
Accumulation and fragmentation of plastic debris in global environments

David K. A. Barnes^{1,*}, François Galgani², Richard C. Thompson³ and Morton Barlaz⁴

¹ British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 0ET, UK

² IFREMER, Laboratoire Environnement Ressources, Provence Azur Corse (LER/PAC), Ifremer Centre de Méditerranée, ZP de Bregailon, BP no. 330, 83507 La Seyne sur Mer, France

³ Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK

⁴ Department of Civil, Construction and Environmental Engineering, North Carolina State University, PO Box 7908, Raleigh, NC 27695-7908, USA

*: Corresponding author : David K. A. Barnes, email address : dkab@bas.ac.uk

Abstract:

One of the most ubiquitous and long-lasting recent changes to the surface of our planet is the accumulation and fragmentation of plastics. Within just a few decades since mass production of plastic products commenced in the 1950s, plastic debris has accumulated in terrestrial environments, in the open ocean, on shorelines of even the most remote islands and in the deep sea. Annual clean-up operations, costing millions of pounds sterling, are now organized in many countries and on every continent. Here we document global plastics production and the accumulation of plastic waste. While plastics typically constitute approximately 10 per cent of discarded waste, they represent a much greater proportion of the debris accumulating on shorelines.

Mega- and macro-plastics have accumulated in the highest densities in the Northern Hemisphere, adjacent to urban centres, in enclosed seas and at water convergences (fronts). We report lower densities on remote island shores, on the continental shelf seabed and the lowest densities (but still a documented presence) in the deep sea and Southern Ocean. The longevity of plastic is estimated to be hundreds to thousands of years, but is likely to be far longer in deep sea and non-surface polar environments. Plastic debris poses considerable threat by choking and starving wildlife, distributing non-native and potentially harmful organisms, absorbing toxic chemicals and degrading to micro-plastics that may subsequently be ingested. Well-established annual surveys on coasts and at sea have shown that trends in mega- and macro-plastic accumulation rates are no longer uniformly increasing: rather stable, increasing and decreasing trends have all been reported. The average size of plastic particles in the environment seems to be decreasing, and the abundance and global distribution of micro-plastic fragments have increased over the last few decades. However, the environmental consequences of such microscopic debris are still poorly understood.

Keywords: persistent organic pollutants, marine debris, plastic production, landfill, microplastic

1. INTRODUCTION

In the last half century there have been many drastic changes on the surface of the planet, but one of the most instantly observable is the ubiquity and abundance of plastic debris. Like many anthropogenic impacts on natural systems, it is one that, despite widespread recognition of the problem, is still growing and even if stopped immediately will persist for centuries. From what started as a perceived aesthetic problem of plastics littering towns, countryside, shores and even far out into the ocean soon emerged as causing the choking and entanglement of wildlife. The number of potentially harmful implications of plastic debris that have been identified has escalated and it is now realised that these items may also transport persistent organic pollutants (POPs – Mato *et al.* 2001), non-indigenous species to new locations (Barnes 2002) and distribute algae associated with red tides (Maso *et al.* 2003). Reports of accumulation of plastics spread rapidly in terms of the taxa influenced, geography and bathymetry of affected sites, and countries beginning monitoring and beach clean-up operations. Schools and voluntary organisations have made annual coastal collections of stranded plastics an important educational issue even on many of the planet's most remote islands. In some areas though, notably on the sea-bed, assessment of plastic accumulation has been relatively neglected (Goldberg 1994). Since 1990, the dumping of rubbish at sea from ships has been prohibited under the international shipping regulation MARPOL annex V. A reduction of ship derived plastic debris should therefore be expected, even if global use of plastics continues to increase. To gain an accurate and meaningful assessment of plastics and their influence, large scale and long-term monitoring is needed across debris sizes (here termed mega [>1 cm diameter], macro [1-10 mm] and micro [>1 mm]), countries and environments, including the sea floor (see Ryan *et al.* this volume).

Natural marine debris of some type (e.g. pumice) has floated on the surface of the global ocean for longer than life itself, but life greatly increased this through floating algae, shells, seeds, fruits and wood. Human activities and travel by water must have further greatly increased flotsam (e.g. by timber) but by far the biggest change in the potential for transport by debris came with the mass production of plastics. The accumulation of both macro- and microplastics, has consistently increased on shores and in sediments for the last four decades (see Barnes 2005 and Thompson *et al.* 2004, respectively). Their inexpensive, lightweight and durable properties have made plastic much more single use and 'throw-away' than previous synthetic artefacts. Such compounds do deteriorate in Ultra Violet (UV) light but haline environments and the cooling effect of the sea mean degradation requires very long exposure times (Gregory 1999). Because plastics become fouled by marine organisms relatively quickly, the debris may also become shielded to some extent from UV and the persistence of this debris

1 was recently illustrated by accounts that plastic swallowed by an albatross had originated from a
2 plane shot down 60 years previously some 9600 km away (Weiss *et al.* 2006).

3
4
5 Mega-debris at sea was highlighted by tens of thousands of each of basketball shoes,
6 hockey gloves and bath-toys released from containers washed off of ships (Weiss *et al.* 2006).
7 There are many sources for plastics accumulating in the environment from direct dropping and
8 dumping of litter on land or at sea to blowing from landfill sites, losses in transport and
9 accidents. Typically 40-80% of mega- and macro-marine debris items are plastic, much of it
10 packaging, carrier bags, footwear, cigarette lighters and other domestic items (Derraik 2002;
11 Barnes 2005). A recent study by Ivar do Sul & Costa (2007) across Central and South America
12 also found marine debris dominated by land-based plastic (though sometimes fishery gear can
13 be abundant along continental shores as well). At more remote islands, fishing related sources
14 of debris are often more prevalent. Following establishment of 'long term' monitoring surveys
15 of stranded debris in the 1990s, there are now sufficient data to explore seasonal, annual and
16 longer-term patterns (see e.g. Morishige *et al.* 2007).

17
18
19
20
21
22 Most waste plastics, including the large proportion used in single-use applications such
23 as packaging, are disposed of in landfill sites. However plastic persists in landfill sites and if not
24 properly buried may later surface to become 'debris'. Durability of plastic ensures that
25 wherever it is, it does not 'go-away'; that is by placing plastics in landfill we may simply be
26 storing a problem for the future. Although accumulation of plastics on land is important, little
27 information is available on the amounts, rates, fate or impacts whereas there has been a major
28 effort to quantify impacts on shorelines and at sea. In this paper, we examine waste generation
29 and disposal, together with the abundance, composition and fragmentation of plastic. We then
30 consider temporal and spatial trends in accumulation of plastics on strandlines, the sea surface
31 and at depth on the sea-bed. We assess published data and present new surveys and
32 observations of spatial and temporal patterns to evaluate whether persistent marine debris, such
33 as plastics, are still increasing and whether it varies geographically?
34
35
36
37
38
39
40

41 **2. ANTHROPOGENIC WASTE AND PLASTIC ACCUMULATION IN LANDFILL**

42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
Plastics are present in most waste and before trends in accumulation of plastic can be explained
it is important to first consider waste generation and disposal. Global production of plastics is
estimated at 225 m.t.year⁻¹ (APME 2006). Waste composition data are useful to identify the
relative quantity and types of plastic. As discussed in the contribution by Takada *et al.* (this
volume), different plastics and resins have widely varying properties with respect to
contaminant sorption and desorption.

1
2
3
4 **(a) waste generation**
5

6 Waste is typically categorized based on its point of generation. Categories include municipal,
7 commercial, industrial, agricultural, and construction and demolition (C&D). However, there is
8 ambiguity within these categories. For example, in the U.S., municipal solid waste (MSW)
9 includes that generated in residential, commercial and institutional (e.g. schools, government
10 offices) sectors, while in other countries MSW may include anything from residential waste
11 only to all waste managed in the municipal system (e.g. C&D, non-hazardous industrial). This
12 complexity is exacerbated by the fact that some municipal systems manage residual materials
13 from the treatment of water and wastewater. This relatively heavy waste will distort the
14 composition of dry wastes such as plastics.
15
16
17
18

19 Considering these multiple categories, it is difficult to compare waste composition between
20 countries. Waste is typically classified by the agency in need of the information and surveys are
21 typically designed with specific goals. For example, a waste sort conducted to support planning
22 of a recycling programme would identify commonly recycled plastics including pigmented and
23 translucent high density polyethylene (HDPE) containers, clear and pigmented polyethylene
24 terephthalate (PET), and classify the remaining plastics as “other.” These categories are useful
25 in this (recycling) context but are less complete for a study of plastics in the environment.
26 Another confounding issue is that the types of plastics present vary between municipal,
27 agricultural and C&D waste. Municipal waste is dominated by containers (e.g. drink bottles)
28 and films (e.g. carrier bags, packaging sheets), agricultural waste may contain large quantities of
29 a single film, and C&D waste may contain polyvinyl chloride (PVC) pipe and large plastic
30 containers. Thus, a municipal stream that contains 10% (by mass) plastics is not equivalent to a
31 C&D stream containing the same percentage.
32
33
34
35
36
37

38 Waste composition may also be presented on either an “as generated” or “as discarded”
39 basis. The former includes all the waste generated in a particular sector, prior to separation for
40 recycling, composting, or other treatment. In contrast, “as discarded” indicates the waste
41 remaining for disposal after the aforementioned separation. In areas with significant recycling
42 programmes, the difference between waste generation and waste disposal could be 20 to 40%,
43 and waste composition will change as recyclables are removed. If properly managed at the end
44 of its useful life, plastic waste may be recycled, burned in combustion facilities to generate
45 energy, or buried in landfill. In each of these alternatives, the waste should be destroyed or
46 contained, so that plastic is not released to the environment. The major release of plastics to the
47 environment is the result of inappropriate waste management and improper human behaviour
48
49
50
51
52
53
54
55
56
57
58
59
60

1 e.g. littering (deliberately abandoning waste away from collection points). For example, plastic
2 films can be released to the environment when not transported properly, and as a result of wind
3 blown litter at the point of burial in a landfill. Well-operated landfills include a daily cover over
4 the waste consisting of soil or a synthetic material, and fences surrounding the landfill to contain
5 wind blown debris.
6
7
8

9 10 **(b) *Plastics production and recycling***

11 Annual global consumption of the major plastic resins is considerable (see Andrady & Neal, this
12 volume). Films (e.g. carrier bags, plastic sheets) are easiest to escape containment as wind-
13 blown debris and are likely the major component of terrestrial plastic litter but plastic litter also
14 includes discarded fishing equipment, food and beverage packaging, and many other items that
15 are present in the marine environment (Koutsodendris *et al.*, 2008). Films are dominated by
16 LDPE/LLDPE. We present information on plastics in MSW in the U.S. and their management
17 (Table 1). The quantities recovered (i.e. for recycling) as a fraction of total discards shows that
18 recycling rates are relatively low. In the U.S., plastic recycling is largely limited to drink
19 containers though local authorities continue to expand the types of plastics collected for
20 recycling. In general, citizen participation rather than industrial capacity limits the quantities of
21 plastics recycled. Efforts to provide incentives for recycling can increase the fraction recycled
22 (Loughlin & Barlaz 2006).
23
24
25
26
27
28

29 In the US durable goods, products that last on average for more than three years and include
30 items such as furniture and appliances, were the most important use for new plastics (Figure 1).
31 Non-durable goods, products that are consumed in less than three years such as trash bags and
32 eating utensils were the next biggest use category. In Europe, data on various packaging
33 applications are typically combined rather than considered separately and hence disposable
34 packaging represents the principal use of plastics (37%, Plastics Europe, 2008).
35
36
37
38

39 **(c) *The fraction of plastic in household waste***

40 Plastics in the waste from various countries is estimated at about 10% (of mass). Such estimates
41 can only be used as an indication of plastics composition for several reasons. First, the data are
42 not all from the same year. Second, where possible, data are on an “as discarded” basis to
43 reflect the composition of waste after diversion for recycling. However, it is not always clear
44 whether the data were reported “as generated” or “as discarded.” Third, the waste components
45 included in national surveys vary within and between countries. For example, the U.S. data are
46 for wastes defined as MSW. Finally, country-specific data compiled for Europe (Eurostat 2007)
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1 are self-reported at the national level and are unlikely to have been generated using a consistent
2 methodology. In the U.S., plastics are estimated to comprise 11.8 and 16.3% of MSW as
3 generated and as discarded mass, respectively. The composition of discarded plastics is given in
4 Table 1 (U.S. EPA 2006). In Europe, plastics are estimated to comprise 7% of waste mass as
5 generated. Similarly, plastics were estimated to represent 5.8, 7.3, 8 to 10, and 10% of waste
6 mass in Singapore, Australia, the UK, and Finland, respectively (Barlaz 2006; Burnley 2007;
7 Sokka *et al.* 2007). Finally, plastics were estimated to comprise 4 and 13% of waste in regions
8 of China that use coal and natural gas, respectively, and the country-wide average for urban
9 areas is projected to be 14% plastics in 2030 (World Bank 2005). Despite the uncertainty,
10 estimates from around the world are reasonably consistent in estimating plastics to comprise
11 about 10% of municipal waste mass. In contrast, plastics comprise 50-80% of the waste
12 stranded on beaches, floating on the ocean surface and on the seabed (Gregory & Ryan 1997;
13 Derraik 2002; Barnes 2005; Morishige *et al.* 2007).

23 3. TEMPORAL AND SPATIAL TRENDS IN ACCUMULATION

25 (a) *Ocean surface and beaches*

26 Many plastics are buoyant (46% US EPA 2006) and remain so until they become waterlogged or
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
Many plastics are buoyant (46% US EPA 2006) and remain so until they become waterlogged or
amass too much epibiota to float. Plastic items are commonly found at the sea surface or
washed up on the shoreline. Mass production of plastics began in the 1950s, so less than a
century ago we estimate the amount of anthropogenic debris at sea would have been three to
four orders of magnitude lower and restricted to much more degradable items. Some of the
earliest accounts of plastic debris in the marine environment are of fragments and pellets
ingested by seabirds in the 1960's (e.g. Kenyon & Kridler 1969, Harper & Fowler 1987), but
now plastic mega- and macro-debris is routinely observed from boats everywhere on the planet.
There has been a rapid and substantial increase in anthropogenic debris on the ocean surface and
beaches over recent decades (e.g. Dixon & Dixon 1981, Derraik 2002, Barnes 2005), but of
more pertinence now are the current spatial trends. Surveys of anthropogenic debris and clean-
up operations have generally focussed on the larger items along strandlines, and there is a wide
geographic variability in the type of data available to examine potential trends. However in the
last three of decades it has become apparent that the raw material for making plastics, tiny
pellets, and microplastics have become more numerous (as marine debris) and, like larger
pieces, these can travel considerable distances. Volunteer observations and collections in a

1 growing number of nations are aiding our understanding of the scale and pattern of distribution
2 of macro- and megaplastics in the marine environment but specialist examination is generally
3 needed to investigate accumulation of microplastic, e.g., in sediments (see Thompson *et al.*
4 2005). Beaches are the most easily accessible areas for studying marine debris (although such
5 studies have some confounding factors), yet despite the establishment of many study sites,
6 irregularity of sampling, differing protocol and observers have led to very few data sets
7 spanning more than a decade (see Barnes & Milner 2005).
8
9
10
11

12 The distribution of plastic debris is very patchy at sea for a variety of reasons, including
13 local wind and current conditions, coastline geography and the points of entry into the system
14 such as urban areas and trade routes. For example, stranding of macro- and megaplastics is
15 between one and two orders of magnitude less per length of coastline on remote shores and at
16 large spatial scales abundance correlates very strongly (Pearson's correlation = 0.971, $P < 0.001$)
17 with human population (per 10 degree latitude, see Barnes 2005). Enclosed seas and semi-
18 enclosed seas such as the Caribbean (Coe *et al.* 1997), typically have high densities of plastic
19 debris but also considerable variability. High densities and variability can also be a feature of
20 open ocean coastlines e.g., Brasil (Santos *et al.* 2005) and Hawaii (Dameron *et al.* 2007). One
21 of the key sources of interannual variability seems to be changes in oceanic circulation driven by
22 El Niño events (Matsumura & Nasu 1997; Morishige *et al.* 2007). Typically about 2000 and
23 500 items of anthropogenic debris strand on north and south Atlantic Ocean shores
24 (respectively) per linear km per year of which more than half is plastic (scaled up from surveys
25 of items >1cm in size along 200 m long beach sections, see Barnes & Milner 2005). More than
26 six times as much plastic strands in the Mediterranean Sea and less than six times as much
27 strands in the Southern Ocean shores (see Barnes & Milner 2005, Table 2). Despite
28 considerable variability in observation and accumulation rates of plastic debris, some temporal
29 trends do emerge. Studies initiated in the 1980s and 1990s indicated that the rate of plastic
30 stranding from oceanic sources showed a sustained and considerable increase over time (e.g.,
31 Ryan & Moloney 1993; Ribic *et al.* 1997; Torres & Jorquera 1999). Similarly the occurrence of
32 macro-plastics associated with wildlife (e.g., in bird nests and stomachs, entangling seals,
33 strangling a wide variety of vertebrates or even used by hermit crabs instead of shells, see
34 Barnes 2005) also drastically increased. For example, between 1992 and 2005 the frequency of
35 plastic garbage items in Kittiwake nests increased from 39.3% to 57.2% in Northwest Denmark
36 (Hartwig *et al.* 2007). Monitoring of strandings and effects on megafauna (such as birds) has
37 now commenced on at least a few remote island shores in every ocean and these, with negligible
38 local sources of plastics, have revealed the scale at which anthropogenic debris is accumulating.
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1 Barnes (2005) found high levels but no consistent temporal trends in the abundance of
2 anthropogenic debris on northern hemisphere shores compared to much lower levels but
3 increased densities through the 1980s, 1990s and early 2000s were reported in the Southern
4 hemisphere. The highest increases were at high southern latitudes (see Barnes 2005). However
5 new data (reported here) show that patterns of stranding on islands is no longer clearly
6 increasing and may be stabilising, though often with a 'noisy' signal of annual variability
7 (Figure 2, see also Ryan *et al.* this volume). A similar lack of clear temporal trend in stranding
8 densities of plastics is apparent in data collected intermittently at Ascension I., in the tropical
9 Atlantic Ocean, and in the Falkland Is., south Atlantic Ocean (Barnes unpublished data). About
10 27% of macro-debris items stranding at Ascension I. was fishery related, similar to remote Tern
11 I. in the Hawaiian Is. (Morishige *et al.* 2007). This is much less than on shores adjacent to
12 important fisheries e.g. in Brazil (Oigman-Pszczol & Creed 2007) or even sub-Antarctic Bird I.
13 (Walker *et al.* 1997). Bird I. and Signy I. in the Southern Ocean (Figure 2) have stranding
14 densities of plastics an order of magnitude lower than remote localities at low latitudes, which in
15 turn have at least an order of magnitude fewer plastics per km than urban sites. Further south in
16 the Southern Ocean, debris washes ashore much more rarely at Adelaide Island (west Antarctic
17 Peninsula). The relatively consistent level of abundance for macro and mega-debris at sea at
18 high southern latitudes is supported by recent resurveys around the Drake Passage, Scotia arc
19 and northern Antarctic Peninsula (Figure 3). Fifteen years after the first (see Barnes & Milner
20 2005), the most recent survey of this area took place early in 2008 and will involve the first
21 marine debris surveys of the south Bellingshausen and Amundsen seas. Visual surveys such as
22 these are weaker as a source of data than surface towed trawls but much more common and thus
23 arguably comparable with data collected elsewhere, despite being semi quantitative. Gregory *et al.*
24 (1984) reported similarly low (on a global scale) levels of floating anthropogenic debris in
25 the Ross Sea (Pacific sector) of the Southern Ocean. Observers from the University of Essex in
26 conjunction with Greenpeace are currently undertaking repeat survey of plastics at sea in this
27 area. As on surrounding strandlines, the North Atlantic and Pacific oceans have high densities
28 of floating plastic debris, especially at 20-40° N within a few hundred km of the coast and in the
29 gyre centres, e.g. between the tropical and subarctic waters (see Matsumura & Nasu 1997). A
30 recent (2005) survey of the subtropical convergence zone in this area showed plastic debris to be
31 concentrating there remotely using satellite imagery (Pichel *et al.* 2007).
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

48 We know much less about the use by and distribution of organisms that hitch-hike on
49 plastics and other anthropogenic debris than about the debris itself. Macro- and megaplastics
50 have the potential to carry a wide range of species and support the growth of many to
51
52
53
54
55
56
57
58
59
60

1 reproductive viability. The high abundance, lengthy durability and travel of plastics to even the
2 most remote coasts, makes them a major potential vector for the dispersal of organisms (see
3 Gregory this volume). New data from surveys of marine debris stranding in the Seychelles in
4 2005 and 2006 showed that on some beaches more than 60% of items carried fouling organisms,
5 the highest reported anywhere (D. Barnes unpublished data). This is of significance because the
6 prevailing currents travel from N. Australia and S. Indonesia during summer (South Equatorial)
7 and from Somalia, India and N. Indonesia during winter (Indian Monsoon) could potentially
8 transport a very wide range of species to less biodiverse, mid-ocean islands. Recent surveys of
9 marine debris at Ascension I. (reported here for the first time) found 38, 40 and 41% of debris
10 colonised by fauna in 2002, 2003 and 2005 respectively. Much of this had probably also
11 travelled considerable distances given the prevailing currents come from the cape of South
12 Africa. The likely response of many species to rapid regional warming is to move pole-ward to
13 stay within their normal thermal envelope but in previous phases of warming (interglacial
14 periods) there were few vectors to travel on. Now plastic debris, ship hulls and other vectors
15 make transport more rapid and frequent and unprecedented warming at high latitudes also means
16 that establishment success of potential invaders is likely to be higher.

25
26 **(b) Seabeds from shallows to abyss**

27
28 As at the surface, both in the open ocean and on strandlines it is clear that the abundance and
29 distribution of anthropogenic debris shows considerable spatial variability. The geographical
30 distribution of plastic debris is strongly influenced by hydrodynamics, geomorphology and
31 human factors. Moreover, there is notable temporal, particularly seasonal, variation with a
32 tendency for accumulation and concentration along coastal and particular geographic areas.

33 Under the weight of fouling by a wide variety of bacteria, algae, animals and
34 accumulated sediment, plastics can sink to the seabed (RCT unpublished data). Change in the
35 nature, presence or abundance of anthropogenic debris on the sea floor is much less widely
36 investigated than surface patterns. Studies that investigate seabed debris typically focus on
37 continental shelves and research into the deeper seabed, which forms about half the planet's
38 surface, is restricted by sampling difficulties and cost. Patterns in even the shallow subtidal can
39 differ substantially from the adjacent strandlines. Oigman-Pszczol & Creed (2007) found plastic
40 to constitute a much greater proportion of debris on the nearshore Brazilian seabed than on the
41 shore. While sonar does not enable discrimination of different types of debris, trawling (e.g.
42 using Agassiz) is probably the most adequate method to date, particularly when mesh size and
43 opening width can be manipulated (Goldberg 1994, 1995; Galgani & Andral 1998). Such nets
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1 are only semi-quantitative and because of their design for collecting epibenthos, probably
2 underestimate the quantities of debris present. Therefore pole trawling, with a constant mouth
3 width, which works deeper in sediments, is considered the best approach. This is also the only
4 trawling method with off-shelf data from submersibles. General strategies to investigate sea-bed
5 debris are similar to methodology for benthic ecology and place more emphasis on the
6 abundance and nature (e.g. bags, bottles, pieces of plastics) of items rather than their mass.
7 Interpretation of trends is made difficult because the ageing of plastics at depth is not well
8 researched and the fall of plastics to the sea-bed began long before specific scientific
9 investigations started in the 1990s. Plastics have been found on the seabed of all seas and
10 oceans across the planet but macro-debris is still very rare in the Southern Ocean, particularly in
11 deep water. For example a recent series of 32 Agassiz trawls and 29 Epibenthic sledge tows (at
12 200-1500 m depth, BAS unpublished data) around the most (human) visited area, the northern
13 Antarctic Peninsula and Scotia arc, found just one plastic piece and one metal shot. Large-scale
14 evaluations of sea-bed debris distribution and densities anywhere are scarce (but see Galgani *et*
15 *al.* 2000; Lee *et al.* 2006; Koutsodendris *et al.* 2008). However, there are a large number of
16 smaller scale studies that have investigated anthropogenic debris in coastal areas such as bays,
17 estuaries and sounds (see table 2 and references therein).

18 The abundance of plastic debris is very dependent upon location with values ranging
19 from 0-7290 items per hectare (Ha) (although an extreme find of 10110 anthropogenic items
20 per Ha was found in 1998 at one position, 43°42.84'N, 7°22.98'E using a pole trawl).
21 Assessments of abundance clearly demonstrate the domination of this debris by plastics, as at
22 more than half the study sites plastics constituted >50% of debris (Table 2). Of the areas
23 investigated to date, Mediterranean sites tend to show the greatest densities due to the
24 combination of a densely populated coastline and shipping in coastal waters, and a lack of
25 dispersion of plastics by little tidal flow or water circulation. In general, bottom debris tends to
26 become trapped in areas of low circulation and high sediment accumulation in contrast to
27 floating debris, which accumulates in frontal areas. Debris that reaches the sea-bed may already
28 have been transported considerable distance, only sinking when weighed down by fouling. The
29 consequence is an accumulation of plastics debris in bays rather than the open sea (Hess *et al.*
30 1999; Stefatos *et al.* 1999). Some accumulation zones in the Atlantic and the Mediterranean
31 Seas have very high debris densities despite being far from coasts. These densities relate to the
32 consequence of large-scale residual ocean circulation patterns. There are higher densities in
33 particular areas such as around rocks and wrecks or in depressions or channels (Galgani *et al.*
34 1996). In the North Sea (Figure 4), accumulation of plastics 320 km offshore from Denmark
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1 (Galgani *et al.* 2000) is a consequence of several factors. These include the eddying circulation
2 in the central north sea (Delhez & Martin 1992) and long-term circulation of water from the gulf
3 stream transporting plastics northwards (Breton & Salomon 1995) and to the convergence zone
4 of seabed sediment movements, due to local decreases of turbidity and turbulence (Tappin *et al.*
5 1997).
6
7
8

9 Large rivers are responsible for substantial inputs of debris to the sea bed (Williams &
10 Simmons 1997). They can transport waste out to sea because of their high flow rate and the
11 strength of bottom currents. In smaller rivers the displacement is slight, and waste can be found
12 in zones adjacent to or in the estuaries and is often coincident with fronts (Acha *et al.* 2003).
13 Patterns of debris transport should therefore be linked to river flow strength and may follow
14 similar patterns to deposition of sediment load (often depositing only small amounts of material
15 immediately along the coast).
16
17
18

19 Deep submarine extensions of coastal rivers also influence the distribution of sea bed
20 debris. In some areas local water movements transport plastics away from the coast to
21 accumulate in zones of high sedimentation. In these conditions, the distal deltas of rivers can fan
22 out in deeper waters, creating areas of high accumulation (Galgani *et al.* 1996). Continental
23 shelves often have lower concentrations of debris since most of the anthropogenic debris in the
24 outer shelf originates from coasts to shelves that are washed offshore by currents associated with
25 river plumes. Data from the shelf areas off the River Rhone (Galgani *et al.* 1995b) and
26 California (Moore & Allen 2000) show circulation can be strongly, locally influenced by storm
27 water events. The accumulation of plastics in coastal canyons may also be related to strong
28 currents occurring in the upper part of canyons, which decrease rapidly in deeper areas resulting
29 from increased confinement. Accordingly, debris distribution seems to be more temporally
30 stable. An inevitable effect of this is the presence of greater amounts of debris in deeper shelf
31 waters than in coastal waters (Galgani *et al.* 1996, 2000).
32
33
34
35
36
37

38 A wide variety of human activities contribute to these patterns of sea-bed debris
39 distribution, including proximity to fishing activities, urban development and tourism. Also
40 with plastic as a main component, debris from the fishing industry is prevalent in fishing areas
41 (Kanehiro *et al.* 1995; Galgani *et al.* 2000). This type of material accounts for a high percentage
42 of debris, for example up to 72 % in eastern China Sea (Lee *et al.* 2006) and 65% in the Celtic
43 sea (Galgani *et al.* 2000). Of sea-bed marine debris in California fishing gear also occupied
44 more space than plastic, metal, and miscellaneous debris (Moore & Allen 2000).
45
46
47
48

49 Investigations using submersibles at depths beyond the continental shelf usually consider
50 the number of items per linear km because of variability in transect width. They have revealed
51
52
53
54
55
56
57
58
59
60

1
2 substantial quantities of debris (Fig 5). Besides the high densities found in coastal canyons (up
3 to 112 items km⁻¹ and 70 % plastics), plastics and other anthropogenic debris were found widely
4 dispersed at slope and abyssal depths (Galgani *et al.* 2000). Deployment of a Remotely
5 Operated Vehicle submarine in the Fram Strait (Arctic) (Galgani & Lecornu 2004) revealed 0.2-
6 0.9 pieces of plastic per linear km at Hausgarten (2500 m). On dives between 5500 and 6770 m,
7 15 items of debris were observed, of which 13 were plastic, probably carried there by the
8 Norwegian current in the North Atlantic. At such latitude and bathymetry there is negligible
9 human activity, suggesting long distance transport of debris. Even more than on the sea surface
10 or strandlines of remote locations, such as in the Southern Ocean, accumulation trends in the
11 deep sea are of special concern. Most polymers are highly persistent in the marine environment
12 and only degrade slowly via photocatalysis when exposed to ultra-violet radiation (Andrady
13 2003). Estimates for the longevity of plastics are variable but are believed to be in the range of
14 hundreds or even thousands of years depending on the physical and chemical properties of the
15 polymer, but this is likely to be greatly increased at depth where oxygen concentrations are low
16 and light is absent. We know little about trends in accumulation of debris in the deep sea as
17 studies are rare but the data we have indicate considerable variability. For example in some
18 areas, such as the bay of Tokyo, debris densities decreased from 1996 to 2003 (Kanehiro *et al.*
19 1995; Kuriyama *et al.* 2003). In contrast, abundance remained stable in the gulf of Lion, France
20 during a similar period (Fig 6). Furthermore in some areas around Greece the abundance of
21 debris at depth has increased over the last 8 years (Stefatos *et al.* 1999; Koutsodendris *et al.*
22 2008). Interpretation of temporal trends is also complicated by annual variations in debris
23 transport, such as seasonal changes in flow rate of rivers. Other seasonal factors include
24 variation in the position of water fronts, the intensity of currents, swell, winds and upwelling
25 which influence both the distribution and densities. Nevertheless if we extrapolate from existing
26 data, it would appear that in the Mediterranean Sea as a whole there are about 3×10^9 debris
27 items (floating or sunk) of which 70-80% are plastic. New initiatives to minimise littering and
28 to reduce, re-use and recycle plastic should ultimately reduce plastic input into the at sea,
29 although usage is still very high. However, fragmentation of macro- and megaplastics to
30 microplastic pieces will also contribute to future trends in the abundance of visible plastics.
31
32
33
34
35
36
37
38
39
40
41
42
43
44

45 **4. FRAGMENTATION OF PLASTICS IN THE ENVIRONMENT**

46
47
48 The longevity of plastics is a matter for some debate, and estimates range from hundreds to
49 thousands of years. It is considered that (with the exception of materials that have been
50
51
52
53
54
55
56
57
58
59
60

1 incinerated) all of the conventional plastic that has ever been introduced into the environment
2 still remains to date unmineralised either as whole items or as fragments (Thompson *et al.*
3 2005). However, since we have only been mass-producing conventional plastics for around 60
4 years it is too early to say exactly how long these materials will persist. Despite the durability of
5 these polymers, plastic items are fragmenting in the environment as a consequence of prolonged
6 exposure to ultraviolet light and physical abrasion (Colton *et al.* 1974; Gregory 1978; Andradý
7 2003; Thompson *et al.* 2004). This is particularly evident on shorelines where photo-degradation
8 and abrasion through wave action makes plastic items brittle increasing their fragmentation.

9
10
11
12
13 Some of the first evidence of accumulation of plastic fragments in the environment came
14 indirectly from examination of the gut contents of sea birds in the 1960's (e.g. Kenyon &
15 Kridler 1969). Later, in the early 1970's, small fragments of plastic were observed in seawater
16 collected with plankton samples from the North Sea (Buchanan 1971) and were subsequently
17 reported on much broader scales in the north-western Atlantic (Colton *et al.* 1974). There have
18 since been numerous reports of fragments in the oceans, on the seabed and on shorelines
19 worldwide (Figure 7) and there is clear evidence that the abundance of these fragments is
20 increasing (Figure 8). The UK Marine Conservation Society, which organises annual voluntary
21 beach cleaning on shores all around the UK, reports a 30% increase in the abundance of large
22 fragments (1-50cm in size) and a 20% increase in the abundance of smaller fragments (<1cm)
23 between 1998 and 2006 (MCS 2007). On shorelines close to Plymouth one of us (RCT) recently
24 recorded strandline material with more than 10% (10.89 ± 0.67 , mean \pm standard deviation) by
25 weight of plastic fragments and pieces (including some plastic spherules, the raw materials for
26 manufacture). In 2004, Thompson *et al.* (2004) reported on the abundance of even smaller
27 fragments of plastic, some just 20 μ m, in diameter, which had accumulated on shorelines around
28 the UK. Using plankton samples archived by the Sir Alistair Hardy Foundation for Ocean
29 Science it was evident that the abundance of this microscopic debris had increased significantly
30 in recent years (Figure 8). Similar fragments have since been identified from shorelines
31 worldwide (Figure 7) and in terms of numerical abundance microplastic can constitute over 80%
32 of intertidal plastic debris at some locations (Browne *et al.* 2007).
33
34
35
36
37
38
39
40
41
42

43 Fragments of plastic can be identified using Fourier Transform Infrared (FT-IR)
44 Spectroscopy to match spectra obtained from unknown debris items to those of known
45 polymers. Using this approach a range of common polymers including polypropylene,
46 polyethylene and polyester have been identified as fragments and microscopic fragments. These
47 materials have a wide range of domestic and industrial uses from rope and packaging to clothing
48 and it seems likely that the fragments are forming from the breakdown of a wide range of
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
everyday plastic products (Thompson *et al.* 2004). In addition to this 'natural' deterioration, it has been suggested that plastic items are also deliberately being shredded on board some ships in order that plastic waste can be concealed in food waste discharged at sea (van Franeker *et al.* 2005). The abundance of small items of plastic is further increased by the use plastic particles as scrubbers and abrasives in commercial cleaning applications (Gregory 1996) and by spillage of pre-production plastic pellets (~ 5mm in diameter) and powders such as those used for rotomoulding (~ 300µm in diameter) (e.g. Carpenter *et al.* 1972; Colton *et al.* 1974; Gregory 1978). Hence it is apparent that small items of plastic are entering the environment directly and that larger items of debris are fragmenting.

15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
The accumulation of plastic fragments is of particular concern because they are difficult to remove from the environment and because they have the potential to be ingested by a much wider range of organisms than larger items of debris. Marine mammals, turtles and numerous other organisms are known to ingest large items of plastic including bags and bottles (Laist 1997; Derraik 2002). Smaller fragments can be ingested by birds, fish and even invertebrates (Thompson *et al.* 2004; Van Franeker *et al.* 2005). Upon ingestion it is possible that these small fragments may present a physical hazard in a similar way to larger items of debris by clogging feeding appendages or the digestive system (Laist 1997; Derraik 2002). Microscopic fragments are also be taken up from the gut into other body tissues (Browne *et al.* 2008). In addition to concerns about the physical hazards presented by this debris it has also been suggested that plastics could transfer harmful chemicals to living organisms (e.g. Oehlmann *et al.*, Talsness *et al.* and Kock *et al.* all in this volume). A range of chemicals are used as additives in the manufacture of plastics. These increase the functionality of the plastics, but some such as phthalate plasticisers and brominated flame retardants are potentially harmful and have been associated with carcinogenic and endocrine disrupting effects (see Takada *et al.* this volume). In seawater, plastics are also known to sorb and concentrate contaminants, which have arisen in the environment from other sources. These contaminants include persistent organic "pollutants" such as PCBs DDE, nonylphenol and phenanthrene can become several orders of magnitude more concentrated on the surface of plastic debris than in the surrounding seawater (Mato *et al.* 2001). It has been widely suggested that these sorbed contaminants and the chemicals additives that are used in manufacture could subsequently be released if the plastics are ingested (see Takada *et al.* this volume). Small and microscopic plastic fragments present a likely route for the transfer of these chemicals because they have a much greater surface area to volume ratio than larger items of debris from which they have originated and because of their size they are available to a wide range of organisms, including deposit feeders like the lug worm, *Arenicola*

1 *marina*, that feed by stripping organic matter from particulates (Mayer *et al.* 1997; Voparil *et al.*
2 2004). Recent in-vitro modelling studies predict that even very small quantities of microplastic
3 have the potential to significantly increase the transport of phenanthrene to *A. marina* (Teuten *et al.*
4 *et al.* 2007) and work in this volume has examined uptake of contaminants from plastics by birds
5 (Takada *et al.* this volume).

6
7
8
9 Given current levels of production and the quantities of plastic that are already present in
10 the environment it seems inevitable that the abundance of plastic fragments will continue to
11 increase for the foreseeable future. More work is therefore needed to model the environmental
12 consequences of this debris and to produce environmental risk assessment models to predict the
13 transport of a range of contaminants by fragments of common polymers (Thompson *et al.* 2005;
14 Thompson 2006; Teuten *et al.* 2007).

15 16 17 18 19 **5. SUMMARY AND CONCLUSIONS**

20 Less than 60 years ago, the mass production of plastics started and now most items that people
21 use, virtually anywhere on the planet are partly or wholly made of this inexpensive, durable
22 material. Plastics have transformed the surface of the planet far beyond areas of human
23 population density – fragments of all sizes are ubiquitous in soils to lake beds, from remote
24 Antarctic island shores to tropical sea-beds. Plastics turn up in bird nests, are worn by hermit
25 crabs instead of shells and are present in turtle stomachs. Human populations generate
26 considerable amounts of waste and the quantities are increasing as standards of living and
27 population also increase. Although quantities vary between countries, about 10% of solid waste
28 is plastic. Up to 80% or sometimes more of the waste that accumulates on land, shorelines, the
29 ocean surface or seabed is plastic. The most common items are plastic films, such as carrier
30 bags, which are easily wind blown as well as discarded fishing equipment and food and
31 beverage packaging. Strandline surveys (beach cleaning operations) are now organised in many
32 countries and provide information about temporal and spatial trends. However, these surveys
33 typically only provide data on coarse trends and larger items. There is considerable variation in
34 methodology between regions and between investigators and more valuable and comparable
35 data could be obtained by standardising monitoring approaches (Ryan *et al.* this volume).
36 Accumulation rates vary widely with many factors such as proximity of urban settlements, shore
37 use, prevailing wind and ocean currents, and region. There were dramatic increases in quantities
38 of mega and macro-plastic debris in the northern hemisphere up to the 1990s. Quantities of
39 debris in the oceans appear to have stabilised in the oceans over the last decade but have
40 increased on shorelines. However this could indicate quantities of debris entering the sea are
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1 declining, but the material already in the sea is progressively being deposited on the shore or
2 sinking to the deep. . Accumulation rates are much lower in the southern hemisphere but are
3 still increasing significantly, although repeat surveys on remote Antarctic islands and ocean
4 areas suggest stabilisation over the last decade. Fouled by organisms and sediment, plastics can
5 sink and form an even higher proportion of human waste reaching the seabed and quantities in
6 excess of tens of thousands of items per km² have been reported. As on beaches and the ocean
7 surface, enclosed seas such as the Mediterranean have the highest densities, but investigations in
8 deeper waters have shown high accumulation rates can stretch far (hundreds of km) from the
9 coast, particularly adjacent to large river mouths or in canyons. As on surface environments,
10 trends of debris accumulation on the seabed increase at some locations, but are stable or
11 decreasing at other sites. Quantities of debris in the oceans appear to have stabilised in the
12 oceans over the last decade but have increased on shorelines. The problem of plastic fragments
13 has taken on increased importance in the last few decades. From the first reports in the 1970s,
14 it was only a few years before the widespread finding of plastic including reports of microscopic
15 fragments (20µm in diameter). The abundance of microscopic fragments was greater in the
16 1980s and 1990s was than in previous decades. It has also been suggested that plastic waste is
17 deliberately being shredded into fragments to conceal and discarded at sea. Plastics of all sizes
18 are now reaching the most remote and deepest parts of the planet and although we have much
19 better knowledge of their sources, quantities, and distribution, we still understand little about
20 their longevity, and affects on organisms. Further, we have made little progress in reducing the
21 release of plastic to the environment. Temporal trends of macroplastics on remote islands
22 suggest regulations to reduce dumping at sea have been successful to some extent. However our
23 sustained demand for plastic means that contamination of the environment by microplastic
24 pieces seems set to increase. In addition, future sampling may reveal increasing quantities of
25 debris in the planet's least known habitat, the deep sea.

26
27
28
29
30
31
32
33
34
35
36
37
38
39
40 Acknowledgements: The authors would like to thank past marine debris observers on beaches and ships who have
41 generously given up their time and effort to recording items. The authors would also like to thank Alison Cook for
42 help in preparation of Figure 7; also Mark Brown and Stuart Niven for analysis of microplastic data in Figure 7.
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
REFERENCES

- Acha, E., Hermes, W., Mianzan, A., Iribarne, C., Domingo, A., Gagliardini, C., Carlos Lasta, A. & Pedro Daleo, D. 2003 The role of the Rio de la Plata bottom salinity front in accumulating debris. *Mar. Poll. Bull.* **46**, 197-202
- Andrady, A.L. 2003 Plastics in the Environment. In: Andrady AL (ed) Plastics in the Environment. John Wiley & Sons, New Jersey, pp 762
- Andrady, A.L. & Neal, *Phil. Trans. Roy. Soc. Lond. B* In press
- APME 2006 An analysis of plastics production, demand and recovery in Europe. Association of Plastics Manufacturers Brussels
- Barlaz, M.A. 2006 "Forest Products Decomposition in Municipal Solid Waste Landfills," *Waste Manage.* **26**, 321-333.
- Barnes, D.K.A. 2002 Invasions by marine life on plastic debris. *Nature* **416**, 808-809
- Barnes, D.K.A. 2005 Remote islands reveal rapid rise of Southern Hemisphere sea debris. *Directions Sci.* **5**, 915-921
- Barnes, D.K.A. & Milner, P. (2005) Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Mar. Biol.* **146**, 815-825
- Breton, M. & Salomon, J. C. 1995 A long term advection- dispersion model for the channel and southern North Sea. *J. Mar. Syst.* **6**, 495-513
- Browne, M.A., Galloway, T. & Thompson, R. (2007) Microplastic – an emerging contaminant of potential concern. *Integr. Envir. Assess. Manage.* **3**, 559-566
- Browne, M.A., Dissanayake, A., Galloway, T.S., Lowe, D.M. & Thompson R.C. (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.) *Environmental Sci. & Technol.* **42**, 5026-5031
- Buchanan, J.B. 1971 Pollution by synthetic fibres. *Mar. Poll. Bull.* **2**, 23
- Burnley S.J. 2007 A Review of Municipal Solid Waste Composition in the United Kingdom. *Waste Manage.* **27**, 1274 - 85
- Cannizarro, L., Garofalo, G., Giusto, G., Rizzo, P. & Levi, D. 1995 Qualitative and quantitative estimate of solid waste in the Channel of Sicily. In Proceedings of the second International, ed. E. Ozhan, Conference on the Mediterranean. Coastal Environment. MED- COAST 95, 24±27 Oct, Tarragona, Spain.
- Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P. & Bradford, B.P. 1972 Polystyrene spherules in coastal waters. *Science* **178**, 749-750

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- Coe, J.M., Andersson, S. & Rogers, D.B. 1997 Marine debris in the Caribbean region, p. 25-34,
In J. M. Coe and D. B. Rogers (eds), *Marine debris: Sources, impact and solutions*,
Springer Verlag, New York.
- Colton, J.B., Knapp, F.D. & Burns, B.R. 1974 Plastic particles in surface waters of the
Northwestern Atlantic. *Science* **185**, 491 - 497
- Convey, P., Barnes, D.K.A. & Morton, A. 2002 Debris accumulation on oceanic island shores of
the Scotia Arc, Antarctica. *Polar Biol.* **25**, 612-617
- Dameron, O. J., Parke, M., Albins, M.A., & Brainard, R.E. 2007 Marine debris accumulation in
the Northwestern Hawaiian Islands: An examination of rates and processes. *Mar. Poll.*
Bull. **53** 423-433
- Delhez, E. & Martin, G. 1992 Preliminary results on 3-D baroclinic models of the mesoscale
and macroscale circulations on the North-western European continental shelf. *J. Mar.*
Syst. **3**, 423-440
- Derraik, J.G.B. 2002 The pollution of the marine environment by plastic debris : a review.
Mar. Poll. Bull. **44**, 842-852
- Dixon, T.R. & Dixon, T.J., 1981 Marine litter surveillance. *Mar. Poll. Bull.* **12**, 289-295.
- Endo, S., Takizawa, R., Okuda, K., Takada, H., Chiba, K., Kanehiro, H., Ogi, H., Yamashita, R.
& Date, T. 2005 Concentration of polychlorinated biphenyls (PCBs) in beached resin
pellets: Variability among individual particles and regional differences. *Mar. Poll. Bull.*
50, 1103-1114
- Eriksson, C. & Burton, H. 2003 Origins and biological accumulation of small plastic particles in
fur seals from Macquarie Island. *Ambio* **32**, 380-384
- Eurostat, 2007 Waste generated and treated in Europe 1995-2003,
[http://epp.eurostat.cec.eu.int/cache/ITY_OFFPUB/KS-55-03-471/EN/KS-55-03-471-
EN.PDF](http://epp.eurostat.cec.eu.int/cache/ITY_OFFPUB/KS-55-03-471/EN/KS-55-03-471-EN.PDF), accessed Dec. 4, 2007
- Galgani, F. & Andral, B. 1998 Methods for evaluating debris on the deep sea floor.
OCEANS'98/IEEE/OEC Conference, Nice 28/09-01/10/98, **3**, 1512-1521.
- Galgani, F., Burgeot, T., Bocquene, G., Vincent, F. & Leaute, J. P. 1995a Abundance of debris
on the continental shelf of the Bay of Biscaye and in the Seine Bay. *Mar. Poll. Bull.* **30**,
58-62.
- Galgani, F., Jaunet, S., Campillo, A., Guenegan, X. & His, E. 1995b. Distribution and
abundance of debris on the continental shelf of the North-western Mediterranean Sea.
Mar. Poll. Bull. **30**, 713-717.

- 1 Galgani, F., Leaute, J.P., Moguedet, P., Souplet, A., Verin, Y., Carpentier, A., Goragner, H.,
2
3 Latrouite, D., Andral, B., Cadiou, Y., Mahe, J.C., Poulard, J.C. & Nerisson, P. 2000
4
5 Litter on the sea floor along European coasts. *Mar. Poll. Bull.* **40**, 516-527
6
7 Galgani, F. & Lecornu, F. 2004 Debris on the sea floor. at "Hausgarten": in The expedition
8
9 ARKTIS XIX/3 of the research vessel POLARSTERN in 2003. *Berichte Polar*
10
11 *Meeresforsch.*, **488**, 260-262.
12
13 Galgani, F., Souplet, A. & Cadiou, Y. 1996 Accumulation of debris on the deep sea floor of the
14
15 French Mediterranean coast. *Mar. Ecol. Progr. Ser.* **142**, 225-234
16
17 Galil, B. S., Golik, A. & Tuerkay, M., 1995 Litter at the bottom of the sea. A sea-bed survey in
18
19 the eastern Mediterranean sea. *Mar. Poll. Bull.* **30**, 22-24.
20
21 Goldberg, E. 1994 Diamonds and plastics are forever? Editorial. *Mar. Poll. Bull.* **28**, 466
22
23 Goldberg, E. 1995 Emerging Problems in the Coastal Zone for the Twenty-First Century. *Mar.*
24
25 *Poll. Bull.*, **31**, 152-158.
26
27 Gregory, M.R. 1978 Accumulation and distribution of virgin plastic granules on New Zealand
28
29 beaches. *New Zealand J. Mar. Freshwat. Res.* **12**, 339-414
30
31 Gregory, M.R. 1996 Plastic 'scrubbers' in hand cleansers: A further (and minor) source for
32
33 marine pollution identified. *Mar. Poll. Bull.* **32**, 867-871
34
35 Gregory, M.R. 1999 Plastics and South Pacific Island shores: environmental implications.
36
37 *Ocean Coastal Manag.* **42**, 603-615
38
39 Gregory, M.R. This issue. Environmental implications of plastic debris in marine settings –
40
41 entanglement, ingestion, smothering, hangers-on, hitch-hiking, and alien invasions. *Phil.*
42
43 *Trans. Roy. Soc. Lond. B* In press
44
45 Gregory, M.R., Kirk, R.M.. & Mabin, M.C.G. 1984 Pelagic tar, oil, plastics and other litter in
46
47 surface waters of the New Zealand sector of the Southern Ocean and on Ross
48
49 Dependency shores. *N.Z. Antarct. Record* **6**, 12-28
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- Gregory, M.R. & Ryan, P. 1997 Pelagic plastics and other seaborne persistent synthetic debris: a review of Southern Hemisphere perspectives. In Coe, J. & Rogers, D. (eds.) Marine debris: sources, impacts and solutions. Springer & Verlag, New York, 49-66
- Habib, B., Locke, D.C. & Cannone, L.J. 1996 Synthetic fibers as indicators of municipal sewage sludge, sludge products and sewage treatment plant effluents. *Water Air Soil Poll.* **103**, 1-8.
- Harper, P. C. & Fowler, J. A. 1987. Plastic pellets in New Zealand storm-killed prions (*Pachyptila* spp.), 1958-1977. *Notornis* 34, 65-70.
- Hartwig, E., Clemens, T. & Heckroth, M. 2007 Plastic debris as nesting material in a Kittiwake- (*Rissa tridactyla*)-colony at the Jammerbugt, Northwest Denmark. *Mar. Poll. Bull.* **54**, 595-597
- Hess, N., Ribic, C., & Vining, Y., 1999 Benthic Marine Debris, with an Emphasis on Fishery-Related Items, Surrounding Kodiak Island, Alaska, 1994-1996. *Mar. Poll. Bull.*, **38**, 885-890
- Ivar do Sul, J.A. & Costa, M.A. 2007 Marine debris review for Latin America and the Wider Caribbean Region: From the 1970s until now, and where do we go from here? *Mar. Poll. Bull.*, **54**, 1087-1104
- June, J. A. 1990 Type, source, and abundance of trawl-caught debris of Oregon, in the Eastern Bering Sea, and in Norton Sound in 1988. In Proceedings of the Second International Conference on Marine Debris, eds. R. S. Shomura and M. L. Godfrey, pp. 279-301. US Department of Commerce, NOAA Technical Memo. NMFS-SWF-SC-154.
- Kanehiro, H., Tokai, T. & Matuda, K., 1995 Marine litter composition and distribution on the sea-bed of Tokyo Bay. *Fisheries Engineering* **31**, 195-199.
- Katsanevakis, S. & Katsarou, A. 2004 Influences on the distribution of marine debris on the seafloor of shallow coastal areas in Greece (Eastern Mediterranean), *Water, Air Soil Poll.* **159**, 325-337.

- 1 Kenyon, K. W. & Kridler, E. 1969. Laysan Albatross swallow indigestible matter. *Auk* 86, 339-
2 343.
3
4 Koch, H.M. and Calafat, A.M. . Human body burdens of chemicals used in plastic manufacture.
5 *Phil. Trans. Roy. Soc. Lond. B* in press - this volume.
6
7 Koutsodendris, A., Papatheodorou, A., Kougiourouki, O. & Georgiadis, M., 2008 Benthic
8 marine litter in four Gulfs in Greece, Eastern Mediterranean; abundance, composition
9 and source identification. *Est. Coast. Shelf Sci.*, **77**, 501-12.
10
11 Kuriyama, Y., Tokai, T., Tabata, K. & Kanehiro, H., 2003 Distribution and composition of litter
12 on seabed of Tokyo Gulf and its age analysis. *Nippon Suisan Gakkaishi* **69**, 770-781.
13
14 Kusui, T. & Noda, M. 2003 International survey on the distribution of stranded and buried litter
15 on beaches along the Sea of Japan. *Mar. Poll. Bull.* **47**, 175-179
16
17 Laist DW (1997) Impacts of marine debris: entanglement of marine life in marine debris
18 including a comprehensive list of species with entanglement and ingestion records. In:
19 Coe JM, Rogers BD (eds) Marine Debris: sources, impacts and solutions. Springer,
20 Berlin, pp 99-141
21
22 Lee D., Hyeon-Seo, C. & Sun-Beom, J. 2006 Distribution characteristics of marine litter on the
23 sea bed of the East China Sea and the South Sea of Korea *Est. Coast. Shelf Sci.*, **70**,
24 187-194.
25
26 Loughlin, D. H. & Barlaz, M. A. 2006 Policies for Strengthening Markets for Recyclables: A
27 Worldwide Perspective. *Env. Sci. Technol.*, **36**, 287 – 326.
28
29 Masó, M., Garcés, J., Pagès, F. & Camp, J. 2003 Drifting plastic debris as a potential vector for
30 dispersing Harmful Algal Blooms (HAB) species. *Sci. Mar.* **67**, 107-111
31
32 Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C. & Kaminuma, T. 2001 Plastic resin
33 pellets as a transport medium for toxic chemicals in the marine environment. *Enviro Sci*
34 *Technol* **35**, 318-324
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- Matsumura, S. & Nasu, K. 1997 Distribution of floating debris in the North Pacific Ocean: sighting surveys 1986-1991, p. 15-24. *In* J. M. Coe and D. B. Rogers [eds], Marine debris: Sources, impact and solutions, Springer Verlag, New York.
- Mayer, L.M., Schick, L.L., Self, R.F.L., Jumars, P.A., Findlay, R.H., Chen, Z. & Sampson, S. 1997 Digestive environments of benthic macroinvertebrate guts: Enzymes, surfactants and dissolved organic matter. *J. Mar. Res.* **55**, 785-812
- MCS 2007 Beachwatch 2006 - The 14th Annual Beach Litter Survey Report. Marine Conservation Society, Ross on Wye
- Moore C.J., Moore, S. L., Leecaster, M.K. & Weisberg, S. B. 2001a A Comparison of Plastic and Plankton in the North Pacific Central Gyre. *Mar. Poll. Bull.* **42**, 1297-1300
- Moore, S.L. & Allen, M.J. 2000 Distribution of anthropogenic and natural litter on the mainland shelf of the Southern California Bight. *Mar. Poll. Bull.* **40**, 83-88.
- Moore, S.L., Gregorio, D., Carreon, M., Weisberg, S. B. & Leecaster, M. K. 2001b Composition and distribution of beach debris in Orange County, California. *Mar. Poll. Bull.* **42**, 241-245
- Morishige, C., Donohue, M.J., Flint, E., Swenson, C. & Woolaway, C. 2007 Factors affecting marine debris deposition at French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument, 1900-2006. *Mar. Poll. Bull.* **54**, 1162-1169
- Ng, K.L. & Obbard, J.P. 2006 Prevalence of microplastics in Singapore's coastal marine environment. *Mar. Poll. Bull.* **52**, 761-767
- Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., Jagnytsch, O., Lutz, I., Kusk, K.O., Wollenberger, L., Santos, E.M., Paull, G.C., Van Look, K.J.W. and Tyler, C.R. in press A critical analysis of the biological impacts of plasticizers on wildlife *Phil. Trans. Roy. Soc. Lond. B* in press - this volume.

- 1 Oigman-Pszczol, S.S. & Creed, J.C. 2007 Quantification and Classification of Marine Litter on
2
3 Beaches along Armação dos Búzios, Rio de Janeiro, Brazil. *J. Coastal Res.* **23**, 421–428
4
5 Pichel, W.G., Churnside, J.N., Veenstra, T., Foley, D.G., Friedman, K., Wilson, J., Brainard,
6
7 R.E., Nicoll, J., Zheng, X. & Clemente-Colón, P. 2007 Detection of Marine Debris in the
8
9 North Pacific Subtropical Convergence Zone. *Mar. Poll. Bull.* **54**, 1207-1211
10
11 Plastics Europe (2008), Annual Report 2007, 36pp. Association of Plastics Manufacturers,
12
13 Brussels, Belgium.
14
15 Reddy, M.S., Basha, S., Adimurthy, S. & Ramachandraiah, G. 2006 Description of the small
16
17 plastics fragments in marine sediments along the Alang-Sosiya ship-breaking yard,
18
19 India. *Est. Coast. Shelf Sci.* **68**, 656-660
20
21 Ribic, C.A., Johnson, S.W., Cole, C.A. 1997 Distribution, type, accumulation, and source of
22
23 marine debris in the United States, 1989-1993, p. 35-48. In J. M. Coe and D. B. Rogers
24
25 [eds], *Marine debris: Sources, impact and solutions*, Springer verlag, New York.
26
27 Ryan, P.G. & Moloney, C.L. 1993 Marine litter keeps increasing. *Nature* **361**, 23
28
29 Ryan, P.G., Moore, C.J., van Franeker, J.A. & Moloney, C.L. This volume. Monitoring the
30
31 abundance of plastic debris in the environment. *Phil. Trans. Roy. Soc. Lond. B* In press
32
33 Santos I.R., Friedrich, A.C. & Baretto, F.P. 2005 Overseas garbage pollution on beaches of
34
35 northeast Brazil. *Mar. Poll. Bull.* **50**, 783-786
36
37 Shaw, D.G. & Day, R.H. 1994 Color and form-dependent loss of plastic micro-debris from the
38
39 North Pacific-Ocean. *Mar. Poll. Bull.* **28**, 39-43
40
41 Sokka L., Antikainen R. & Kauppi, P.E. 2007 Municipal solid waste production and
42
43 composition in Finland - Changes in the period 1960-2002 and prospects until 2020
44
45 *Resources Conserv. Recycling* **50**, 475 - 88.
46
47 Stefatos, M., Charalampakis, M., Papatheodorou, G. & Ferentinos, G. 1999 Marine Debris on
48
49 the Sea-floor of the Mediterranean Sea: Examples from Two Enclosed Gulfs in Western
50
51 Greece. *Mar. Poll. Bull.* **36**, 389-393.
52
53
54
55
56
57
58
59
60

- 1
2 Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., Rowland,
3
4 S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, R., Watanuki, Mohamad,
5
6 P.Z., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M.,
7
8 Takada, H. (in press) Transport and release of chemicals from plastics to the
9
10 environment and to wildlife *Phil. Trans. Roy. Soc. Lond. B* in press - this volume.
- 11
12 Talsness, C.E. Andrade, A.J.M. and vom Saal F.S. (in press) Components of plastic:
13
14 experimental studies in animals and relevance for human health . *Trans. Roy. Soc. Lond.*
15
16 *B* in press - this volume.
- 17
18 Tappin, A., Burton, J. D., Millward, G. E. & Statham, P. J. 1997 A numerical transport model
19
20 for predicting the distributions of Cd, Cu, Ni, Pb and Zn in the southern North Sea: The
21
22 sensitivity of model results to uncertainties in the magnitudes of metal inputs. *J. Mar.*
23
24 *Syst.* **13**, 173- 204.
- 25
26 Teuten, E.L., Rowland, S.J., Galloway, T.S. & Thompson, R.C. 2007 Potential for plastics to
27
28 transport hydrophobic contaminants. *Environment. Sci. Technol* **41**, 7759-7764
- 29
30 Thompson, R., Moore, C., Andrady, A., Gregory, M., Takada, H. & Weisberg, S. 2005 New
31
32 directions in plastic debris. *Science* **310**, 1117
- 33
34 Thompson, R.C. 2006 Plastic debris in the marine environment: consequences and solutions. In:
35
36 Krause JC, von Nordheim H, Brager S (eds) *Marine Nature Conservation in Europe.*
37
38 Federal Agency for Nature Conservation, Stralsund, Germany, pp 107-116
- 39
40 Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle,
41
42 D. & Russell A.E. 2004 Lost at sea: Where is all the plastic? *Science* **304**, 838
- 43
44 Torres, D. & Jorquera, D. 1999 Synthesis of marine debris survey at Cape Shirreff, Livingston
45
46 Island, during the Antarctic season 1998/99. CCAMLR-XVIII/BG/39. CCAMLR,
47
48 Hobart, Australia.
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2 US EPA 2006 Municipal Solid Waste in the United States; 2005 Facts and Figures. United
3
4 States Environmental Protection Agency, Office of Solid Waste, EPA530-R-06-011,
5
6 Washington, D.C.
- 7
8 van Franeker, J.A. & Bell, P.J. 1988 Plastic ingestion by petrels breeding in Antarctica. *Mar.*
9
10 *Poll. Bull.* **19**, 672-674
- 11
12 van Franeker, J.A., Meijboom, A. & de Jong, M.L. 2004 Marine litter monitoring by Northern
13
14 Fulmars in the Netherlands 1982-2003. Alterra, 1093, Wageningen
- 15
16 Van Franeker, J. A., Heubeck, M., Fairclough, K., Turner, D. M., Grantham, M., Stienen, E. W.
17
18 M., Guse, N., Pedersen, J., Olsen, K. O., Andersson, P. J. & Olsen, B. 2005. 'Save the
19
20 North Sea' Fulmar Study 2002-2004: a regional pilot project for the Fulmar-Litter-
21
22 EcoQO in the OSPAR area. Alterra-rapport 1162. Wageningen: Alterra (available at
23
24 www.zeevogelgroep.nl)
- 25
26 Voparil, I.M., Burgess, R.M., Mayer, L.M., Tien, R., Cantwell, M.G. & Ryba, S.A. 2004
27
28 Digestive bioavailability to a deposit feeder (*Arenicola marina*) of polycyclic aromatic
29
30 hydrocarbons associated with anthropogenic particles. *Environment. Toxicol. Chem.* **23**,
31
32 2618-2626
- 33
34 Walker, T.R., Reid, K., Arnould, J.P.Y. & Croxall, J. (1997) Marine debris surveys at Bird
35
36 Island, South Georgia 1990-1995. *Mar. Poll. Bull.* **34**, 61-65
- 37
38 Weiss, K.R., McFarling, U.L. & Loomis, R. (2006) Plague of plastic chokes the seas. Los
39
40 Angeles Times, August 2.
- 41
42 Williams, A. & Simmons, S. 1997 Estuarine litter at the estuarine/ beach interface in the Bristol
43
44 Channel. *J. Coast. Res.*, **13**, 1159-1165.
- 45
46 World Bank 2005 Waste Management in China: Issues and recommendations. Urban
47
48 Development Working Papers, East Asia Infrastructure Development, Working Paper
49
50 No. 9.
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure and table legends

Figure 1 Production of Plastic Products in the U.S. in 2005 (adopted from US EPA, 2006)

Figure 2 Annual accumulation of marine debris on shores of selected islands with year. Data for Bird I. and Signy I. are from Walker *et al.* (1997), Convey *et al.* (2002) and CCAMLR. Data for Tern I. are from Morishige *et al.* (2007) and for the UK from Beachwatch 2006 (MCS 2007).

Figure 3 Densities of marine debris at sea in the South-West Atlantic and Atlantic sector of the Southern Ocean by 10 degree latitude and longitude areas. Shades of light to dark blue code for densities 0-1, 2-10, 11-100, 101-1000 and 1001+ items per km² respectively. The survey years are April 1993 (a), April 2002 (b) and April 2006 (c). Data from Barnes & Milner (2005) and present study.

Comment [r1]: Will need to modify if published in Black & White

Figure 4 Plastic debris on the sea-bed from the southern North Sea (North Atlantic) in 1999. Plastics were counted after 30 minutes trawl time (16 m mouth, 20 mm mesh) at 64 stations (●) on the continental shelf. Results are given as items per Ha (10,000 m²).

Figure 5 Accumulation of debris in deep sea environments. Submersible observations in Mediterranean canyons (A & B: plastic bottles at 1000 m depth at two different locations in the Marseille canyon, 43°03′.00N 05°00′.00 E) and above the polar circle, under ice floe (C & D: individual plastic bags, 2200-2600 m depth at Hausgarten, Fram strait, 79°03′.80 N 04°11′.60 E).

Figure 6 Plastic debris on the sea floor from the Gulf of Lion (Mediterranean Sea, France) between 1994 and 2004. Plastics were counted after 60 minutes trawl time (net = 16 m mouth, 10 mm mesh) at 65 stations (●) located on the continental shelf and adjacent canyons (down to 800m) from the gulf. Results are given as items per Ha (10,000 m²).

Figure 7 Reports of plastic fragments in the marine environment presented in chronological order: 1, Harper & Fowler (1987) report on plastic (mainly pre-production pellets) ingested by seabirds since 1960; 2, (Kenyon & Kridler 1969) plastic fragments found in body cavity of dead Laysan Albatrosses during 1966 survey; 3, (Buchanan 1971) synthetic fibres in medium plankton net hauls (size not specified); 4, (Carpenter *et al.* 1972) polystyrene spherules (average 500 µm) in coastal waters; 5, (Colton *et al.* 1974) particles, spheres and discs (1-5mm) in surface waters; 6, (Gregory 1978) resin pellets (~5mm) on shoreline; 7 (Ryan and Moloney 1990) temporal trends in abundance and composition of plastic on beaches 1984 to 1989; 8, (van Franeker & Bell 1988) plastic particles (~ 3mm) in gut of Storm Petrels; 9, (Shaw & Day 1994) fragments (≥ 500µm) at sea surface; 10, (Habib *et al.* 1996) Microplastic fibres (≥ 20µm) in sewage sludge; 11, (Galgani *et al.* 2000) Fragments in deep sea (size not specified); 12, (Moore *et al.* 2001a) fragments (≥ 350µm) at sea surface; 13, (Moore *et al.* 2001b) fragments and resin pellets on shoreline (size not specified); 14, (Eriksson & Burton 2003) fragments (≥1mm) in scats of fur seals; 15, (Kusui & Noda 2003) fragments (≥1mm) on beaches; 16, (Thompson *et al.* 2004) Microplastics (≥ 20µm) in surface waters and on beaches; 17, (Endo *et al.* 2005) resin pellets (~5mm) on beaches; 18, (Reddy *et al.* 2006) microplastics (≥10µm) on shorelines near ship breaking yards; 19, (Ng & Obbard 2006) Microplastics in surface waters and sediments (≥1.6µm). Red squares show distribution of microplastics (≥ 20µm) in intertidal sediments (Thompson *et al.* unpublished data). White dots show mega and macroplastic strandline surveys (Barnes 2002, 2005).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 8 Microscopic plastic in surface waters, collected with Continuous Plankton Recorder, revealed a significant increase in abundance when samples from the 1960s and 1970s were compared with the 1980s and 1990s ($* = F_{3,3} = 14.42, P < 0.05$). Global production of plastic overlain for comparison (APME 2006). Adapted from Thompson *et al.* (2004).

For Review Only

Table 1

Plastics Production, Recovery and Disposal in the U.S. in 2005 (thousands of metric tons). This Table was adopted from US EPA (2006). The data originated in reports of The American Plastics Council and includes net imports. Plastic from the construction and agricultural sectors are not included in these quantities.

	Generation of Plastics in MSW	Recovery	Discards
PET	2600	491	2109
HDPE	5355	473	4882
PVC	1491	0	1491
LDPE/LLDPE	5864	173	5691
Polypropylene	3636	9	3627
Polystyrene	2355	0	2355
Other	4982	355	4627
Total	26282	1500	24782

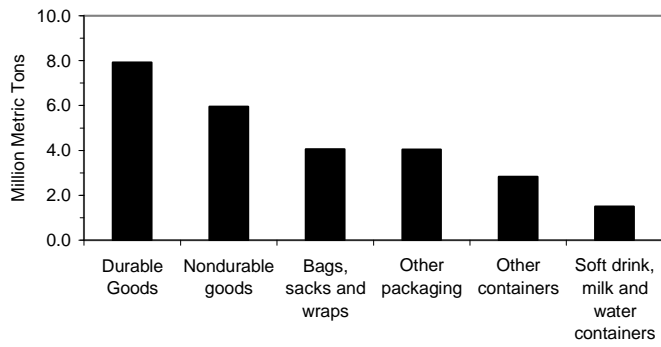
Table 2

Densities and proportion of plastics among benthic marine litter worldwide (per number of items). EA: Eastern Atlantic Ocean; M: Mediterranean Sea; B: Baltic Sea; N: North Sea; NP: Northern Pacific Ocean; WP: Western Pacific Ocean. T: trawling, PT: Pole Trawling.

Region	Sea	Method	Item/Ha	Plastic %	Reference
NA	Bay of Biscay	T	1.42+/- 0.25	62.2	Galgani <i>et al.</i> 1995a
M	NW Mediterranean	T	19.35 +/- 6.33	77.1	Galgani <i>et al.</i> 1995b
B	Baltic Sea	T	1.26 +/- 0.82	35.7	Galgani <i>et al.</i> 2000
NA	North Sea	T	1.56+/- 0.37	48.3	Galgani <i>et al.</i> 2000
NA	Channel East	T	1.17.6+/- 0.067	84.6	Galgani <i>et al.</i> 2000
NA	Bay of Seine	T	1.72 +/-0.058	89	Galgani <i>et al.</i> 2000
NA	Celtic Sea	T	5.28+/- 2.47	29.5 *	Galgani <i>et al.</i> 2000
SA	Rio de la Plata	T	0- 15.09	74	Acha <i>et al.</i> 2003
M	Greece, 59 sites	T	149	55.5	Katsanevakis & Katsarou 2004
M	Greece, Patras gulf	T	0.89-2.40	79-83	Stefatos <i>et al.</i> 1999
M	W & S Greece	T	0.72-4.37	55.9	Koutsodendris <i>et al.</i> 2008
M	Gulf of Lion	T	1.43+/-0.19	70.5	Galgani <i>et al.</i> 2000
M	East Corsica	T	2.29 +/- 0.72	45.8	Galgani <i>et al.</i> 2000
M	Adriatic Sea	T	3.78+/-2.51	69.5	Galgani <i>et al.</i> 2000
M	Sicily /Tunisia channel	T	4.01	75	Cannizarro <i>et al.</i> 1995
M	Oriental basin	P T	5.85 -161.98	37	Galil <i>et al.</i> 1995
NP	Kodiak Island, Alaska	T	0.11-1.47	47-59	Hess <i>et al.</i> 1999
NP	Oregon Coast	T	1.49	26*	June 1990
NP	Bering Sea	T	0.075 - 0.51	27=	June 1990
NP	Norton Sound	T	2.49	49 0	June 1990
WP	Tokyo Bay	T	2.70-5.50	40.1-41.6	Kanehiro <i>et al.</i> 1995
WP	Tokyo Bay	T	1.85-3.38	48.3-58.9	Kuriyama <i>et al.</i> 2003
WP	Eastern China Sea	T		<5	Lee <i>et al.</i> 2006
WP	South Sea of Korea	T		<10	Lee <i>et al.</i> 2006

Formatted

Figure 1



For Review Only

Figure 2

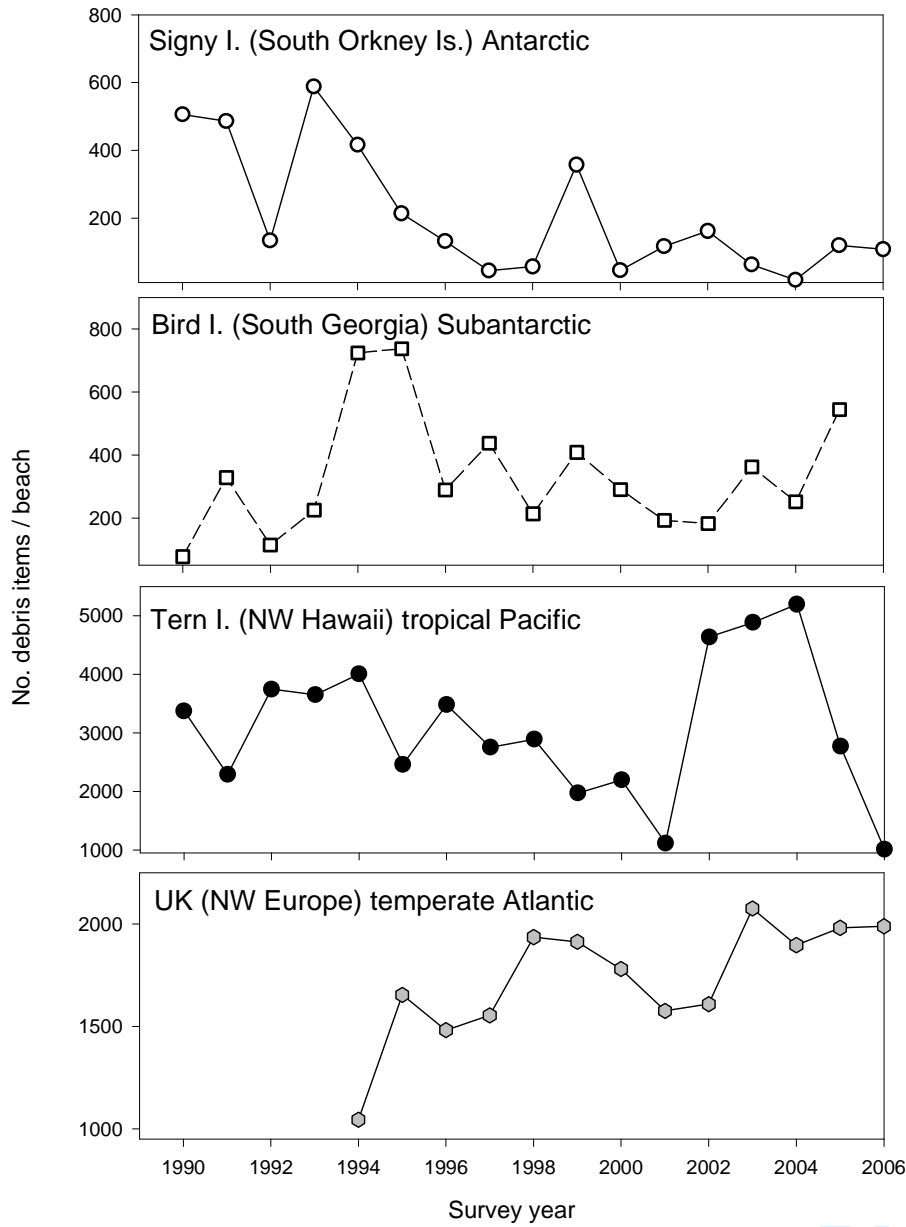


Figure 3

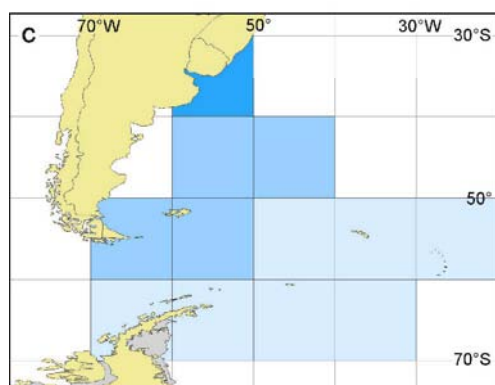
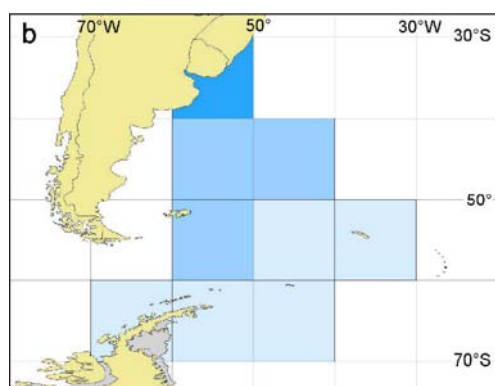
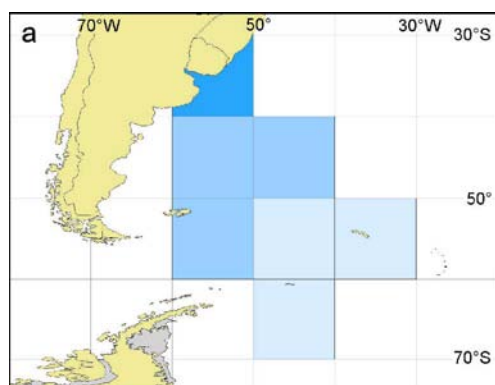
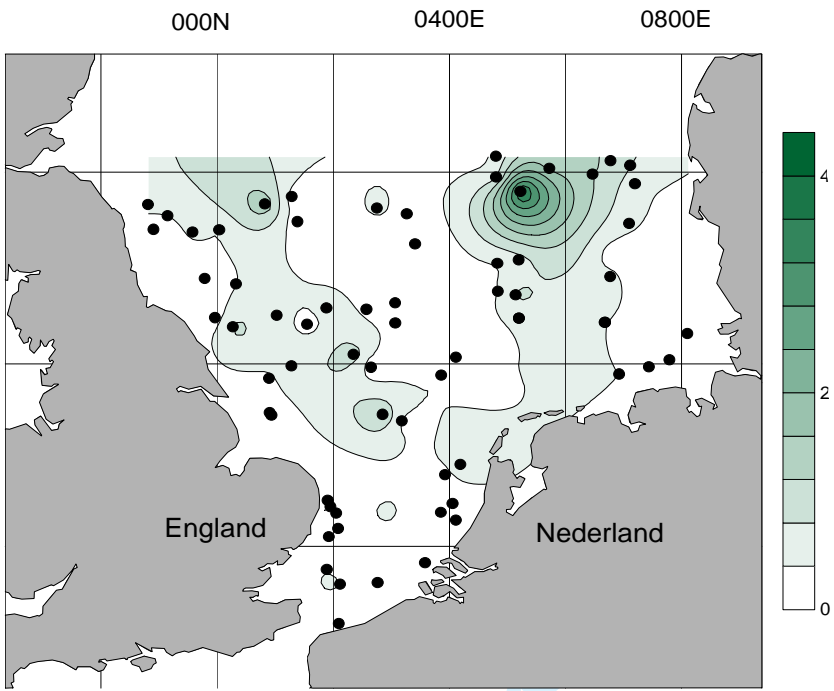


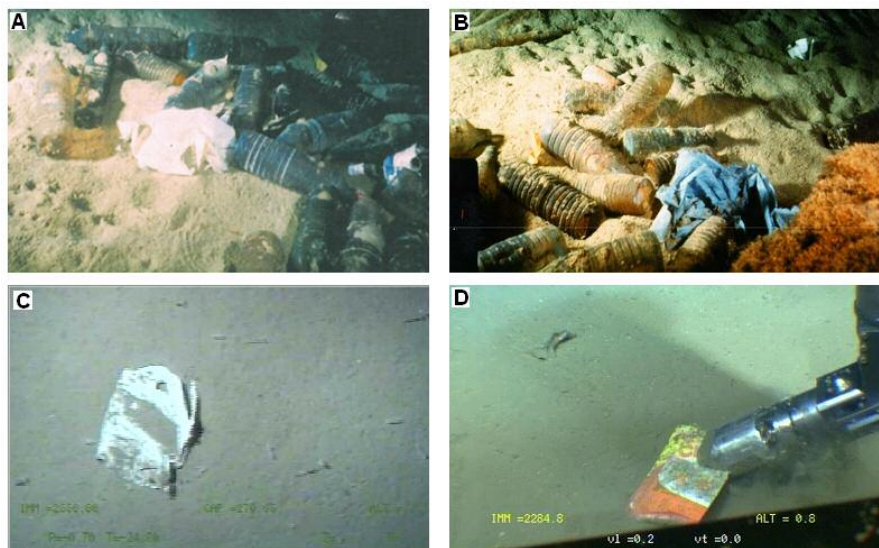
Figure 4



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Review Only

Figure 5



Or Review Only

Figure 6

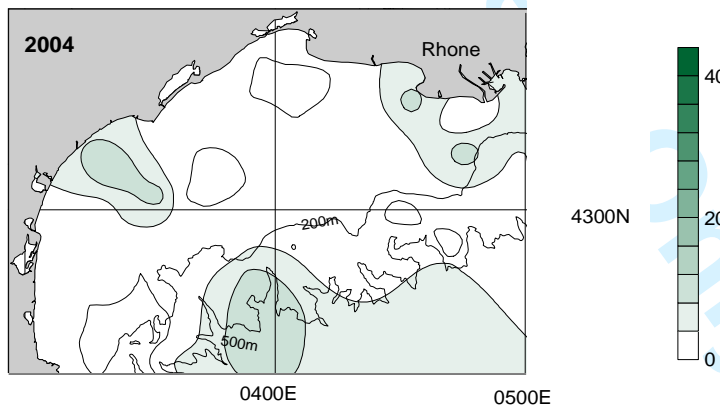
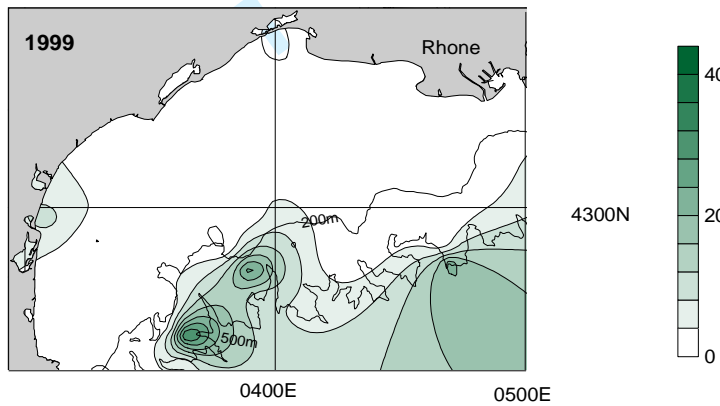
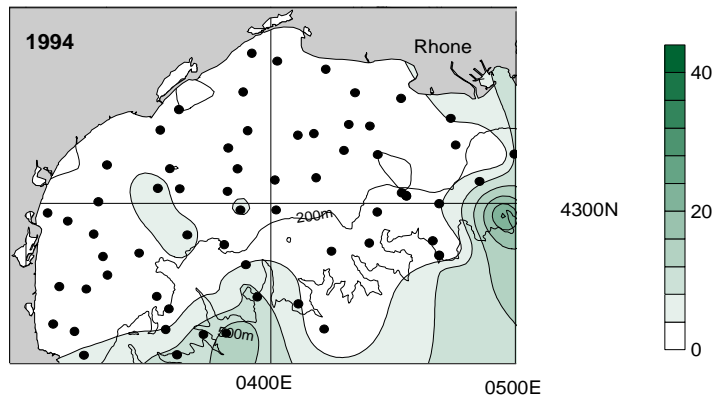


Figure 7

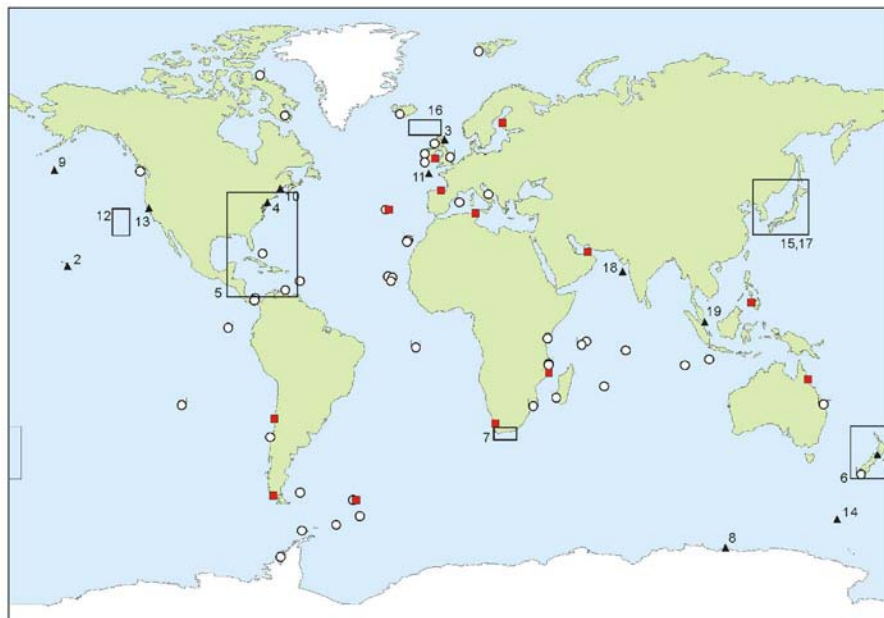
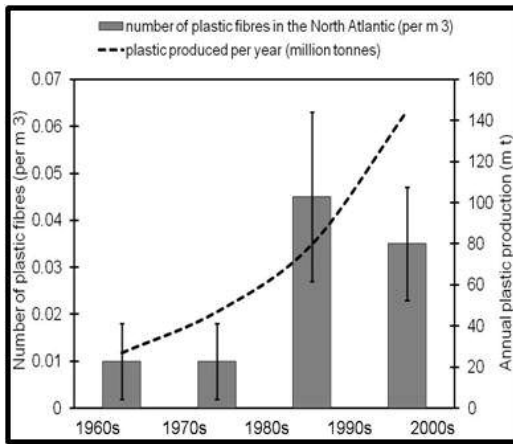


Figure 8



For Review Only