes (Barnes 2002). This poses particular problems for several reasons; first, the Southern Ocean has the highest levels of endemism in many taxa, for example, bryozoans and amphipods at approximately 80% and Pycnogona at approximately 90% (Winston 1992; Arntz et al. 1997). Species loss in areas of high endemism is generally least desirable. Second, the Southern Ocean is probably the only marine environment that has no known exotic introductions, and third, the Atlantic section of Antarctica, the Antarctic Peninsula, is the fastest demonstrably warming region (Quayle et al. 2002). This is important, as the freezing sea surface temperatures may be the biggest single barrier to rubbish rafting exotics. To date, rafting organisms and anthropogenic debris have been rare in high polar environments (Barnes and Fraser 2003).

The latitudinal span of the Atlantic Ocean is certainly a highly appropriate place to quantify amounts and effects of marine debris especially as an Antarctic invasion from the South Atlantic seems likely for at least two reasons: (1) there are a number of high-latitude Atlantic archipelagos just to the north and south of the Polar Frontal Zone in the region of the Antarctic Peninsula; and (2) probably most tourist and much fishery shipping in the Southern Ocean operates between the south Atlantic and the Antarctic Peninsula.

In this article we outline the quantities, types, and colonisers of marine debris in the Atlantic and the Atlantic sector of the Southern Ocean both afloat and ashore on remote islands. We conducted transects on several island shores and north–south along the Atlantic Ocean from 79°N to 68°S and hypothesised that (1) anthropogenic debris would be more numerous in the North Atlantic around western Europe; (2) plastic would dominate debris; (3) organism colonisation would be most intense at low latitude; and (4) debris at sea would have similar composition to that on remote island shores. Finally we reviewed temporal patterns of marine debris change on remote island shores for which medium-term surveys have been established and reported.

Materials and methods

Sighting debris at sea

An observer with binoculars on the research ship R.R.S. 'Bransfield' daily in the Southern and Atlantic Oceans (latitude range 60°–45°S) recorded floating debris for 2 h per day (over midday) in March and April 1993. A decade later, similar observations were made in the same

Table 1 Timing and location of floating marine debris sightings shown with density and composition of debris items. The debris items were plastic (*plc*), wood (*wd*), shells, seeds, or other animal/plant parts (*org*), marine algae (*kelp*), or other materials, for example, metal and glass (*oth*). *Numbers in parentheses* refer to numbers of items observed

Date (2002)	Location	Debris items km^{-2}	Item nature
24–26 March	Antarctic Peninsula	0–1	Plc (2), wd (1)
26–28 March	Drake's Passage	0–3	Plc (5), wood (3)
1–2 April	Drake's Passage	0–1	Kelp (3), plc (1)
8–11 April	Signy Is. → South Georgia	0–4	Kelp (23)
20–22 April	South Georgia → Falklands	0–4	Kelp (24)
27–29 April	50–40°S	0–4	Plc (3), kelp (56)
30 April–1 May	40–30°S	0–5	Plc (1), wd (1), org (13)
2–4 May	30–20°S	2–5	Plc (12), kelp (1), oth (1)
5–6 May	20–10°S	0–10	Plc (12), kelp (1), oth (1)
7–8 May	10–0°S	0	
2 April	7°S	1–5	Plc (3), wood (2)
9–10 May	0–10°N	0–1	Plc (1)
11–13 May	10–20°N	0–3	Plc (3)
14–15 May	20–30°N	2–10	Plc (11), oth (1)
16–18 May	30–40°N	3–9	Plc (7), wd (1), kelp (1), oth (1)
19–20 May	40–50°N	3–20	Plc (16), wd (5), oth (3)
21–23 May	English Channel	10–100+	Plc (66%), wd (10%), oth (24%)
24 June	Aberdeen–Shetland Is.	1–5	Plc (5), wd (2)
21–31 July	West Spitsbergen	0–3	Kelp (6), plc (5), wd (2)

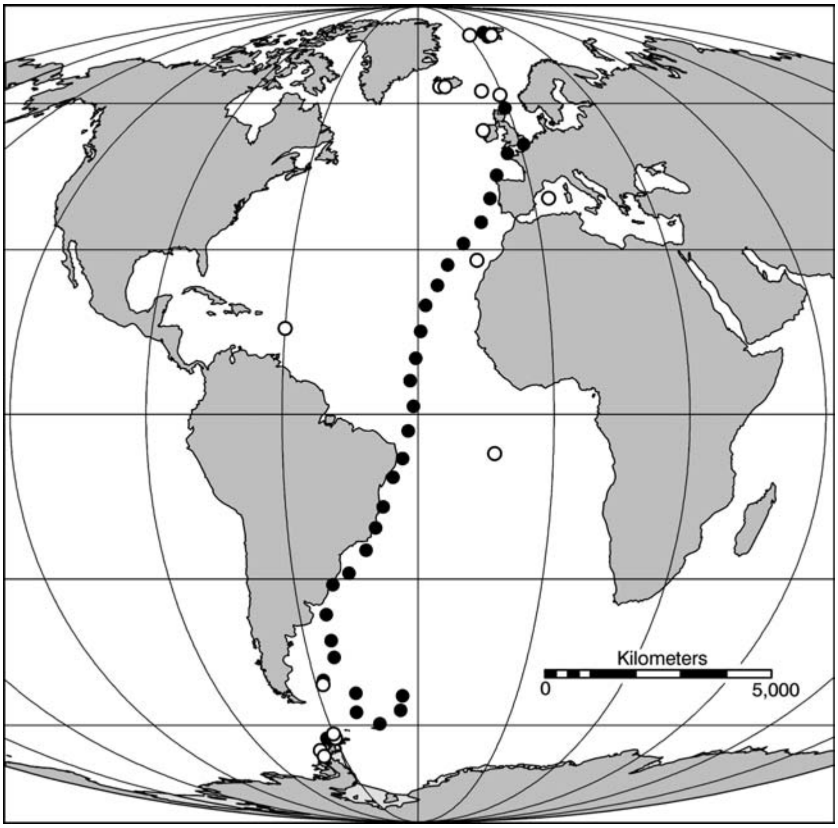

Fig. 1 Projection of the Atlantic and the Atlantic sectors of the Arctic and Southern Ocean showing the location of sampling points. *Filled circles* Floating debris observation points; *open circles* stranded marine debris sampled on island shorelines

ocean areas by the same observer onboard R.R.S. 'Ernest Shackleton' (latitude range 60°–45°S). Furthermore daily observations were made across nearly the entire latitudinal range of the Atlantic from 26 March to 22 May 2002 (Table 1). The 2002 sightings were carried out along a transect from west of the Antarctic Peninsula at 68°S to the east coast of the United Kingdom at 50.5°N (Fig. 1). All 'mega-litter' (> 10 cm in diameter) floating items at sea were categorised as being plastic, wood (lumber), other anthropogenic, or natural (driftwood, seaweed, pumice, etc.). Further sightings were made on voyages to the Shetland Islands at 58–62°N (from Aberdeen in the UK in June 2002) and 77–79°N traversing west Spitsbergen (in the Svalbard Archipelago, July 2002), both using similar methods. The locations of sea sighting points are shown on Fig. 1.

Table 2 Timing and location of shore-stranded marine debris sampling sites shown with density and colonisation of debris items. *A* Annelida, *B* Bryozoa, *Cn* Cnidaria, *Cr* Crustacea, and *M* Mollusca. Colonising fauna are shown in rank order (most abundant to least abundant, left to right)

Date	Location (Island)	Latitude	Debris items m^{-1}	Percentage items colonised	Colonising fauna
March 2001/2002	Scolt Head (U.K.)	53°N	0.63/0.68	7%	A, B
March 2001	La Gomera (Canary Is.)	28°N	1.91	22%	B, A, M, Cn
July 2001/2002	Spitsbergen (Arctic)	77–79°N	0.04/0.2[a]	5.5%	B, Cr
August 2001	Clare (Ireland)	54°N	0.28	3.8%	A, B,
September 2001	Menorca (Balearic Is.)	40°N	8.8	18.8%	B, A, M
December 2001	Dominica (Carribean)	15.5°N	1.5	15%	B, A, Cn
March 2002	Trump (Antarctica)	66°S	0	–	–
March 2002	Adelaide (Antarctica)	67.5°S	0.003	0	–
March 2002	Wienke (Antarctica)	63°S	0	–	–
March 2002	King George (Antarctica)	62°S	0.18[a]	0%	–
March 2002	Falkland (South Atlantic)	51°S	0.43	4.4%	A, B, Cn
April 2002	Ascension (Mid Atlantic)	07°S	3.40	36%	M, Cr, A, Cn
June 2002	Shetland (UK)	62°N	0.29	6.9%	B, A, Cr, M
July 2002	SW Iceland	64°N	0.23	4.3%	Cr, A, B
August 2002	Westmann (SE Iceland)	64°N	0.17	2.9%	A, Cr, B
August 2002	Streymoy (Faeroe Is.)	63°N	0.21	3%	B, A, Cr

[a] Both Spitsbergen and King George Island had large amounts of kelp stranded on shores that are not included in this value (inclusive values exceed 5 items/m)

Sampling debris stranded on shores

Debris stranded on windward shores of 16 islands were examined from March 2001 to August 2002. In the northern hemisphere these locations ranged from Arctic Spitsbergen (Kongsfjord and Horsund Fjord) to Dominica in the Caribbean. A similar range of latitudes was encompassed in the southern hemisphere shores studied: Ascension to Trump Island off the Antarctic Peninsula (Table 2). The locations of shore sample points are shown on Fig. 1. The numbers of items per 200-m section of beach were counted in a swath 4 m wide. Two hundred items were then randomly selected, and each of these was assigned to the same categories as floating debris and examined for encrusting fauna. The proportion of these 200 items colonised by fauna was recorded, and on each item the number of colonists per square meter was noted. Each unitary and colonial animal was counted as one recruit. In many instances identification of fauna was not possible as taxa dried or rotted on debris on tropical shores, only burrows were testimony to either isopod or mollusc presence, or volunteers collected data to phylum or order level only (Dominica).

Comparisons of data

Original data collected from our vessel-based sightings was compared with other major surveys of oceanic flotsam with other vessel-based sighting methods from the literature. This included a comparison of our Southern Ocean data (Atlantic sector) with that from the Pacific sector of the same ocean (at similar latitudes) reported by Gregory et al. (1984). We also

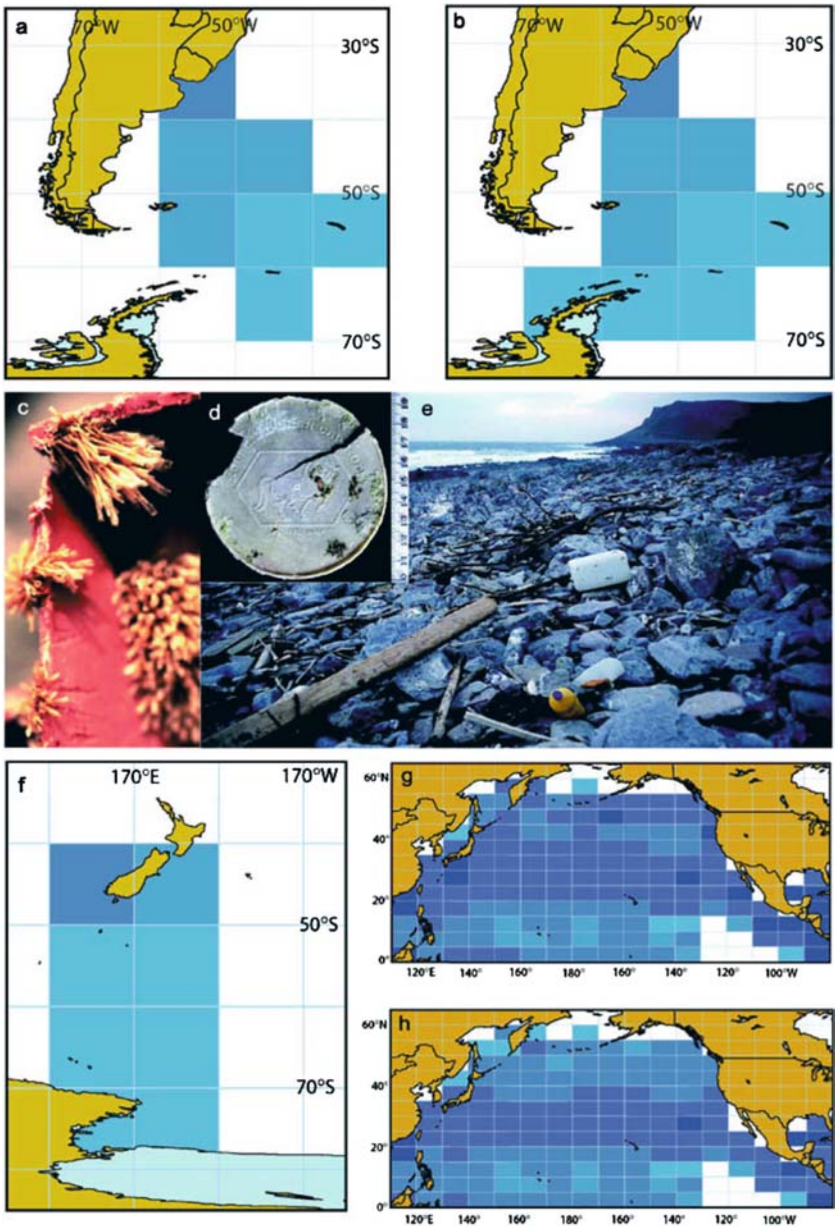

Fig. 2 Maps *a*, *b*, *f*, *g*, and *h* show densities of marine debris by 10° latitude and longitude areas. *Shades of light to dark blue* code for densities 0–1, 2–10, 11–100, 101–1,000, and 1,001+ items/km^2, respectively. Images are (*a*) April 1993 densities of South Atlantic and Southern Ocean debris; (*b*) April 2002 densities of South Atlantic and Southern Ocean debris; (*c*) and (*d*) hydroids and bryozoans colonising plastic (scale of *c* is 4×2.2 cm); (*e*) typical annual accumulation of debris on a UK shore (shore is 15 m wide);(*f*) 1981–1983 densities of South Pacific and Southern Ocean debris plotted using data from Gregory et al. (1984); densities of North Pacific and Caribbean Atlantic debris (*g*) and plastics (*h*) plotted using data from Matsumura and Nasu (1997)

contrasted the North Atlantic floating debris densities we found with equivalent values for the North Pacific in Matsumura and Nasu (1997). We similarly placed our findings of shore debris density and faunal colonisation levels in the context of wider Atlantic data (Ryan 1987; Ryan and Moloney 1993; Lucas 1995; Coe et al. 1997; Ribic et al. 1997, Winston et al. 1997) and Atlantic sector Antarctic literature (Torres and Jorquera 1996; Walker et al. 1997; Convey et al. 2002).

Results

Floating debris

The results of our survey transect of marine debris, across the entire latitude of the Atlantic Ocean, found debris (and plastics in particular) floating within every 10° latitude belt from 68°S to 79°N. Densities of debris ranged from 0 to 10 items/km^2 (excluding kelp) in the southern hemisphere but even Southern Ocean values reached 3 items/km^2 in places (Table 1). In the northern hemisphere debris densities ranged over three orders of magnitude peaking around the United Kingdom and north-west Europe. The values we give do not include kelp for clarity of pattern interpretation. At high latitudes (both north and south) floating debris largely consisted of kelp rafts but algae was rare within subtropical and tropical waters. The three most common types, plastics, kelp, and wood (driftwood and lumber), accounted for a mean of 91.3% of items (SE ±4.84).

Anthropogenic artefacts dominated oceanic flotsam at most latitudes including the most southerly surveys along the Antarctic Peninsula. Plastic was the most ubiquitous type of item and was the single most abundant item in most surveys.

The levels of all floating debris in the south-west Atlantic and Scotia Arc region of the Southern Ocean were essentially similar to those surveyed a decade ago in the same regions (Fig. 2a, b). The levels of floating debris were higher around the Falkland Islands and

Table 3 Debris on Atlantic, Mediterranean, and Southern Ocean shores from the literature

Region	Latitude	Island or shore	Debris m^{-1}		Percentage plastic	Year	Survey length
			Min	Max			
Northern Atlantic	57°N	Rhum	0.15	–	48%	1996[a]	200 m
	55	Inch	0.89	–	68%	1993[c]	200 m
	53	Scolt Head	0.49	0.68	59%	1994–2000[b]	200 m
	51.5	Sherkin	0.94	1.4	63%	1999[a]	891 m
	45	Sable	2.63	–	92%	1984–1986[h]	–
	42	Cape Cod	4.50	–	–	1992[i]	5,000 m
	38	Sao Miguel	0.76	–	35%	1996[b]	200 m
	38	Assateague	1.30	–	–	1992[i]	200 m
	30	Gulf	2.20	–	–	1989–1992[i]	5,000 m
	28	Tenerife	2.24	2.9	53%	2001[a]	300 m
	27	Padre	70.9	–	–	1989–1992[i]	5,000 m
	24	San Salvador	2.0	–	42%	2000[n]	200 m
	18.5	UK Virgin	0.7	–	–	1991–1992[e]	100 m
	18	Puerto Rico	3.5	4.8	–	1990[e]	–
	15.5	Dominica	1.5	3.9	24%	1991[e]	100 m
	15	Sal	1.60	2.44	35%	1996[b]	200 m
	15	Sao Antao	1.36	12.5	40%	1996[a]	200 m
	14	St. Lucia	0.20	3.5	59%	1991–1992[e]	100 m
	9.5	San Blas	2.75	–	37%	1998[a]	200 m
Mediterranean	44°N	Jabuka (Croatia)	6.4	–	55%	2000[a]	100 m
	38	Sicily	9.0	231	45%	1988[g]	500 m
	37	Spain	33.2	–	63%	1991[g]	–
	36	Cyprus	10.4	–	64%	1988[g]	–
	33	Israel	7.3	8.7	65%	1988–1989[g]	–
Southern Atlantic	37.2°S	Tristan da Cunha	0.319	0.813	58%	1984[j]	900 m
	37.2	Inaccessible	0.559	2.3	72%	1984[j]–1990[c]	900 m
	41.2	Gough	0.019	–	84%	1984[j]	7,630 m
Southern Ocean	54°S	Bird	0.017	2.49	74%	1990–2001[m]	291 m
	54	South Georgia	0.36	–	80%	1993[b]	200 m
	57	Candlemas	0.008	0.026	85%	1997[f]	1,000 m
	57.4	Saunders	0.285	–	30%	1997[f]	200 m
	54	Bouvet	0.077	–	40%	1997[d]	24,300 m
	60.5	Signy	0.012	0.224	82%	1990–2001[b,f]	200 m
	62	Livingstone	0.019	0.304	86%	1984–1998[k,l]	13,986 m
	63	Ardley	0.006	–	40%	1996[d]	12,500 m

Data sources: [a]Barnes 2002, [b]Barnes and Sanderson 2000, [c]Benton 1995, [d]CCAMLR 1997, [e]Coe et al. 1997, [f]Convey et al. 2002, [g]Golik 1997, [h]Lucas 1995, [i]Ribic et al. 1997, [j]Ryan 1987; Ryan and Moloney 1993, [k]Torres and Jorquera 1996, [l]Torres and Jorquera 1999, [m]Walker et al. 1997, [n]Unpublished data north of the Polar Frontal Zone than in the Southern Ocean but were generally low except close to the South American mainland.

Shoreline stranded debris

Only two (Trump and Wienke) of the 16 islands surveyed had no stranded debris on their shores (Table 2). Both of these were uninhabited islands on the west of the Antarctic Peninsula. The abundance of flotsam stranding on island shores showed some similarities but also striking differences compared with geographic patterns of floating material. With the exception of kelp on the King George Island coast, stranding of floating debris was rare on Southern Ocean shores (Table 2), especially south of 62°S, but an item of smooth and worn lumber was found at 68°S (Adelaide Island), the furthest south marine debris has been reported to travel. Plastics were common on Spitsbergen shores, which at 79°N represents the furthest north that artefacts have been recorded stranded. Moreover, at 0.2 items per meter of shore the 2002 value from Spitsbergen was of similar magnitude to abundances on other North Atlantic Islands (Shetland, Iceland, and Faeroes) despite the considerable differences in geography or climate. The highest abundances of materials stranded on shores were in the subtropics and tropics (or Mediterranean). Menorca (Mediterranean Sea), the mid-Atlantic island of Ascension, La Gomera (Canary Islands), and Dominica (Caribbean) all had more than one item per meter of shoreline. Similar to patterns in floating debris, most of the material was anthropogenic and in particular plastic (60.2% of items, SE ±6.33). In contrast to open-ocean patterns, however, stranding values were not high around the United Kingdom area compared to surveys in other geographic regions.

The Scolt-Head Island and Spitsbergen surveys, which were carried out in 2001 and 2002 (Table 2), both recorded higher values in the later survey. Combining the data presented here, the Atlantic data from Barnes (2002), and other literature (Table 3) we calculated Mediterranean Sea values to be significantly higher for their latitude (ANCOVA, $F_1 = 4.45$, $P = 0.047$). The difference was even more significant when only remote (non-urban) sites were compared (ANCOVA, $F_1 = 10.3$, $P = 0.004$). It is clear there is a comparative wealth of published data in the northern Atlantic relative to the south. Although information on stranding accumulation of marine debris has a wide geographic base (Table 3), patterns in time are more difficult to interpret.

Macro-biota colonising debris

None of the Southern Ocean marine debris carried colonists but 3–7% of the northern polar debris was colonised at all the study island shores even as far north as 79°N Kongsfjord, Spitsbergen. The presence of many individuals of the balanomorph barnacle *Semibalanus balanoides* and a large living colony of the bryozoan *Membranipora membranacea* at 79°N is, to the authors' knowledge, by far the most extreme latitude organism hitchhikers have been found to reach. *S. balanoides* was present on marine debris throughout the sub-Arctic and Arctic study sites, but the exotic invasive barnacle species *Elminius modestus* was also found on plastic in the Shetland Islands. One of the most common colonists of debris, pedunculate (Lepadomorph) barnacles, was found as far north as the Shetland Islands (*Lepas anatifera*) and as far south as the Falkland Islands (*Lepas australis*). Other plastic colonists included various hydroids and bryozoans (Fig. 2c, d) as well as polychaetes. Colonists of wood, which like plastic was highly abundant and occasionally dominated shore debris (Fig. 2e), were usually burrowers such as boring molluscs and isopods. Kelp, though highly abundant at a few sites, carried significantly fewer encrusting colonists [general linear model (GLM) ANOVA, $F_1 = 32.7$, $P < 0.01$, with latitude as covariate, but kelp of course may transport many motile species not studied here].

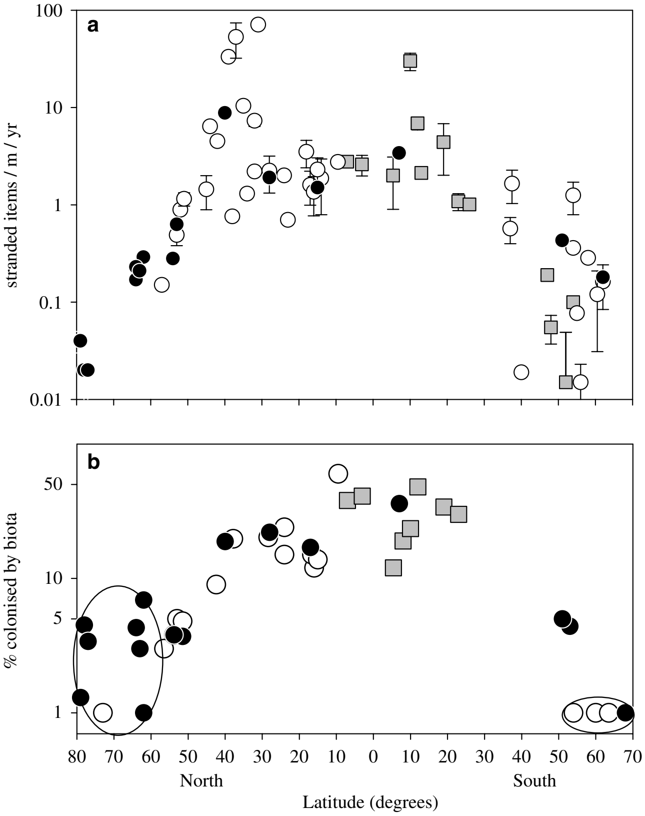

Fig. 3 Densities (**a**) and colonisation levels (**b**) of stranded items. For both plots the symbols are *open circles* for Atlantic Ocean data from the literature, *filled circles* for this study, and *grey squares* for Indian Ocean data from Barnes (2004). The time scale shown (per year) is due to mostly yearly sampling programmes or sampling on smaller time frames and scaling up. Data are shown as means with SE. Colonisation data (**b**) from northern and southern polar regions are *circled* to emphasise differences

The highest values of colonisation were found at the same sites with the highest abundances of debris. The proportions of debris with colonists ranged from 2.9% in the Westmann Islands (64°N) to 36% at Ascension Island (7°S, Table 2). These values are comparable with similarly collected Atlantic and Indian Ocean data (Barnes 2002; 2004) and fit suggested relationships with latitude for other Atlantic data (Fig. 3). The Arctic colonisation values reported by Barnes (2002) from the north-west Atlantic (Baffin and Bylot Islands) were outside (lower) the 95% confidence interval of (polar) north-east Atlantic data from the present study (means 0.0 and 4.52, respectively). This previous study found no hemispheric differences in colonisation rates. We pooled the data of both studies and then separated the data by hemisphere. In contrast to the findings of Barnes (2002), northern debris was significantly more heavily colonised [GLM ANOVA of $\log(y+1)$, $F_1 = 12.32$, $P = 0.001$] than that in the south (see circled data in Fig. 3).

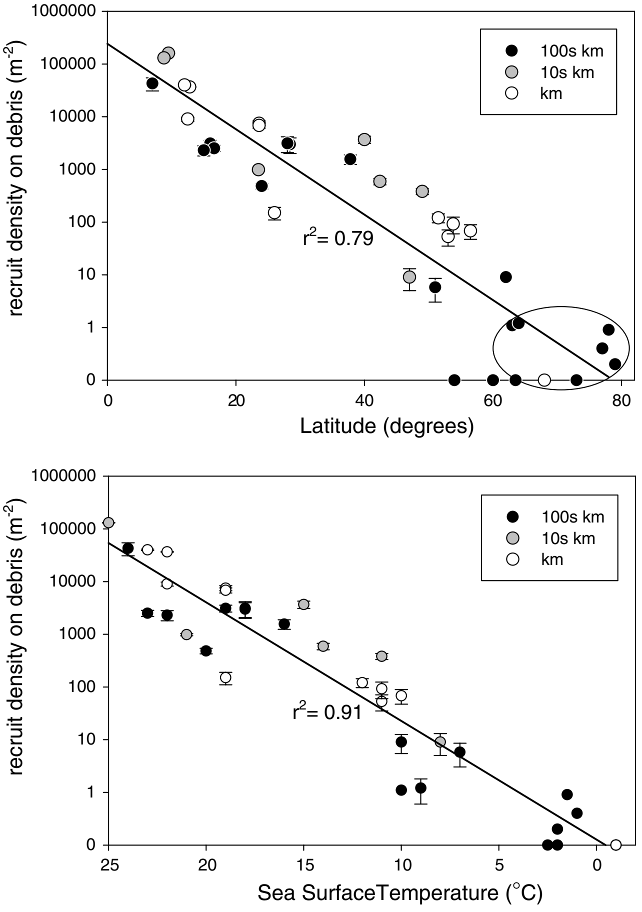

Fig. 4 Density of recruits on marine debris from island shores in Atlantic and Atlantic sectors of polar oceans. Data are shown as means with SE ($n = 200$ for each point). Levels of island isolation shown on plot as hundreds of kilometers from continents (*black circles*) to tens of kilometers from continents (*grey circles*) to just a few kilometers from continents (*open circles*). Regression lines fitted have associated ANOVA, $F = 98$, $P < 0.01$ (latitude); $F = 98$, $P < 0.01$ (sea surface temperature)

The mean density of recruits on marine debris items varied over six orders of magnitude between the sample localities. A principal source of variability, as with proportion of items colonised, was probably sea surface temperature and, as a covariate, latitude (Fig. 4). The log-linear relationship showed typical mean densities on polar debris to be around 1 recruit/m^2, increasing to thousands or hundreds of thousands/m^2 at equatorial latitudes. Differences with shore isolation or hemisphere were not apparent.

Discussion

The opportunities for organism dispersal at the air–sea interface have always been changing. Humans have been accelerating this process: for thousands of years ships have probably transported organisms, but when Thor Heyerdahl (1970) rafted across the Atlantic the most common debris his expedition encountered was plastic pieces. Many coastal countries now have marine debris surveys at either volunteer or commercial levels and at local, regional, or national scales (e.g. see Ribic et al. 1997; Derraik 2002). At relatively few localities (Inaccessible Island, Tristan da Cunha group; Bird Island, South Georgia group; Marion and Prince Edward islands, Prince Edward group, Signy Island, South Orkney group; and Livingstone Island, South Shetland group) surveys have been carried out for a decade or more. Those coastal litter surveys and cleanup campaigns are now widespread even on remote archipelagos to indicate the seriousness of the problem in terms of ecology and economics. Wide-scale reviews of Atlantic marine debris have been undertaken (Derraik 2002) and many countries and islands with Atlantic coasts now have yearly coast collections by volunteers. Synthesising the majority of data collected by volunteer groups to interpret patterns at a whole-ocean scale is problematical. There are differences in methodologies between sites and observers, information is often difficult to access, and surveys are scarce that actually record organisms that were associated with marine debris. To date, few studies have combined open-ocean and shoreline surveys (Gregory et al. 1984), and never to the authors' knowledge have any also included quantitative associated organism data.

In the transect we report here (which was almost the entire length of the Atlantic) conducted both at sea and on island shores, we have shown that mega-anthropogenic debris is particularly numerous in the North Atlantic around Europe and that plastic does typically dominate debris at most latitudes, both as hypothesised. We found similarities in patterns of debris at sea and washing ashore, but an obvious major difference was the lowest level of floating debris we found was at 0–10°S in contrast to the high values we found accumulating at Ascension Island (7°S).

Are there consistent spatial trends to marine debris?

The densities of marine mega-debris we found in the South Atlantic and Southern Ocean (Atlantic sector) were similar to those found in the Pacific sector of the Southern Ocean by Gregory et al. (1984; Fig. 2a, b, f). Furthermore the pattern of increasing densities across the Polar Frontal Zone (from the Southern Ocean into southern parts of the Atlantic and Pacific oceans) was similar. That we found (non-historic) marine debris further south (on both island shores and at sea) probably reflects the more recent timing of the surveys relative to that by Gregory et al. (1984). Ryan and Moloney (1993), Ryan and Swanepoel (1996), Torres and Jorquera (1996, 1999), and Barnes (2004) have all documented increases in debris accumulation rates on (mid-high latitude) southern hemisphere coasts. The South Atlantic and Southern Ocean values are low in comparison with those reported from the North Pacific Ocean (Fig. 2g, h; Matsumura and Nasu 1997). Except around the United Kingdom, even the North Atlantic floating debris densities we found were low compared with equivalent values for the North Pacific and Caribbean Atlantic (Matsumura and Nasu 1997). Matsumura and Nasu (1997) found the highest densities of floating debris to be adjacent to low-latitude continental coast and along equatorial currents. The highest values we found in the Atlantic were adjacent to high-latitude continental coast but our samples included little equatorial coast. The composition of debris (mainly plastics with patchy flotillas of kelp) appears to be similar in the Atlantic and North Pacific.

The moderate debris densities we found in the east Atlantic at high latitudes contrasted with low values in the west (though our west samples were only $n=3$). Arctic values were slightly higher than Antarctic but the overwhelming trend was a tropics-to-poles decrease peaking at about 3 items/km^2 in equatorial waters and coasts (Tables 2, 3). Densities as high as hundreds of items per meter may occur on Indonesian island beaches (Uneputty and Evans 1997) and wash up daily on the Philippines' shores (L. Conway, personal communication). Similarly high values are reported from the tropical west Pacific and east Atlantic (Table 3, Coe et al. 1997; Matsumura and Nasu 1997). Semi-enclosed seas surrounded by developed areas are likely to have particularly high (relative to oceanic) anthropogenic debris levels and certainly this seems to be the case in the Mediterranean Sea (Table 3; Golik 1997). There does not, however, seem to be any obvious effect of isolation, as remote oceanic islands may have similar levels of debris to those adjacent to heavily industrialised coasts in both the Pacific (Benton 1995) and elsewhere (Table 3, Fig. 3; Barnes 2002).

Strong oceanic fronts, such as the Polar Frontal Zone (PFZ), might intuitively be considered as a natural center for aggregation of drift debris. We found no evidence of this despite crossing the PFZ on four occasions during our sampling/sighting. Spatial and temporal patterns of marine debris are important for establishment of baselines, trends, and anomalies and to interpret possible sources. To understand the extent of the problem, as well as to combat it and measure effectiveness at doing so, temporal patterns as well as education are crucial.

Are there consistent temporal trends in marine debris evident?

In the early 1980s about 8 million items were estimated to go from ship to sea each day (Horseman 1982). Surveys around U.K. waters at this time showed much material floating in north-west European seas (Dixon and Dixon 1981), but stranding debris peaked (at ~1.9 items/m coast) in 1998/1999 in the United Kingdom and is similar to levels of a decade ago (~1.6 items/m coast, see Table 7 of Conway and Fanshawe 2003). In the southern Atlantic, beach-cleaning effort and costs increased by an order of magnitude in five decades (Ryan and Swanepoel 1996). Rubbish-strewn shores of even the most remote Atlantic islands (Ryan and Watkins 1988), Pacific atolls (Benton 1991), and sub-Antarctic shores (Gregory et al. 1984; Ryan 1987) have been reported. The densities of marine debris washing up on the few remote shores monitored have demonstrably increased whilst scientific attention (measured as number of studies) seems to be waning (Ryan and Moloney 1993). By 1995 2.5–3.5 kg of rubbish/person per day was estimated to be entering the sea from ships alone (NRC 1995). This approximates to 0.6 million tons of litter annually, but the growth of rubbish on land and sea has been only part of the issue; composition change has been perhaps more important.

The proportion of plastics in annual municipal waste in the United States increased from $<1\%$ in 1960 to $>10\%$ in the 1990s (Franklin Associates 1994). New laws prohibiting dumping at sea (e.g. MARPOL V) and on land encouraging recycling may slow the increase of material entering the oceans but evaluating this may prove difficult, as the number of sites surveyed is so small and from such a restricted geographic area. The best-studied and more remote Atlantic shores (which are most likely to give meaningful estimates of oceanic debris) suggest unabated increase (Ryan and Moloney 1993) though there is considerable variability; there were probably a number of time scales used, though annual frequencies are most studied (Merrell 1980, Eriksson and Burton 2001). The two high-northern-latitude localities resurveyed in this study also showed increased shore stranding debris densities (Table 2). In contrast, patterns on the shores of Amchitka Island, Alaska over a similar period have shown no increase (Merrell 1980), and neither have mega-debris patterns at sea in the southern Atlantic and the Southern Ocean (Fig. 2a, b). Data reported here establish baseline points for a wide variety of remote shores throughout the Atlantic. Our resurvey of the South Atlantic does not suggest any significant changes in abundances of oceanic mega-debris. Intended future resurveys of both the ocean transect and the wide geographic range of remote shores will enable a more comprehensive and reliable view of the state of the Atlantic surface, effectiveness of marine pollution laws, and effects on marine organism transport.

What influences is marine debris having on organisms?

As hypothesised, colonisation of debris was most intense at low latitude, but contrary to expectations even high (79°N) northern polar debris had attached animals. Most of the shores surveyed as part of this study were remote, so marine debris has probably travelled for great periods and distances before stranding. Ryan and Moloney (1993) reported, for example, that most of the identifiable items on Tristan da Cunha (S. Atlantic) shores had possibly travelled 3,000 km before stranding. With such long periods and travels, and being so numerous, marine debris has the potential for considerable influence on dispersal of biota.

The initial established effects of marine debris on organisms were poisoning, entangling, and choking of mega-fauna on beaches or at sea (Croxall et al. 1990; Bjorndal et al. 1994; Walker et al. 1997; Gregory 1999). This has additional economic consequences through 'ghost fishing' (drifting nets, bags, and line trapping and killing fish). Rafting has also come to the fore (Jokiel 1990) as plastics provide a colonisable and transportable surface for certain biota (Winston 1982, Winston et al. 1997; Barnes and Sanderson 2000; Barnes 2002).

The effect that surface type (plastic, metal, wood, etc.) has on settlement of larvae has attracted much study over the last few decades (Scheer 1945; Pomerat and Weiss 1946; Crisp and Ryland 1960; McGuiness 1989; Anderson and Underwood 1994). Despite the intensity of study there is no clear consensus in the literature; for example, some have demonstrated preferences for rugose and/or porous surfaces (Pomerat and Weiss 1946; Anderson and Underwood 1994) whilst others have not (Crisp and Ryland 1960). It is clear that settlement preferences are complex, but plastic is now widely used for settlement panels. These and marine debris studies (Winston 1982; Winston et al. 1997; Barnes and Sanderson 2000; Barnes 2002; Aliani et al. 2003) have shown that plastic is quickly and intensively colonised by a wide range of species.

Even with a paucity of study it is clear that rafting biota is diverse: representatives of many kingdoms and phyla have been found (Winston et al. 1997; Censky et al. 1998; Barnes and Sanderson 2000; Masó et al. 2003). Recently ships' ballast water has also had a major impact on movement of probably huge numbers of sea-surface species (Carlton 1987; Carlton and Geller 1993). The impact of marine debris on species distributions is difficult to measure, even more so with respect to comparisons with other sources (such as shipping) or epibiosis on natural motile hosts (Key et al. 1995, 1996). This study of marine debris and that of the combined literature (Tables 1, 3) have shown anthropogenic synthetic material constitutes a high proportion of oceanic and stranded material. Not only is anthropogenic debris ubiquitous and abundant, but also a high proportion of all debris afloat or stranding may be colonised, especially at low latitudes (Barnes 2002). As well as being highly colonisable, plastics may take decades or even centuries to degrade (Gregory 1999). Plastic durability effectively opens new pathways for drift debris as the potential time spent at sea is years, relative to organic material such as kelp, which may degrade and sink (on an approximate time frame of months) at sea (Schoener and Rowe 1970). The gradual pace of flotsam travel may also increase viability of colonists relative to ships by reduction of thermohaline shock travelling between major water masses (Barnes 2002). Whether coastal biota attached to rafts remain viable on such considerable journeys or not, due to starvation in the open ocean, remains to be investigated. Comparison between vectors of marine organism travel is difficult to make with so many factors, but we suspect marine debris to be drastically increasing opportunities for dispersal.

Despite few marine debris surveys actually recording the presence of associated biota, drift plastics are known to have introduced exotic marine species to the Atlantic (e.g. *Thalamoporella evelinae*) and other oceans (Winston et al. 1997; Derraik 2002). The presence of the invasive and exotic barnacle *Elminius modestus* on drift plastic in the Shetland Islands (though its presence on Shetland rocky intertidal coasts was already being monitored Moore et al. 1995) is a demonstration of the potential for colonisation and movement of fauna to new environments on flotsam. There is insufficient data for evaluation of potential impact of marine debris on animal introductions. It seems clear, however, that plastic ranks high in comparison with other potential vectors of exotic organism and merits immediate consideration. One particular and novel area in which floating marine debris may have a major effect is on the distribution, movement, and reproduction of oceanic neustic communities (J.T. Carlton, personal communication).

Substantial information about the levels of macroplastic drifting in Atlantic surface waters and its coastlines, as well as that of other oceans, is being gained, but the problem still needs to be tackled at its source. To date, major effort and expenditure have been made clearing up Atlantic shorelines (see, for example, Ryan and Swanepoel 1996), but as well as being an increasingly short-term and expensive action, it has no direct effect on the problem. Terrestrial introductions of species have been one of the great problems causing loss of biodiversity but at least an increasing number of mammals are being successfully removed from some smaller islands. Even recognising marine introductions is not always easy, and removing exotic marine invertebrates once established is improbable. Floating marine debris may be changing the ocean surfaces and coastlines globally, but at least we can quantify the extent of the problem and ultimately tackle some of the causes. A more difficult issue altogether, unseen marine debris is also sinking to the ocean floor (Gregory 1999; Hess et al. 1999).

Conclusion

Our study establishes that amounts of marine debris stranding on remote oceanic shores differ little across much of the span of the Atlantic (50°N to 40°S) and Indian Oceans. However, our sampling regime poorly sampled the tropics and the west Atlantic, and this is likely to have influenced our results significantly. Future data from these areas are needed for a more inclusive picture. That we examined the most northerly and southerly latitudes to date is important as the levels of debris stranding in both polar regions is at least an order of magnitude lower. The colonisation of marine debris, however, differed considerably between the Arctic and the Antarctic. We tentatively suggest that the difference in water temperatures (Southern Ocean sea surface temperatures are cooler in summer) could explain such a difference. Both the values of stranding and colonisation levels of marine debris provide a baseline to enable future quantification of changing patterns in either. We show that even in the Arctic, marine debris can carry colonists including exotic barnacles (*Elminius modestus*).

Our study is the first attempt to investigate marine debris at sea and stranding over the same region and we did not find a match in our results (i.e. our observations at sea showed high European levels whilst stranding levels were high in the tropics). Further, in contrast to some recent literature, we found no change in floating debris densities in the South Atlantic Ocean 10 years after our first survey. As introduced species are perceived as one of the most serious threats to biodiversity and marine introductions are so difficult to counter, we suggest that marine debris should be considered as a serious potential vector.

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