Plastics accumulation and monitoring efforts around the globe

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Introduction

Marine debris or marine litter is defined as any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment (UN Environment Program, 2009). The growing interest in understanding the movement, sources, fate and impact of marine debris are demonstrated by the increase in published litter studies in recent years. Much of this research to date, however, has focused on the impacts of litter on marine fauna around the world, with reports of litter interacting with species as small as plankton and as large as seabirds, dolphins and whales (Gall and Thompson 2014). While litter can interact with wildlife on land and in the coastal margins, researchers have more typically focused on litter in the oceanic environment. This litter has been observed in seas around the world, from high concentrations that are reported in the accumulation zones or gyres where floating plastic may exceed 600,000 pieces per km^2 (Law *et al.* 2010) to more remote regions such as the waters of the Arctic (Bergmann *et al.* 2015) and the Antarctic (Barnes *et al.* 2010) where fewer plastic pieces are observed. No matter where on the planet we are, evidence of human's discarded litter can be found, from the coastlines to the surface of the oceans and even the deep sea (Woodall *et al.* 2014).

There are numerous approaches to monitoring marine litter. Some of the more common methods include coastal clean ups and litter surveys, at-sea surveys of floating litter, seabed and sediment surveys, and quantification of litter ingested by marine fauna. Some of these monitoring methods yield direct estimates of litter, whereas others provide a more indirect assessment of the types, sources and amounts of litter. Understandably, given the sheer number of clean up activities around the world with different aims and goals in mind, there are myriad approaches currently underway. To date, there has been no single systematic, statistically-robust globally applied approach to monitoring marine litter, though there are numerous activities that take place regularly around the globe. The many clean up activities (some with associated datasets) that have been undertaken over the past decades have often evolved through time, as aims have shifted, priorities have re-aligned, and opportunities have presented themselves.

Currently, we know far more about the amounts, types, sources and distribution of litter on our coastlines than we do about the marine litter in the ocean. While coastal (and, indeed, inland) litter surveys have taken place for decades (through efforts such as Keep America Beautiful, Keep Australia Beautiful, the International Coastal Cleanup and others), it is only more recently that surveys have taken place in the open ocean and coastal marine environments. This may be at least partly due to accessibility and resources with respect to time and financial costs of surveys in the ocean. It may also be associated with the visual, olfactory and health aspects (e.g. aesthetics) of littering, which are more likely to be a point of focus on land than in the ocean.

In addition to coastal clean-ups and litter surveys, researchers use oceanographic modelling approaches to assess pathways of litter movement and to identify regions with high concentrations of plastic in the marine environment. Modelling can also be used map transport and accumulation regions for debris from tsunamis and other extreme weather events (Lebreton and Borrero 2013; Maximenko *et al.* 2015) and has been applied to predict the likely location of aircraft debris from drift modelling (e.g. the recent MH 370 aircraft and other aircraft wreckages; https://www.atsb.gov.au/publications/2015/mh370-drift-analysis.aspx).

Here we consider plastic accumulation and monitoring efforts that have taken place at a variety of spatial and temporal scales around the world. Specifically, in this report we emphasize modelling and monitoring of marine litter at local and regional scales. We examine data types and sources, from coastal and sea-surface sampling to seabed and sediment monitoring. We consider the value of both clean up efforts and systematic data collection. We identify regional hotspots for litter generation and deposition, and we identify priority actions and suggest pilot projects for further action. Finally, we discuss the value of a global harmonization of data collection approaches, suggest cross-cutting opportunities for collaboration and highlight the need for integrated monitoring efforts at appropriate geographic and temporal scales.

Monitoring marine litter

Plastics in the ocean come from both land and sea based sources, with approximately 70-80% estimated to come from land. Identifying sources, sinks and hotspots for litter relies upon sustained, consistent monitoring not only at coastal sites, but also on the surface of the ocean, through the water column, in the seabed and sediments, and, perhaps, in wildlife as well. As mentioned in other reports, plastics in the ocean can be considered to occur in five generally non-overlapping compartments. Marine debris and plastics can be found along the coastal margins, on or near the ocean surface (including the upper mixed layer), throughout the water column, on the seafloor, and in marine fauna. The physical and chemical processes acting on the plastics in each of the reservoirs are different, and the risks and opportunities for mitigation might also be very different.

Most of our understanding and surveys of marine litter comes from coastal clean-ups and land-based litter surveys. Aside from the coastline and the ocean's surface, there is a severe paucity in data on the amount of plastic in each of the compartments, and there is even less known about the fluxes of plastic between the compartments. Closing the global plastic budget will require large-scale, targeted sampling of all of the compartments. However, it may be possible to prioritize these investigations according to ease of sampling and likely important, based on our current understanding of their relative contribution to the total volume of plastic in the environment. We will consider coastal litter, floating plastic litter, water column, seabed and biota monitoring methods in the following sections.

Coastal litter surveys

It is now beyond debate that plastic debris is an important and growing source of pollution with numerous impacts. However, understanding the sources and trends of plastic remains difficult. Collection of data from surface sampling at sea remains limited, largely due to cost and most at-sea sampling is either sparse or geographically limited (e.g. Erikson *et al.* 2014). There are extensive coastal samples, largely from volunteer cleanup programs such as the International Coastal Cleanup (ICC), project AWARE's underwater litter surveys, as well as numerous local, regional, statewide and national efforts around the world. Many such projects have significant spatial and temporal coverage. However, they are typically focused specifically on debris removal and they often do not follow sampling designs that readily lend themselves to analysis.

Coastal litter surveys can provide valuable information about the types, quantities and sources of litter floating at sea, lost into the environment from the nearby areas and trapped within the coastal zone. They can also be a valuable mechanism for education and outreach and for building community understanding and engagement. Such surveys remain one of the easiest and most cost-effective means of providing an index of marine litter (Dixon and Dixon 1981, Merrell 1985). However, there are a number of different methodologies and approaches currently employed to identify, count, sort and quantify marine litter. While many methods have overlap or similarity in approaches, few collect or report information using a systematic statistically robust approach, in spite of the fact that decades ago, researchers pointed to the importance of standardization of survey methodologies (Ribic 1990).

Coastal litter surveys take place over different time frames, use variable methodologies, cover different spatial extents and data collection is often highly variable, particularly when involving volunteers or citizen scientists. Monitoring may occur idiosyncratically or on an annual, bi-monthly, weekly or even daily basis. Coastal surveys may either occur as part of clean up activities (in which litter is removed) or may take the form of 'standing stock' litter assessments whereby observed items are recorded but left in situ. The difference in survey approaches may be due to a number of factors. Often there is historical or legacy data so surveys continue in the same fashion as they had previously.

Some examples of coastal litter monitoring programs around the globe

It is not possible to fully describe every coastal litter monitoring that has occurred and currently takes place around the globe. Hence, we will include some long-standing examples from different regions. The International Coastal Cleanup (ICC) operated by the Ocean Conservancy, is an annual event which takes place in numerous countries. It is touted as the longest running coastal clean up anywhere in the world, with nearly 650,000 volunteers having collected approximately 6 million kilograms of trash in approximately 100 countries in 2013 alone. Their data collection and compilation methods have been systematically developed and integrated to quantify the results of marine debris and coastal removal efforts, and their efforts are largely supported through volunteer activities. While Ocean Conservancy's dataset has broad geographic representation and has been collected for nearly 30 years, there are missing data points. Some sites and regions are not represented every year and monitoring methods have been modified over time. Furthermore, some volunteers do not record all information and in some cases data have combined before they were submitted to Ocean Conservancy, thus losing spatial resolution and resultant statistical power.

In Korea there is a national beach monitoring program which was initially led by the Korea Marine Rescue Center and subsequently by the Korea Marine Environment Management Corporation in collaboration with volunteers who collect coastal litter. The project aims to collect data on the levels of marine debris pollution and identify litter sources. The 20 monitoring sites are well-distributed around the coastline (Figure 1). The Korean government has responded to the marine litter issue by investing in gear and litter retrieval programs and research projects since the 1990s. In 2008 the Marine Environment management Act was revised, providing the legal basis for management of marine litter. Without reliable scientific information on the sources, types, distribution and impacts of marine debris, however, identifying targets has been challenging. The implementation on consistent monitoring methods in Korea provides scientific information to inform policy and to make recommendations for identifying collection and treatment solutions for marine litter. The main aim of the program is to assess the level of beach debris pollution and to aid in identification of management priorities for coastal debris in Korea (Hong et al. 2014).

Fig. 1. Location of beach debris monitoring sites in Korea during the period 2008–2009.

Figure 1. Location of marine debris coastal monitoring sites in Korea. Figure taken from Hong *et al.* 2014; used with author's permission.

In the United States, addressing marine debris issues falls within the National Oceanic and Atmospheric Administration's mandate (NOAA). This government body is the US Federal government's lead program for addressing marine debris. The program has developed guidelines for coastal litter monitoring (http://marinedebris.noaa.gov/). They currently have two repeated survey long-term monitoring programs. One is a standing stock litter assessment survey method in which litter is observed, counted (but not removed), and the other is a repeated coastal survey method in which coastal debris is removed during surveys. However, the consistency and frequency of data collection amongst monitoring sites has been variable, and maintaining ongoing efforts will continue to require sustained funding (though this is something to which NOAA's national marine debris program is committed). The NOAA marine debris program also funds projects and has supported numerous outreach, education, and research projects since the program's inception in 2006.

In Australia, there is a national policy to address marine debris, and in particular its impact on threatened vertebrate marine fauna (the Federal Threat Abatement Plan, Department of the Environment 2009). As in many countries around the world, in Australia there are numerous volunteer clean up efforts and coastal care initiatives led by not-for profit groups such as Surf Rider Foundation, Tangaroa Blue, the Two Hands project, Take 3, Clean Up Australia and others. In addition, numerous state and councils host coastal debris clean up activities in addition to litter prevention and awareness raising campaigns. From these efforts, there was some information on debris along the coastline. However, there was no large-scale systematic dataset. In response to this need, a Commonwealth Scientific and Industrial Research Organization research team developed a statistically robust coastal survey method that was carried out nationally. Using this dataset analyses controlled for sampling bias to estimate the distribution of debris along the entire coastline of Australian continent (Hardesty *et al.*, 2014; 2015 in revision). The team also investigated factors influencing the contribution of terrestrial sources to coastal debris and make recommendations to reduce coastal litter.

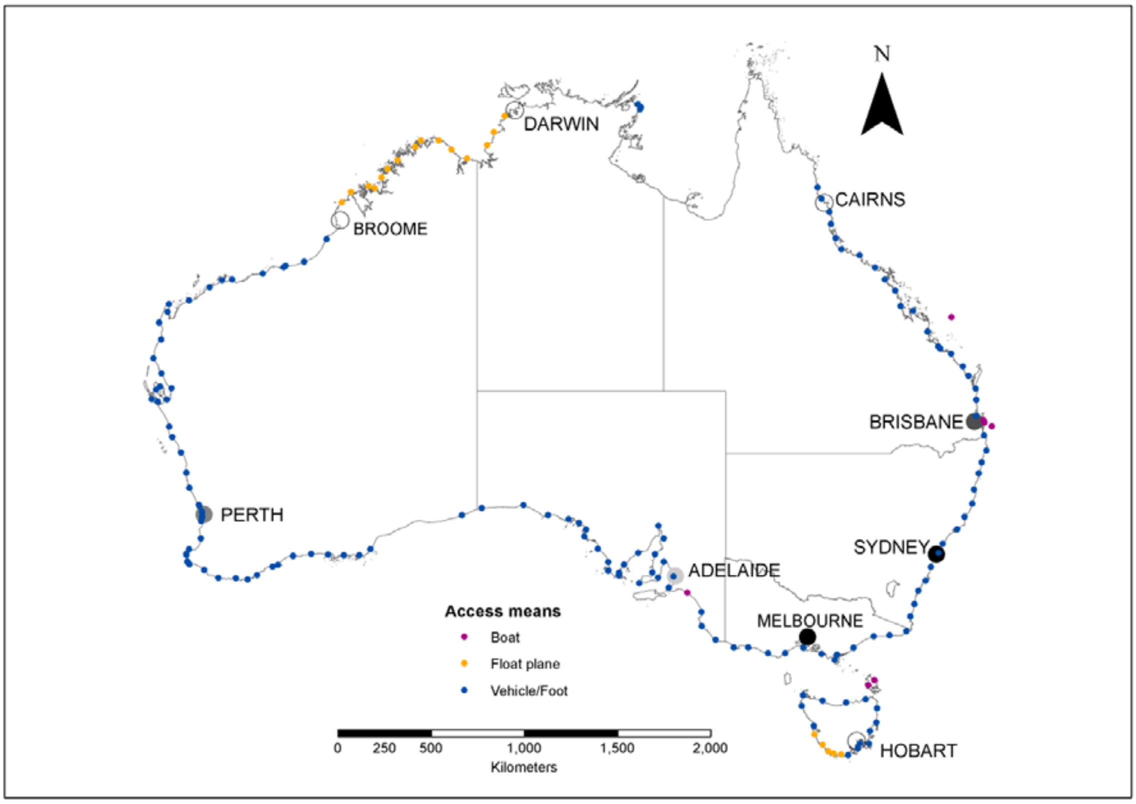

Figure 2. Map showing location and means of access to each CSIRO coastal debris survey site around mainland Australia and Tasmania.

In Europe, there is the Marine Strategy Framework Directive (MSFD, 2010/477/EU) which decrees that European Union Member States shall determine a set of characteristics that define Good Environmental Status (GES) of their relevant waters, based on a list of 56 indicators that include four indicators specific for marine litter (Descriptor 10). In addition, there are regional plans that have been adopted for the management of marine litter in most European waters with the idea to create frameworks for enhanced knowledge, monitoring and assessment, research, awareness and cooperation (see example below, OSPAR).

The OSPAR commission (Oslo/Parison Convention for the Protection of the Marine Environment of the North-East Atlantic; http://www.ospar.org/work-areas/eiha/marine-litter) has committed to reducing marine litter and protecting vulnerable species and habitats in the North-East Atlantic. There is a regional action plan on marine litter that has been developed (which addresses both land and sea based litter sources) and they will soon publish a marine litter plan (expected before the end of 2015). Within the OSPAR region, more than 250 surveys take place in coastal areas around Europe. Surveys follow a standard data collection protocol with information freely posted and available online. Such efforts and their continued existence is fundamentally important to identify trends and changes in litter types, amounts, and composition in coastal areas.

Figure 3. Beach litter survey sites where repeated monitoring takes place using consistent protocol. Map from OSPAR beach litter survey website (http://www.mcsuk.org/ospar/map).

In the NOWPAP region (East China, Korea, Japan and Far East Russia), monitoring efforts have also been underway. In this understudied region, a snap shot on marine litter was created from information collected at 82 beaches (2 in China, 20 in Korea, 53 in Japan and 7 in Russia) in 2009 (NOWPAP CEARAC, 2009).

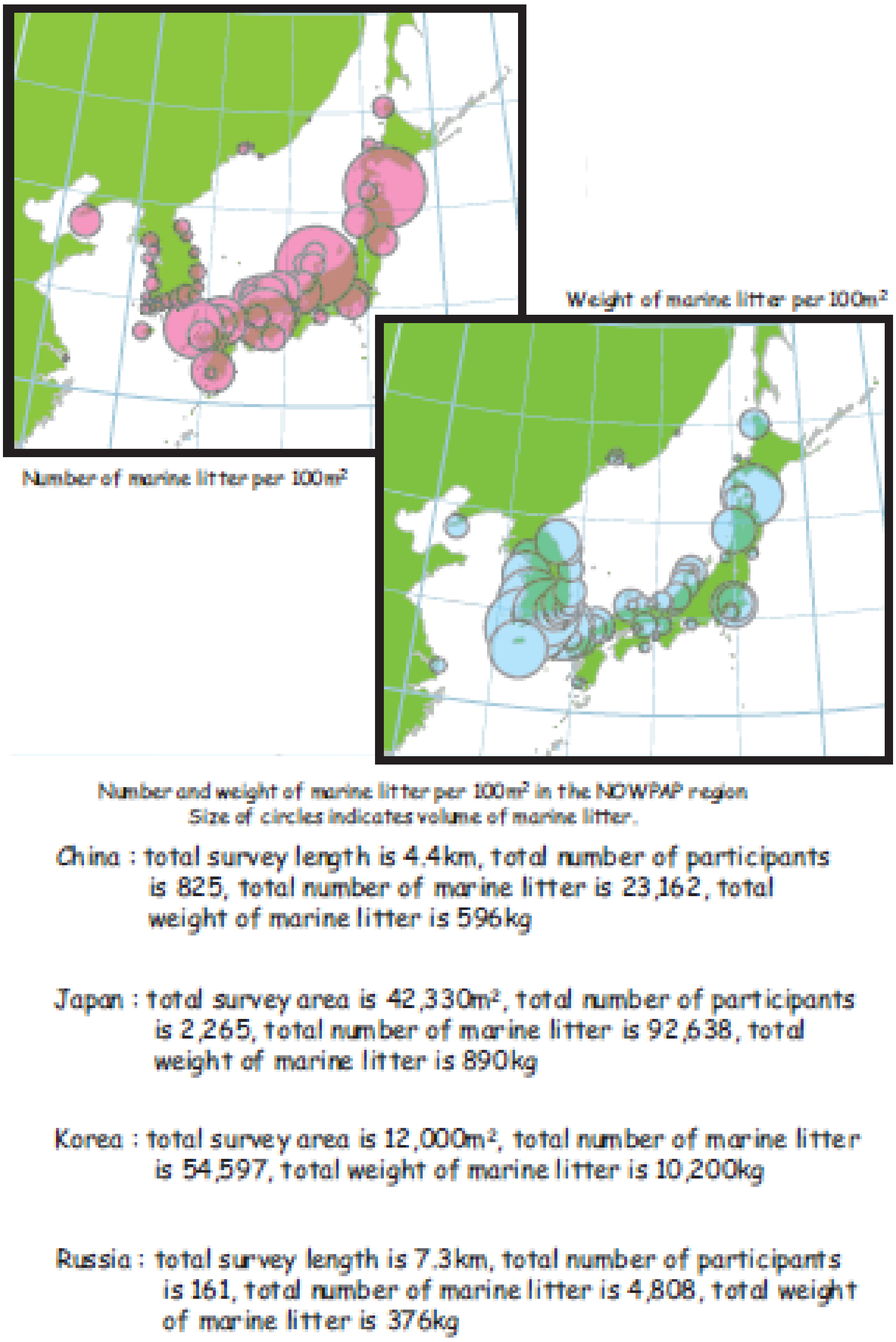

Figure 4. Figure showing the relative amount of marine litter at each member state, based on coastal litter surveys in the NOWPAP region. A summary of the total area surveyed and weight of litter collected is also provided. (NOWPAP CEARAC report, 2009)

In China, nationwide monitoring started in 2007 at beaches, on the sea surface, and at sea bottom sites from eastern to southern coastal areas. The number of sites has been increasing, offering snap shots of litter in multiple locations during different years. The results from the annual monitoring has been shared through 'Bulletin of Marine Environmental Status of China'. Furthermore, monitoring results from surveys carried out at nine beaches around the northern South China Sea in 2009 and 2010 was reported by Zhou *et al.* (2011).

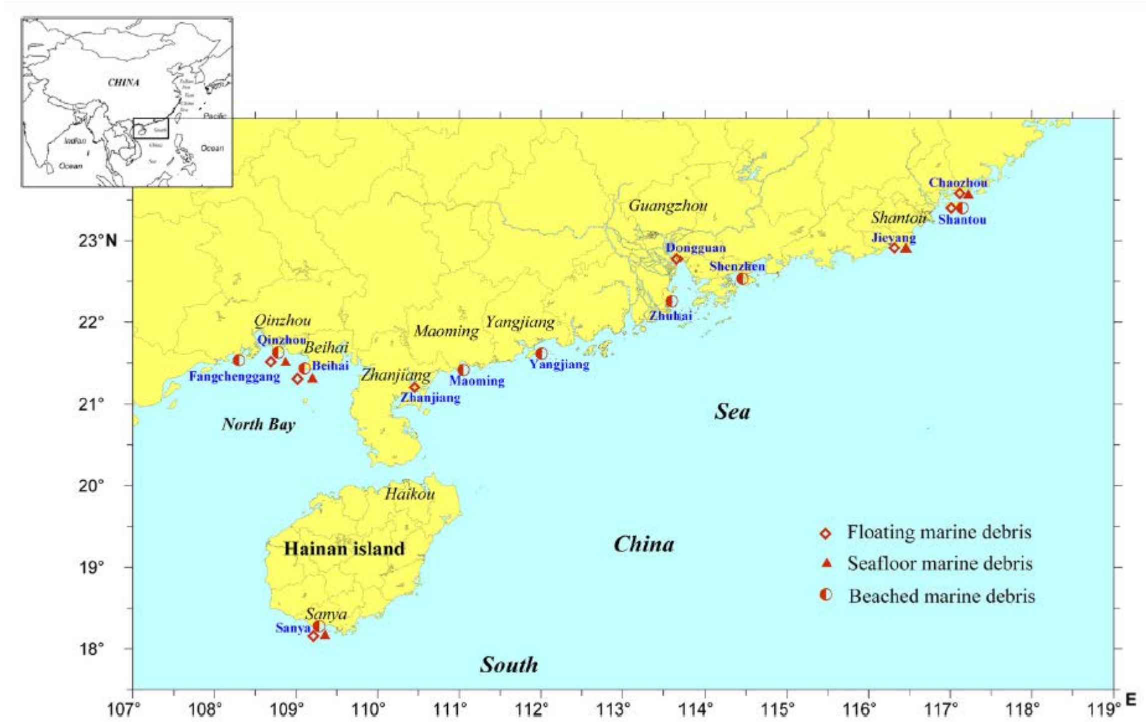

Figure 5. Survey sites in coastal China for floating, seafloor and beached marine debris (from Zhou *et al.* 2011)

In addition to the regions mentioned above, there are numerous other clean up efforts, litter prevention and reduction programs and surveys that take place idiosyncratically, optimistically and through well-organized programs around the world. To date, there are there are few global datasets available (but see the International Coastal Cleanup long term beach clean up efforts, ICC 2015), though there is great interest in global harmonization of survey methodologies and data collection.

Table 1. A summary of historical and recent surveys at multiple sites around the world, with the location and sample site, year of study, frequency of surveys, number of sites, whether carried out by citizen scientist volunteers or researchers, and reference(s). Adapted from Hong 2013).

Location Sample site	Year	Frequency (No. of surveys)	Sites (No.)	Citizen / Scientist	Reference
South Africa					
Central Transkei (local)	1994~ 1995	Monthly (13)	6	S	Madzena and Lasiak (1997)
South Atlantic					
South Georgia, Bird island (local)	1995	Monthly (6)	1	S	Walker *et al.* (1997)
Falkland island (local)	2002	Monthly (4)	1	S	Otley and Ingham (2003)
Macquarie island (local)	2001	Monthly (12)	1	S	Eriksson and Burton (2001)
Candlemas island (local)	1997	Monthly (1)	1	S	Convey *et al.* (2002)
North Atlantic					
Europe (international)	2001~ 2006	Seasonally (24)	51	C	OSPAR (2007)
Nova Scotia (Canada, local)	2005	Monthly (6)	1	S	Walker *et al.* (2006)
North Pacific					
NOWPAP (international)	2009	Once	82	C	NOWPAP CEARAC (2009) (cearac.nowpap.org)
Japan (local)	2004 ~200 5	Bimonthly (7)	3	S	Shimizu *et al.* (2008)
Japan (national)	2009	1~4	53	C	NOWPAP.org
Korea (national)	2008~	Bimonthly	20 (40 since 2015)	C	Hong *et al.* (2014)
China (national)	2007~	Once	14 (increase)	C	Hu (2010)
China (Taiwan, local)	2009~ 2010	Bimonthly	4	S	Liu *et al.* (2013)
	2012~ 2013	Seasonally	6	S	Kuo & Huang (2014)
South Pacific					
Australia (national)	2011- 2013	Once	560	S, C	Hardesty *et al.* (2014)

With respect to coastal litter surveys, much of the world's coastline remains unsurveyed. The monitoring that does take place or has been carried out, is often irregular, and there is a lack of consistency in data recorded, reported, and frequency of sampling. Particularly in difficult to access parts of the coastline, some areas, particularly remote islands, remain under-surveyed. There are however, some valiant efforts that have taken place in many areas which are difficult to access (e.g. remote pacific Islands, Alaskan islands, etc.) This is in part due to logistical difficulties, transport challenges and cost of access (much less litter removal). Furthermore, in many parts of the world there is simply not the infrastructure available to support coastal litter monitoring. Rivers and oceans in many areas are consistently and regularly used for dumping of waste.

Figure 6. Coastal community in Papua New Guinea, surveyed for coastal litter in 2015 © Sustainable Coastlines Papua New Guinea.

Monitoring floating plastic litter

Sampling methods are relatively well established for at-sea measurement of marine plastics, and there has been a recent explosion of publications reporting on how much plastic is in the marine environment, based on extrapolations from buoyant plastic litter monitoring. However, even in the 1970's floating plastic from sea-based surveys observed plastic densities of thousands of particles per km^2 (Ryan 1988; Figure 7). Larger items can and are typically sampled using visual surveys with observers recording objects detected from aboard ships of opportunity or research vessels (sensu Thiel *et al.* 2003; Eriksen *et al.* 2015; Ryan 2013; Hinojosa and Thiel 2009; others). These ship-based surveys can be used to provide quantitative estimates of densities, however there are numerous challenges that persist. In addition to the expense and logistics, given the expansiveness of the ocean and the human visual capacity for detection, visual shipboard surveys are unlikely to be feasible for large scale assessment for floating litter at a global scale. Furthermore, there remain issues with combining estimates across surveys due to differences in observability and other factors (Ryan 2013).

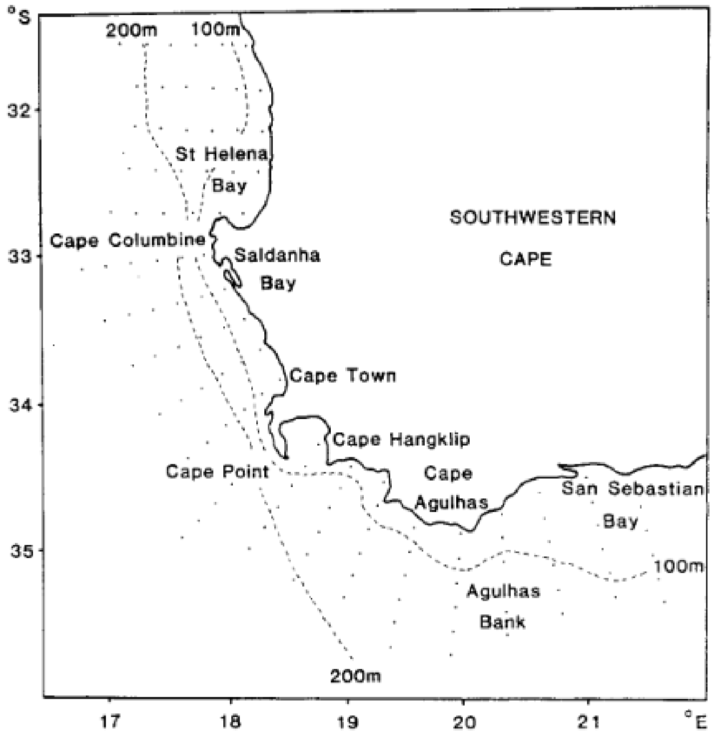

Fig. 1. The study area, showing the sampling grid, the localities mentioned in the text, and 100 m and 200 m isobaths.

Figure 7. from Ryan 1988 depicting trawl survey locations and local isobaths for 1224 neuston trawls carried out in 1977-1978. Note the grid layout for surface tows.

Smaller debris (e.g. microplastic) has generally been sampled using various types of surface nets which were developed for other purposes (e.g. Cozar *et al.* 2014; Eriksen *et al.* 2014;

Galgani *et al.* 2010, Law *et al.* 2010, Reisser *et al.* 2013; 2014; others). These methods were relatively well established and standardized prior being applied to sample marine debris. As a result, there has been a reasonable measure of success in combining measurements across surveys for analysis (e.g. Cozar *et al.* 2014, van Sebille *et al.* 2015). Again, however, given the vastness of the ocean, the cost of operation and large distances involved, floating plastic litter surveys are often limited to particular regions and there are significant gaps in the global coverage of such surveys.

Some examples of sea-surface monitoring programs around the globe

One of the largest floating plastic litter datasets has been collected by the Sea Education Association (SEA; http://www.sea.edu/plastics). This organization runs a program that combines educational opportunities for students with data collection for surface microplastics (among other activities). The 25+ year data set of plastic counts for more than 7500 surface tows is the longest standing monitoring of ocean plastics. The results from these efforts have been fundamental in informing the global discussion on surface plastic debris (Law *et al.* 2010; Law and Thompson 2014; van Franeker and Law 2015; others). The program continues to collect data based on voyages that continue to take place each year.

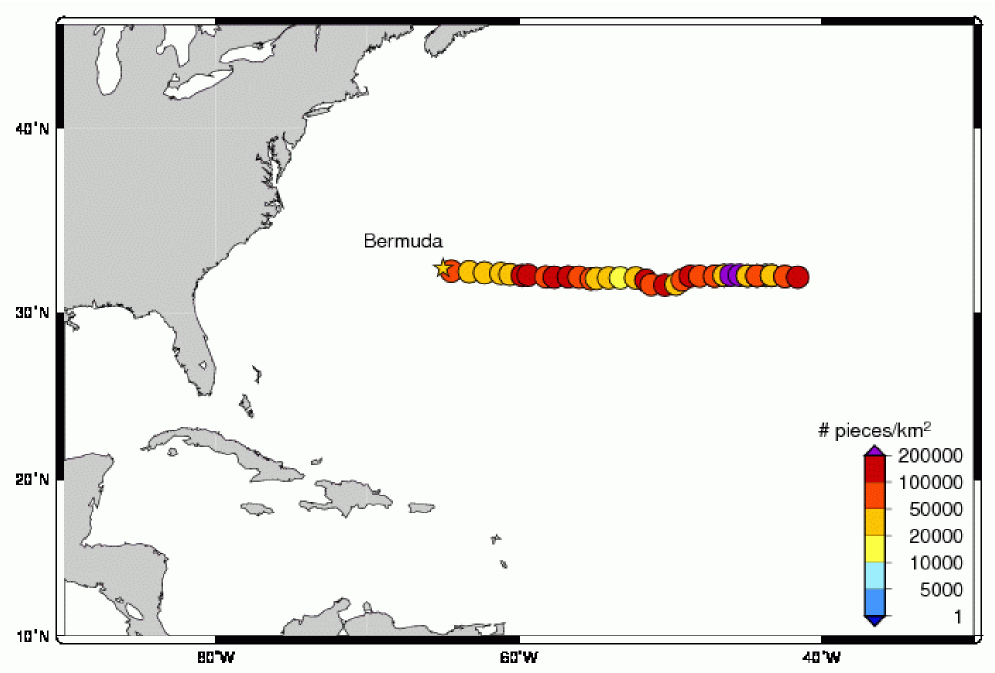

Figure 8. Surface tow samples from near Bermuda in 2010 indicating very high plastic concentrations; from SEA website (http://www.sea.edu/plastics2010/science-results6-21.htm)

In 2010, the Spanish government supported the Malaspina circumnavigation expedition. This interdisciplinary research endeavour set out to assess global change, explore biodiversity, promote marine science and raise interest in marine sciences. During the expedition, researchers collected floating plastic debris from surface trawls. Results from the expedition found concentration of plastic debris in surface waters of the global ocean to be less than expected, but the researchers pointed out both potential sampling bias resulting in loss of small particles and identified a gap in the size distribution reported for floating plastic debris (Cozar *et al.* 2015). Metadata are available for public and authorised users (http://scientific.expedicionmalaspina.es/#!/n/malaspina-digital/s209).

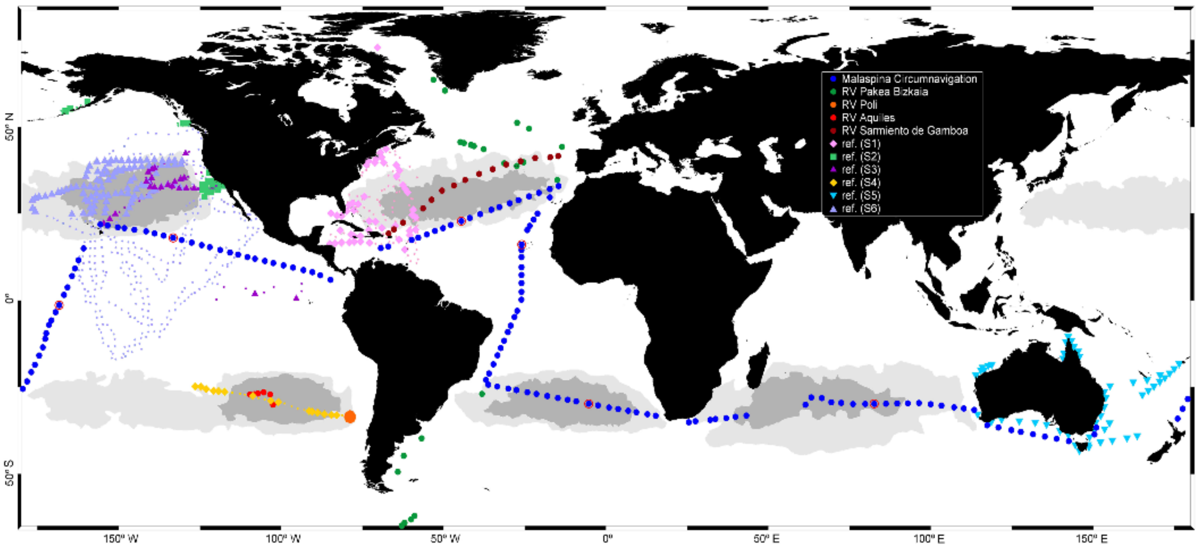

Figure 9. from Supplementary Information in Cozar *et al.* 2015). Spatial distribution of data by sources. Figure legend indicates the vessel for the original data and the bibliographic reference for the datasets published. Large solid symbols show wind-corrected data (442 grid cells, 1127 surface net tows). Small dots show literature data classified as affected by high wind conditions and not included in the wind-corrected dataset (409 grid cells, 1943 surface net tows). Sampling sites where size distribution of non-plastic particles was measured are marked with red circles.

The Algalita Research Foundation, founded by Captain Charles Moore also has a long term monitoring program that has been focused on plastic pollution, particularly in the 'Great Pacific Garbage Path'. Expeditions have taken place to survey floating plastic in this accumulation region since the late 1990s. Researchers there are evaluating the long term trends and changes in floating plastic pollution with current and future monitoring expected to continue (Eriksen *et al.* 2015).

Numerous other monitoring efforts and surveys of the ocean's buoyant plastics have taken place over the last several decades from surveys in South African waters (Ryan 1988) and the Antarctic (Barnes *et al.* 2010) to the Artic (Bergman *et al.* 2015) and in between. Harmonizing approaches to data collection and continued sharing of datasets and international collaboration will clearly be an important means of increasing knowledge as well as for identifying target areas for remediation and source reduction.

Recent synthesis

Greater emphasis is increasingly being placed on the value of combining data from multiple survey and/or monitoring programs (sensu Cozar *et al.* 2015; Eriksen *et al.* 2015) and even in comparing model solutions (e.g. van Sebille *et al.* 2015). Recently, van Sebille and colleagues (2015), compared estimates of microplastic abundance and mass using a rigorous statistical framework and empirical surface trawl data. The authors standardized a large global dataset of plastic marine litter based on surface surveys of more than 11,000 samples. They also compared the three ocean circulation modelling approaches of Lebreton *et al.* (2012), Maximenko *et al.* (2012) and van Sebille *et al.* (2014), using each to estimate the global standing stock of small floating plastic litter. Importantly, they resolved sampling biases and other variations by applying a statistical model to standardize the dataset to appropriately scale the three model solutions. They compared where the models converge and identify regions where discrepancies need to be resolved between the modelling approaches. This provides an important step forward in considering variations in model solutions and identifying under sampled regions where further research efforts can improve global estimates of floating litter stocks.

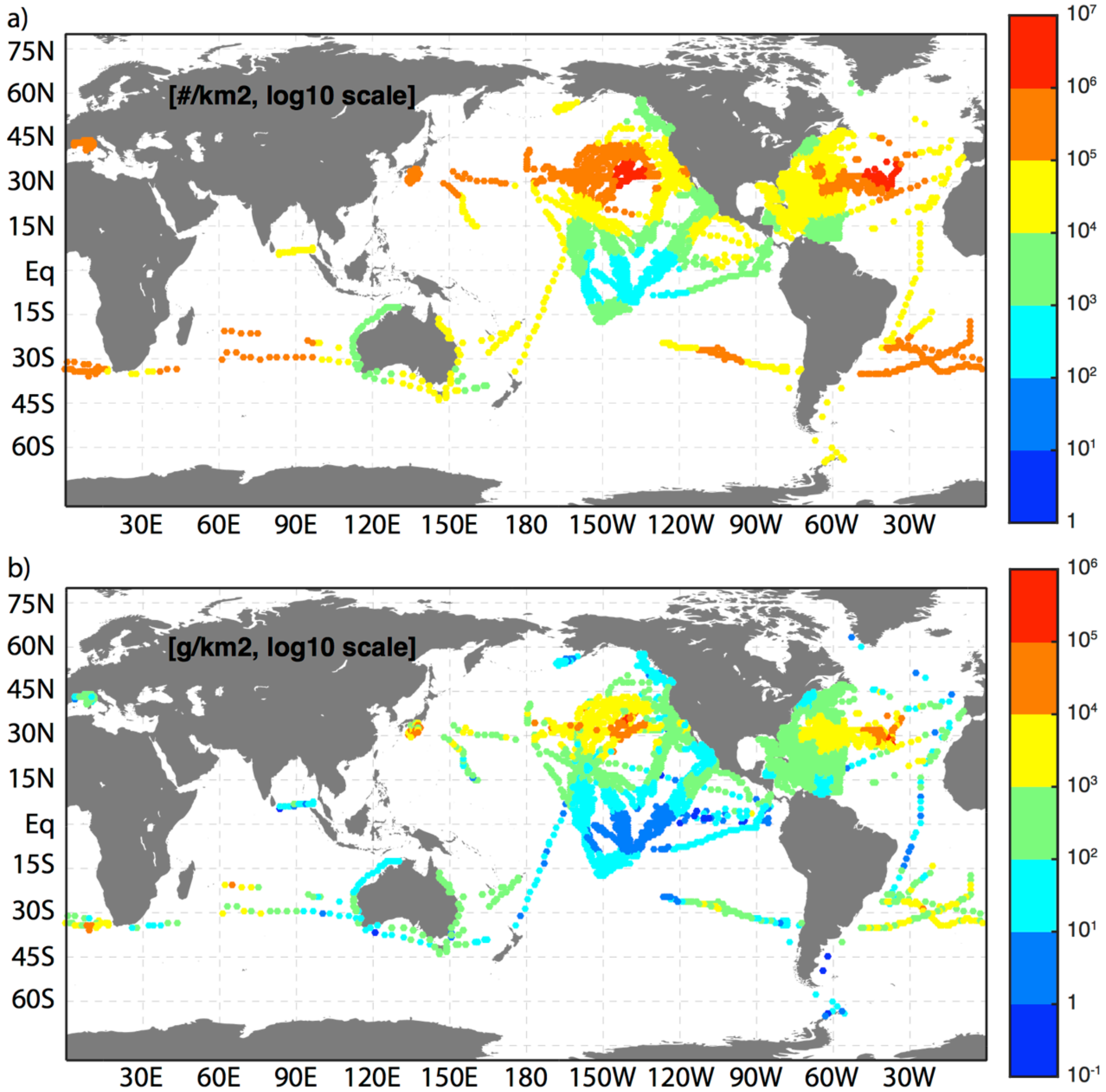

Figure 10. Re-printed from van Sebille *et al.* (2015). The location and standardized (a) microplastic count and (b) microplastic mass of all surface trawl data used in this analysis, on a log10 scale. Standardization is done with respect to year of study, geographic location, and wind speed. The spatial term includes a discontinuity at the Americas to allow for differences between the Caribbean Sea and tropical Pacific Ocean.

Water column surveys

Our understanding of plastic litter in the water column remains a tremendous knowledge gap. To date, few have surveyed the vertical distribution of plastics throughout the water column, with most monitoring taking place at the surface or within the upper 5-10 m (sensu Reisser *et al.* 2015). Lattin and colleagues (2004) carried out monitoring at three depths in coastal California, where they surveyed the ocean surface (using a manta net, mid-depth (using a bongo net) and bottom samples with an epibenthic sled. The authors observed that the density of anthropogenic litter was greatest near the bottom of the ocean’s surface, with the least debris detected in mid-water surveys. In general, an improved understanding of the vertical transport and movement of plastics between ocean compartments is needed to improve estimates of the size distribution, concentration and missing stock of plastics in the ocean (Kukulka *et al.* 2012, Law *et al.* 2014, Isobe *et al.* 2014).

Seabed surveys

Surveying the deep ocean is notoriously difficult and expensive and there are numerous monitoring methods that have been used to date. Survey methods known to be useful include those that have utilized bottom trawl nets such as those used in fisheries, imaging technologies such as ROVs, manned or unmanned submersibles, towed camera systems, or scuba diving enthusiasts (e.g. Project Aware; www.projectaware.org). Due to the inherent difficulties of sampling at depth, no large-scale global assessment of the distribution and densities of sunken litter has been undertaken. However, numerous regional monitoring efforts have taken place, with a recent boom of information available in the scientific literature in the last decade (see review of monitoring from 1999 onwards in Pham *et al.* 2014). A comprehensive review of monitoring methods for evaluating debris on the seabed can be found in Galgani and Andral (1998).

Logically, plastics with a density that exceeds that of seawater (>1.02 g cm^3) will sink and accumulate in the sediment, while low-density particles tend to float on the sea surface or in the water column. If 70% of plastics are known to eventually sink (Barnes *et al.* 2009), increased monitoring the ocean floor is clearly essential. It has been suggested, however, that even low-density plastics can reach the seafloor.

Examples seabed and sediment monitoring around the globe

Microplastics have been reported in marine seabeds and sediments worldwide (Claessens *et al.* 2011, Galgani *et al.* 2000, van Cauwenberghe *et al.* 2013a and 2015, Phram *et al.* 2014, Woodall *et al.* 2015) but the first report in subtidal sediments date back to 2004 (Thompson *et al.* 2004). Deep sea sediments have been demonstrated to also accumulate microplastics (van Cauwenberghe *et al.* 2013a; 2015, Woodall *et al.* 2015) with composition that appears different from surface waters. Interestingly, fibers were found at up to four orders of magnitude more abundant in deep-sea sediments from the Atlantic Ocean, Mediterranean Sea and Indian Ocean, than in contaminated sea-surface waters (Woodall *et al.* 2015). Sediments are suggested to be a long-term sink for microplastics (Cozar *et al.* 2014; Eriksen *et al.* 2014; Woodall *et al.* 2015).

Based on sediment surveys, Vianello *et al.* (2013) detected the lowest microplastic concentrations where water currents are higher (Venice Italy, outer lagoon, >1 m s^1) than in the inner Lagoon, which is characterized by lower hydrodynamics and had higher fine particle (<63 mm) fraction in the sediment.

Known seabed areas with high deposition loads of anthropogenic litter include harbor sediments (Claessens *et al.* 2011), reaching up to 391 micro plastics/kg of dry sediment. Similarly, In Slovenia (Bajt *et al.* 2015), concentrations were found between 3 and 87 particles per 100g generally with coastal areas more affected. Seamounts (Woodall *et al.* 2015) and shipping lanes (Stefatos *et al.* 1999) are also reported as having higher litter loads. More work to date has focused on continental shelves (Barnes *et al.* 2009) and deep sea mounts (Woodall 2015) than other deep sea areas.

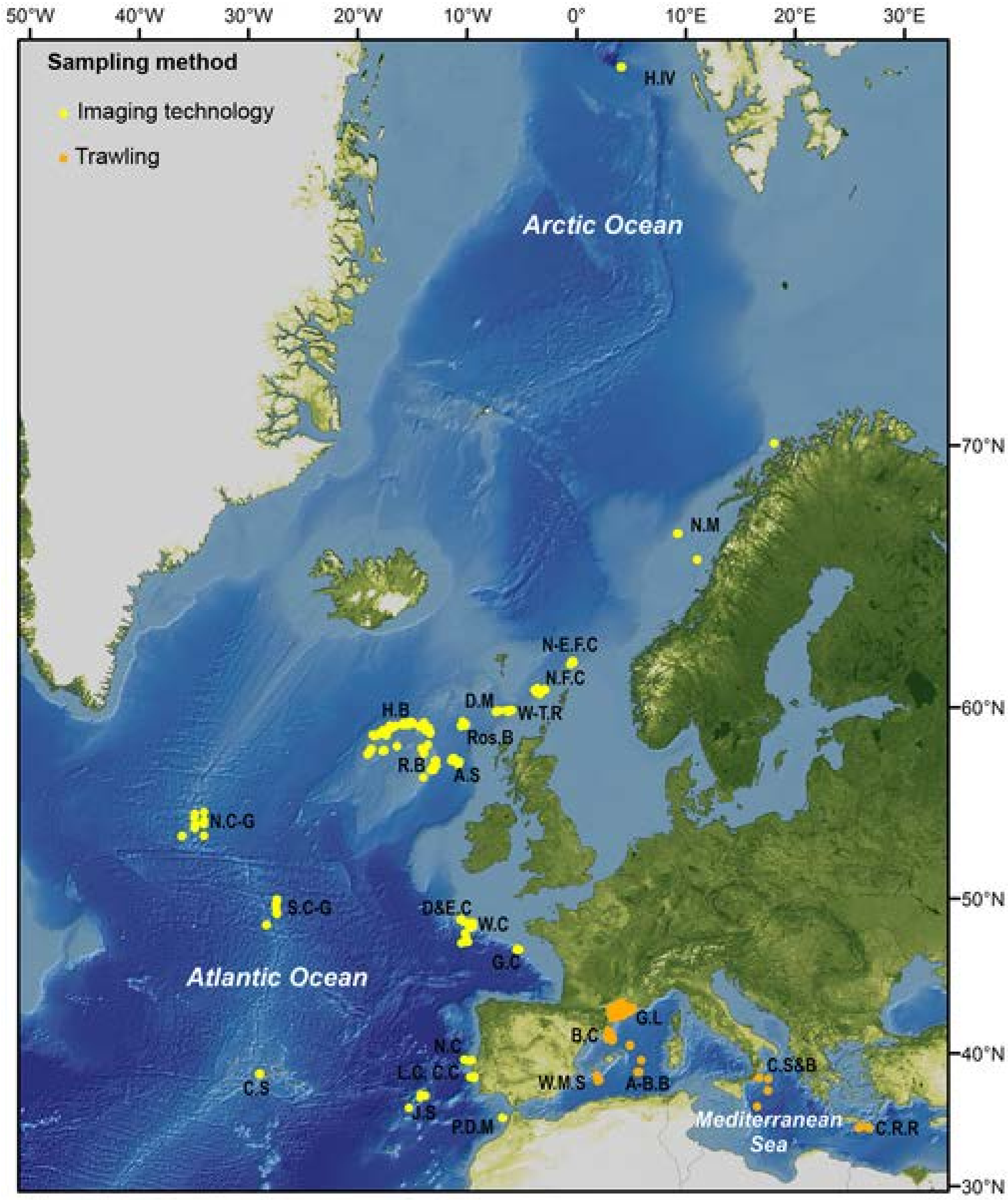

Figure 11. Reprinted from Phram *et al.* 2014 DOI: 10.1371/journal.pone.0095839. Locations of the study sites sampled with imaging technology (ROVs, manned submersible, towed camera systems) and trawling.

A-B.B = Algero-Balearic Basin (W. Med.), A.S = Anton Dohrn Seamount, B.C = Blanes Canyon (NW Med.), C.C = Cascais Canyon, C.S = Condor Seamount, Calabrian Slope & Basin = C.S&B, Crete-Rhodes Ridge = C.R.R, D&E.C = Dangeard & Explorer Canyons, D.M = Darwin Mounds, G.L.C = Gulf of Lion canyons (NW Med.), G.L = Gulf of Lion, G.C = Guilvinec Canyon, H.B = Hatton Bank, H.IV = HAUSGARTEN, station IV, J.S= Josephine Seamount, L.C= Lisbon Canyon, N.C = Nazaré Canyon, N.C-G = North Charlie Gibbs Fracture Zone, N-E.F.C = North-East Faroe-Shetland Channel, N.F.C = North Faroe-Shetland Channel, N.W= Norwegian margin, P.D.M = Pen Duick Alpha/Beta Mound, R.B = Rockall Bank, Ros.B = Rosemary Bank, S.C = Setúbal Canyon, S.C-G = South Charlie Gibbs Fracture Zone, W.C = Whittard Canyon, W.M.S = Western Mediterranean slope, W-T.R = Wyville-Thomson Ridge.

Between 1992 and 1998, a research team sampled the continental shelf and slopes along major European seas during nearly thirty oceanographic cruises. They found high geographic variation in concentration and types of litter items, though plastic was the dominant material type of items (comprising 70% of all items found) (Galgani *et al.* 2000). Due to the multi-year monitoring program and geographic expanse of the study, researchers were able to identify spatial and temporal trends, as well as detect the influence of local activities, geomorphologic factors and riverine inputs (Galgani *et al.* 2000).

Stefatos and colleagues (1999) have also reported on marine debris detected during seafloor surveys in Western Greece. The high percentage of beverage containers detected during their surveys they attributed to ship-based traffic, with packaging items attributed to land-based sources.

The Arctic is an area with low human population density and accordingly, there are reduced local inputs to the ocean within the region. Nonetheless, even in this remote region, significant densities of debris have been found on the deep sea floor (Galgani and Lecornu 2004) and microplastics have been detected in polar ice (Obbard et al. 2014).

In addition to the monitoring methods mentioned above, other approaches have been applied to gain insight to the density and distribution of seabed litter. For example, the "Fishing for Litter" project in Dutch waters has collected more than 500 tonnes of debris between 2000 and 2006. Debris items of note have included tyres, refrigerators, packaging material, lost shipping items, fishing gear, ropes, and many other items (Hammer *et al.* 2012, KIMO 2010). In addition, the Korean government recently supported the removal of derelict fishing gear of the seabed of the East Sea. Fishers employed bottom trawling with heavy hooks and ropes to removal deep sea litter. In 2009 and 2010, 208 and 252 tonnes of marine debris (respectively) was removed – most of which was derelict fishing gear (Cho 2011).

In the Mediterranean Sea and within the European Data Collection Framework (DCF), the MEDITS survey programme (International Bottom Trawl Survey in the Mediterranean; http://www.sibm.it/SITO%20MEDITS/principaleprogramme.htm) intends to produce basic information on benthic and demersal species in terms of population distribution as well as demographic structure, on the continental shelves and along the upper slopes (80-800 m) at a global scale in the Mediterranean Sea through systematic bottom trawl surveys and using a common, standardized sampling method and protocols. The last version (seven) of the protocol has incorporated a common standard for the voluntary collection of data on marine litter, in agreement with the requirements of the MSFD and the Barcelona

Convention Regional Action Plan on marine litter. This will facilitate the organization and collection of data on a regular basis and will provide assessments of litter at the basin scale. To date, 1280 sampling stations are considered, covering mostly (but not only) the European coastline and there remains the potential to extend to the wider basin region. As an example, Figure 12 (below) provides results from the Gulf of Lion where monitoring initiated in 1994, thus enabling the evaluation of trends through time. Analyses of these data demonstrates the absence of a change in quantities of plastics during the surveyed period.

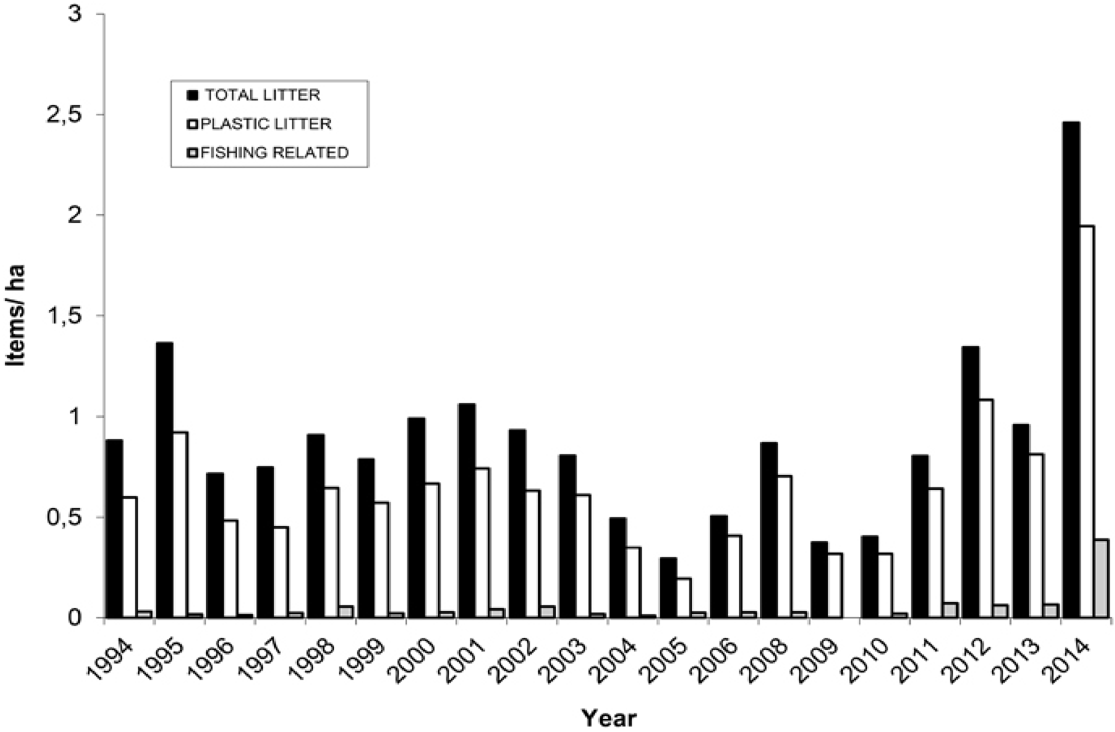

Figure 12. The density of litter collected on the sea floor between 1994 and 2014 in the Gulf of Lion, Mediterranean Sea. Litter (mean values for 70 sites) was collected during the Mediterranean International Bottom Trawl Surveys (MEDITS) cruises dedicated to fish stock assessments using a stratified sampling scheme and 20 mm mesh. The protocol can be found at http://www.sibm.it/SITO%20MEDITS/principaleprogramme.htm. Results are expressed as items/ha. Figure used with permission from Galgani 2015; http://dx.doi.org/10.3389/fmars.2015.00087.

Identifying regional hotspots for litter generation, pathways and deposition

The recent Science paper by Jambeck and colleagues (2015) reported litter inputs from land to the sea based on estimates of waste mismanagement from 192 countries around the world. The top countries ranked by mass of mismanaged plastic waste were expected to occur in China, Indonesia, the Philippines, Vietnam and Sri Lanka (Jambeck et al. 2015) while accounting for over 50 per cent of the total coastal input of marine litter. In Asia and other parts of the world, emerging nations that have benefitted from rapid growth in GDP, improved quality of life, reduced poverty and significant increase of consumer goods demand, did not always meet modern standards in waste management infrastructure and policies. However, there has not been a consistent long-term monitoring effort in these regions.

One means of identifying regional hotspots for litter generation and deposition is to develop dispersal models that simulate marine litter trajectories in the ocean. Debris are represented by particles that are continuously released from source locations. The source distributions are computed using proxies such as levels of waste generation per inhabitant as presented by Jambeck et al. (2015). Using data on waste management infrastructure and population density for identified regions of interest, Lagrangian particles release scenarios were created for:

- China,
- Japan, North Korea, South Korea and Russia
- Southeast Asia,
- Australia and the South Pacific region,
- The Pacific coastline of North and Central America,
- The Atlantic coastline of North and Central America (including the Caribbean),
- West Africa,
- East Africa,
- India, Bangladesh, Sri Lanka and the Arabic Peninsula, and
- Western and Northern Europe.

Figure 13 shows the mass of mismanaged waste generated per inhabitant and per day in the regions of interest. The average quantities range in average from 5 grams per person and per day in Europe to 92 grams per person and per day in China.

Figure 13. Average mismanaged waste generation per inhabitant and per region of interest (adapted from Jambeck et al, 2015)

In this framework, the contribution to marine litter input of an individual region is function of its coastal population density. The population living within 50 km of the shoreline represents above 260 million people in China and around 400 million people in Southeast Asia. This is highly reflected in the estimate of total mismanaged waste production in these two areas compared to the rest of the regions of interest (Figure 14).

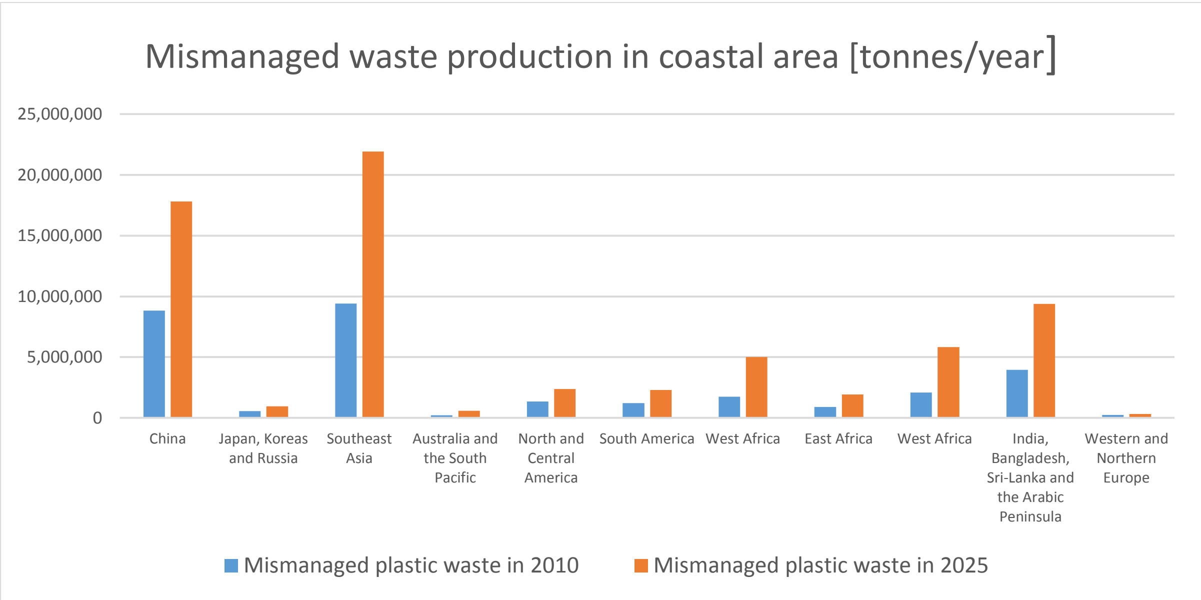

Figure 14. Total mismanaged waste production per year in regions of interest for 2012 and 2025 (adapted from Jambeck et al. 2015)

Data on population density and growth rates from the IPCC scenario SRES B2 (Yetman *et al.*, 2004) was extracted to produce the particle source distributions. Modelled particles are continuously released in the ocean and advected using several environmental forcing terms such as sea surface current, sea surface wind and wave induced stokes drift. For this simulation, wind forcing was considered equal to 0.5% of sea surface wind speed (windage coefficient) representing debris with roughly 98% of its frontal cross area emerged in water.

The sea surface current were sourced from a 2004-2014 composite database of model outputs from the data-assimilating and eddy resolving HYCOM 1/12° reanalysis (experiment 19.0, 19.1, 90.9, 91.0 and 91.1, Cummings and Smedstad, 2013, Cummings, 2005, Fox *et al.*, 2002) distributed by the Naval Research Laboratory (NRL) of the US Navy. Wind speed and direction data were sourced from the 1948-present NCEP/NCAR global reanalysis (Kalnay *et al.*, 1996) distributed by the Earth System Research Laboratory (ESRL) of NOAA. Finally, wave induced stokes drift was calculated using wave spectrum bulk coefficients from Wavewatch3 model outputs (Tolman, 1997) sourced from the NCEP Climate Forecast System Reanalysis (CFSR) and NOAA Marine Modelling and Analysis Branch (MMAB).

Marine litter pathways are represented by modelled particle trajectories. Each trajectory is linked to a source origin (region, country and city) and a date of release. A stochastic analysis of particle trajectories, densities but also ages allows to better understand dispersal dynamics for individual regions. Three types of metric are reported:

- The frequency of particle visits per model cells as a percentage of total particles describing zones of high chances of occurrence and deposition of marine litter.
- The minimum age of a particle that visited a model cell depicting how fast marine litter can spread from its origin.
- The average age of particles contained per model cells from 0 to 10 years showing time scale dependencies and movement of marine litter masses in time.

China

China, with 260 million of its citizens living within 50 km of the coast, contribute to over a quarter of the estimated global amount of mismanaged plastic waste entering the ocean in 2010 with 1,323 to 3,528 thousand tonnes of plastic marine litter generation per year (Jambeck, 2015).

Modelled particle frequency and travel time analyses are depicted in Figure 15. The dispersal model suggests that particles released from China are mainly found around the country's shoreline in the Yellow Sea and in the East and South China Seas but also in the North Pacific convergence zone indicating that the fate of marine litter originated from China is eventually far offshore. Model particles can travel to the edge of the Kuroshio Current, along the coast of Japan within six months and then enter the eastern part of the North Pacific Ocean within one year. Depending on the season and prevailing winds, the model shows that marine litter can also enter the Gulf of Thailand and the Java Sea within one year.

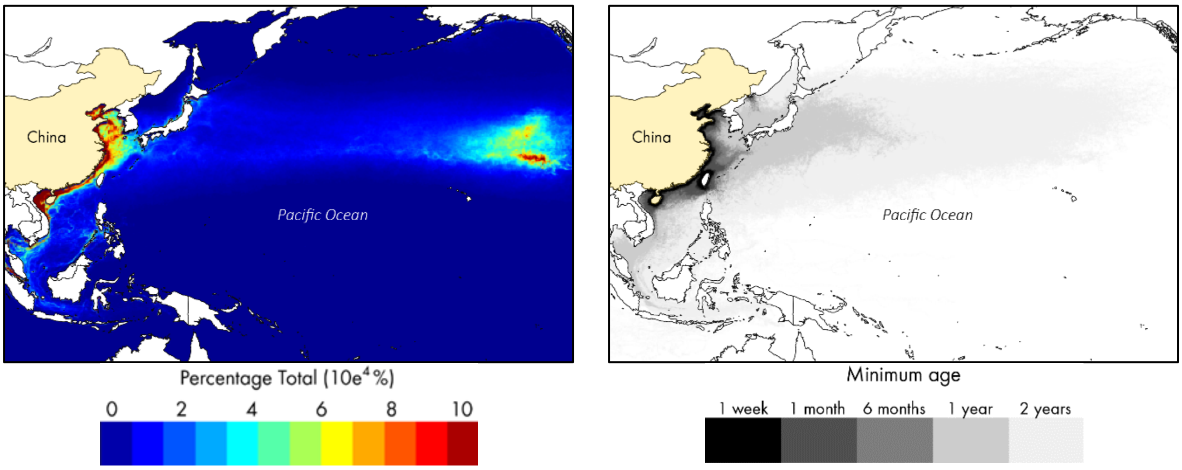

Figure 15. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from China's coastline to the ocean.

Investigating the average age of particles in individual model cells allows to better describe the movement of marine litter masses over time. Figure 16 depicts the main modelled pathways of marine litter released from the Chinese seas. While most young particles (0-2 years) circulate inside the Yellow and Japan Seas and along the coastline of South China, older particles (above 5 years) are found in three different oceans (North Pacific, Indian Ocean and South Atlantic Ocean). Most particles enter the North Pacific Ocean through the Kuroshio Current and slowly drift in the subtropical convergence zone. However some of the particles are transported south inside the Java Sea where they can reside for several years and eventually enter the Indian Ocean through the Malacca Strait and other straits of the Indonesian Archipelago.

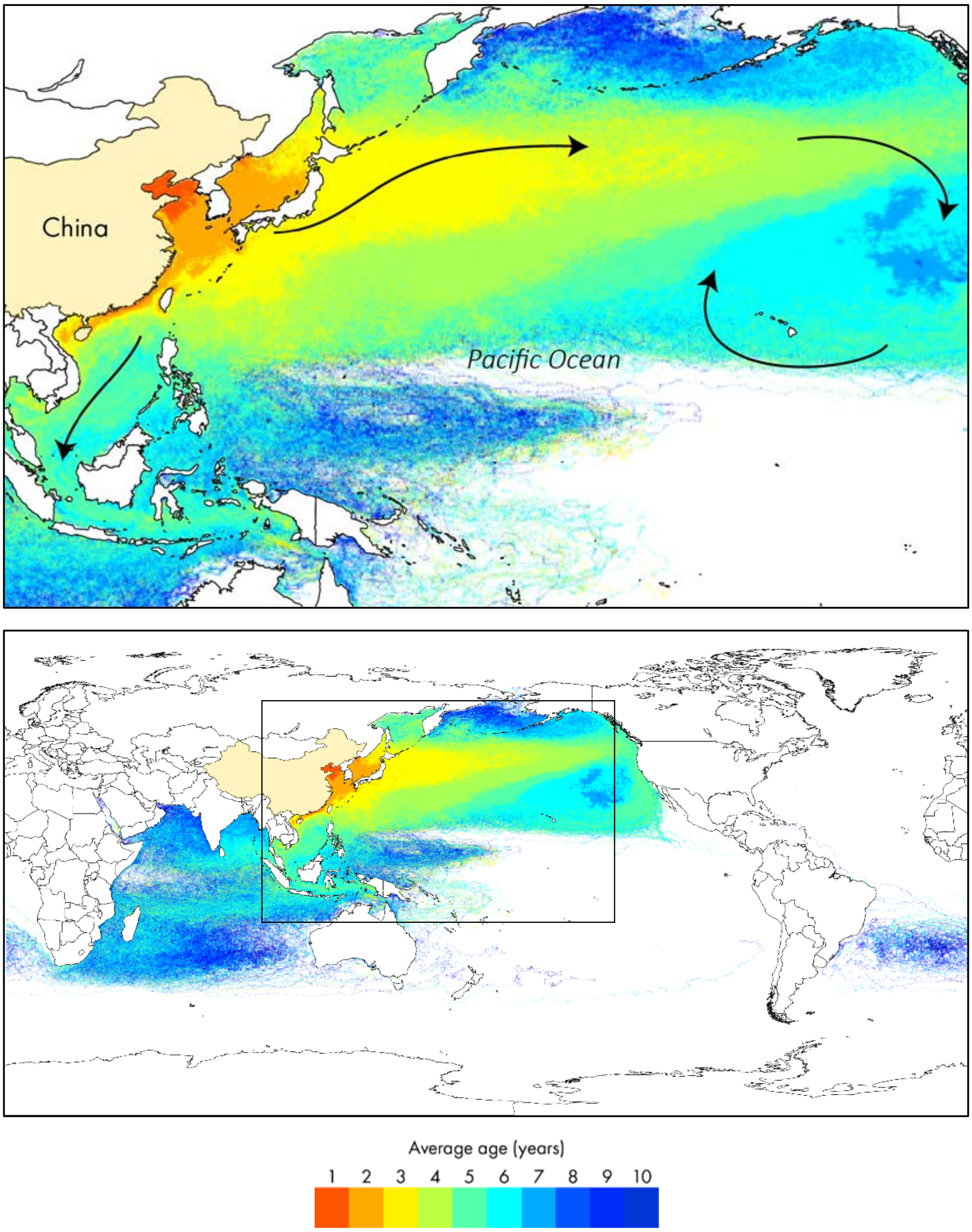

Figure 16. Average age in years of particles originating from China (1994-2014) in the North Pacific Ocean (top) and globally (bottom).

Japan, South Korea, North Korea and Russia

Despite a relatively high population concentration in Japan (115 million coastal inhabitants) and South Korea (42 million coastal inhabitants), both countries generate a significantly lower amount of plastic debris than China with annual predictions between 21 and 57 thousand tonnes and between 5 and 13 thousand tonnes respectively. Jambeck and colleagues (2015) estimate that North Korea with a coastal population of 17 million people is the largest litter producer for this region with 46 to 122 thousand tonnes of plastic entering the ocean every year. This is assuming a rate of litter generation per person and per day of 48 g which is considerably higher than its neighbours (1 g in South Korea and 3 g in Japan).

Similarly to China, the model particles released in this region mainly enter the North Pacific Ocean and accumulate in the subtropical convergence zone. The ratio between particle frequency in the North Pacific gyre and the coastal areas is even higher than for the scenario in China. This suggests that debris released north of the Kuroshio Current are more likely to rapidly enter the North Pacific belt and travel eastward.

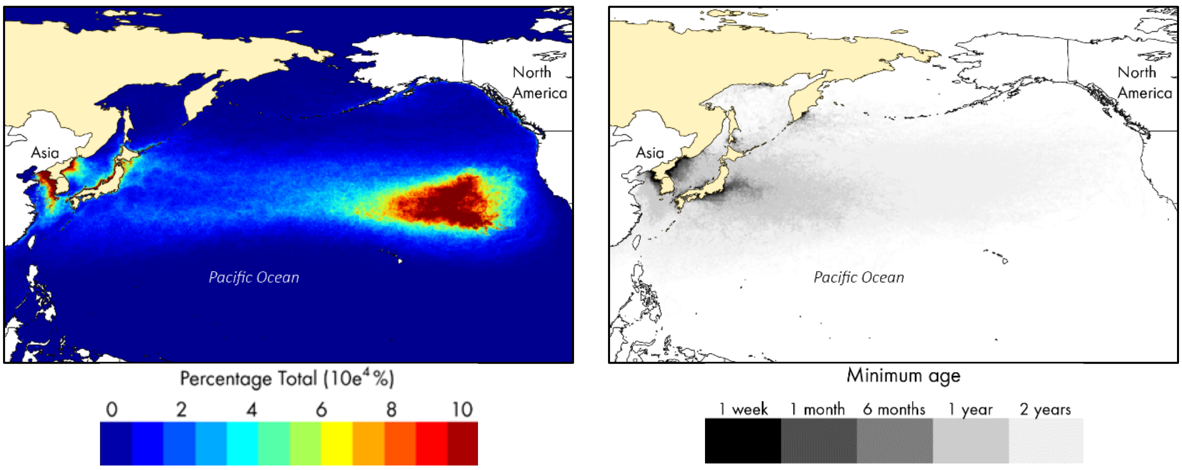

Figure 17. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from Japan, the Koreas and the east coast of Russia to the ocean.

The dispersal model suggests that particles released from Japan, the Koreas or the East coast of Russia can reach the North American continent within 3 years. It should be noted that this result is highly dependent on debris shape and floatability, therefore its exposure to wind. The vast quantity of floating debris produced by the 2011 Tōhoku earthquake-induced tsunami has been well documented (Bagulayan et al., 2012; Lebreton and Borrero, 2013; Calder et al., 2014). Vessels and other high windage objects of Japanese origin where observed in Alaska and British Columbia within only one year after the catastrophe. However, for this study, less buoyant debris are considered as a lower floatability is more representative of litter from consumer goods generated by coastal populations.

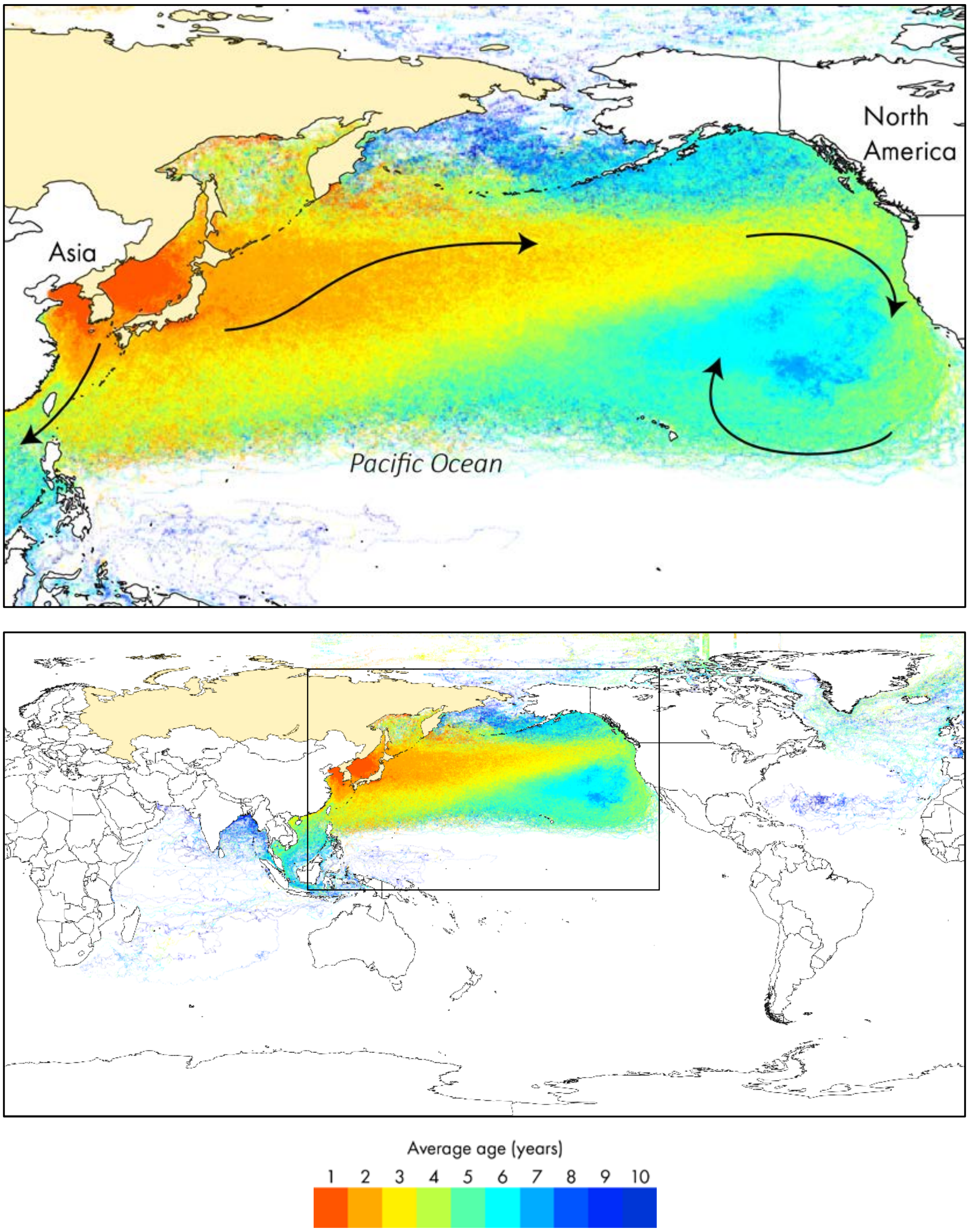

Figure 18. Average age in years of particles originating from Japan, the Koreas and the east coast of Russia (1994-2014) in the Pacific Ocean (top) and globally (bottom).

Southeast Asia

Southeast Asia represents 400 million coastal inhabitants, citizens of Brunei Darussalam, Myanmar, Indonesia, Malaysia, Philippines, East Timor, Singapore, Thailand, Cambodia and Vietnam. Three of these countries (Indonesia, Philippines and Vietnam) are in the top four of countries generating mismanaged waste in coastal areas. The annual amount of plastic marine debris produced by these countries were respectively estimated at 483 to 1,287 thousand tonnes for Indonesia, 283 to 753 thousand tonnes for the Philippines and 275 to 734 thousand tonnes for Vietnam (Jambeck, 2015).

Model predicted trajectories show that marine litter from Southeast Asia is likely to enter the Indian, the Pacific and the Atlantic Oceans within less than 10 years. However, normalized particle visit frequencies (Figure 19) show that a significant amount of material is still found around land masses, between the various islands and straits of the archipelago. Particularly, the model shows the Bay of Bengal, the Gulf of Thailand, the Malacca Strait, the Gulf of Tonkin and most east-facing sides of Indonesian Islands as regional deposition hotspots. Marine litter can however escape the Southeast Asian archipelago relatively quickly as some of the particles travelled as far as in the subtropical latitudes of the Indian Ocean or near the start of the Kuroshio Current within one year.

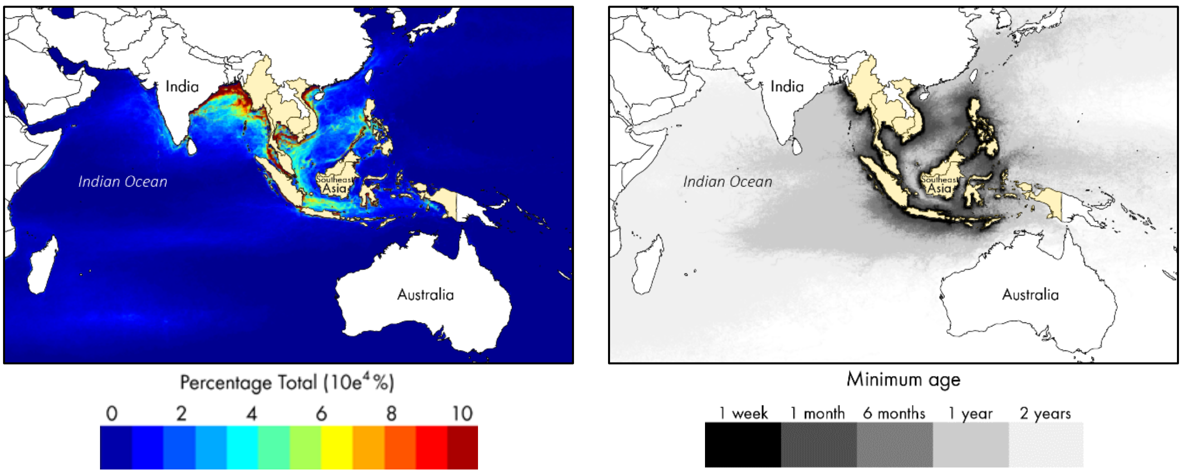

Figure 19. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from Southeast Asia's coastline to the ocean

Modelled marine litter usually enter the Indian Ocean from Southeast Asia within one to two years (Figure 20). From there, it drifts away from the equatorial latitude towards the subtropics. In the south, the particles enter the Indian Ocean convergence zone, south-east of Madagascar and can eventually leak into the South Pacific Ocean or the Atlantic Ocean within five to ten years. In the north, the particles are contained between the equatorial counter current and the Indian subcontinent. Episodes of monsoon in the regions regularly push the material back to the coastline with an average age of particles inside the Arabian Sea and the Bay of Bengal above five years. Particles can also enter the North Pacific Ocean from Southeast Asia through the Kuroshio Current and eventually accumulate in the subtropical convergence zone.

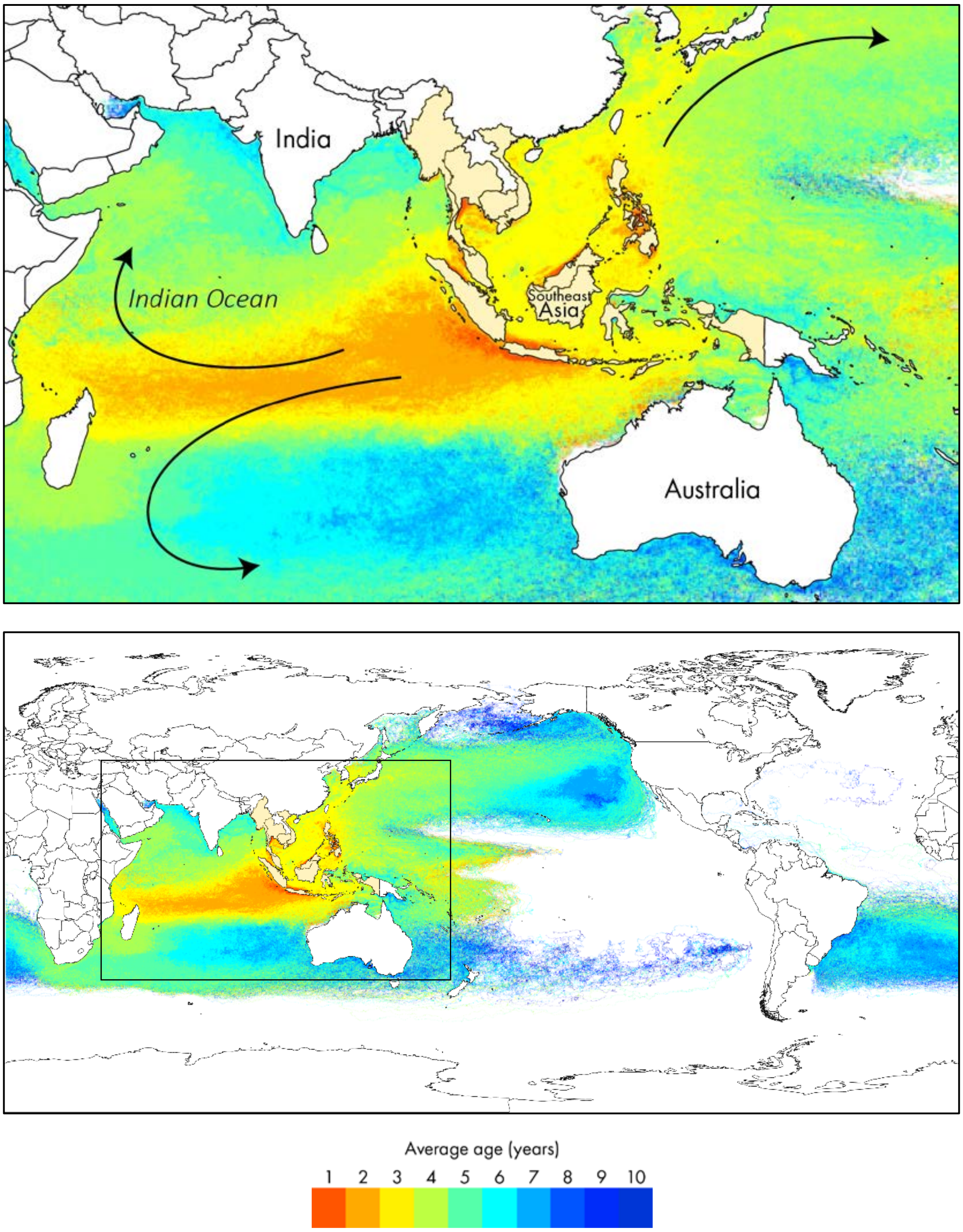

Figure 20. Average age in years of particles originating from Southeast Asia (1994-2014) in the Indian and Pacific Oceans (top) and globally (bottom).

Australia and the South Pacific

The South Pacific region is far less populated than the Asian continent and is reasonably regarded as a minor source of marine litter at global scale. However the estimated quantity of mismanaged plastic waste generated per inhabitant is relatively high in the region, particularly for Pacific Islands. The total amount of marine litter entering the ocean from the South Pacific region is expected to triple by 2025.

Particles were released from Australia, New Zealand, Solomon Islands, Fiji, French Polynesia, New Caledonia, Vanuatu, Papua New Guinea and, Samoa. The trajectories extend to four different oceans within ten years of simulation: the North and South Pacific Oceans, the Indian Ocean and the South Atlantic Ocean. Locally, Australian waters, north of the Great Barrier Reef, and also the Gulf of Papua show high frequencies of model particle visits (Figure 21) suggesting potential regional hotspots for accumulation.

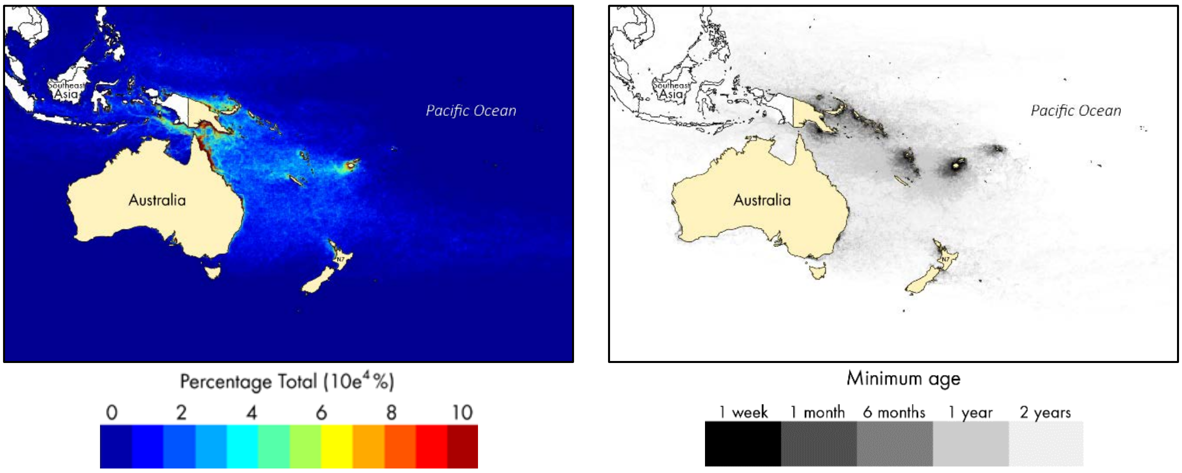

Figure 21. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from the South Pacific region's coastline to the ocean.

The model predicts that marine litter from South Pacific islands will usually circulate at tropical latitudes within the first year, pushed by trade winds towards the Coral Sea and Australia. Some particles travel south following the East Australian Current to enter the Tasman Sea and eventually the South Pacific subtropical convergence zone. Other particles however will drift north towards the Southeast Asian archipelago and know the same fate as debris from this region by eventually entering the Indian Ocean or the North Pacific Ocean. Particles released from New Zealand mostly escape eastward towards the South Pacific. In Australia, very few model particles released in the west or south leaves the continental shelf within the first few years. The particles are regularly pushed back to the landmass by episodes of swells and storm winds and travel along the coastline in the predominant direction.

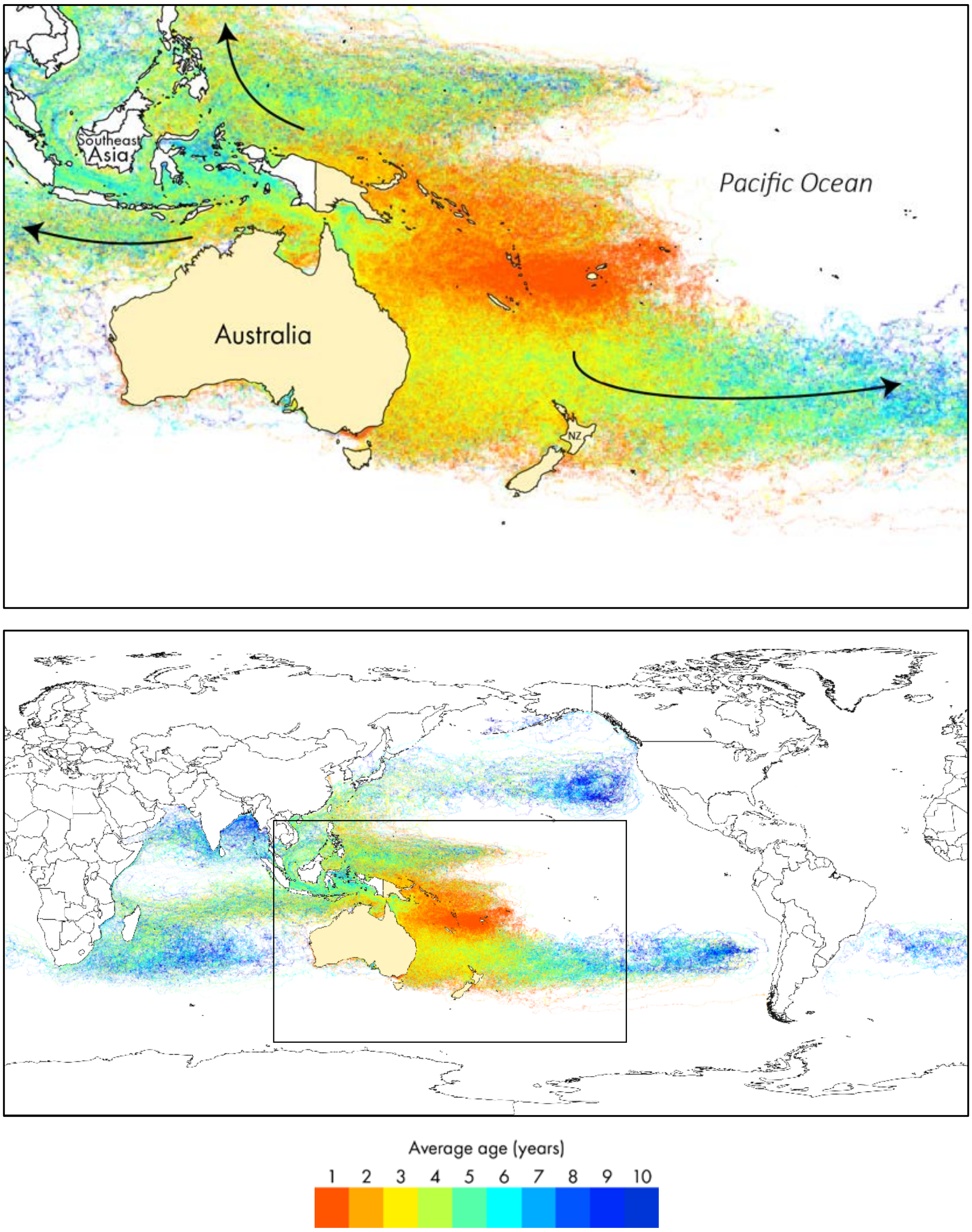

Figure 22. Average age in years of particles originating from the South Pacific region (1994-2014) in the Pacific Ocean (top) and globally (bottom).

North and Central America (Pacific coastline)

North and Central American countries facing the Pacific Ocean are Canada, the USA, Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica and Panama. In Central America, El Salvador is considered as the largest producer of marine plastic litter with 18 to 47 thousand tonnes of annual input assuming a rate of 51 g per coastal inhabitant and per day (Jambeck et al, 2015). In North America, the USA is the largest emitter of litter with 41 to 110 thousand tonnes of plastic litter per year. This figure, however represent both side of the country (Pacific and Atlantic sides) and the East side of the country is significantly more populated.

Model particles released in the Pacific waters of the North American continent travel southward with the California current and rapidly migrate offshore when they reach the tropical latitudes. From there, the particles cross the Pacific Ocean and can reach Southeast Asia within two years. Eventually, most particles will then travel back east towards the North Pacific convergence zone where they will accumulate after five to ten years in average.

As a comparison, between 2012 and 2014, the boat of fisherman Jose Salvador Alvarenga was reported lost off the coast of Mexico and was only found 13 months later on Marshall Islands on the other side of the Pacific Ocean.

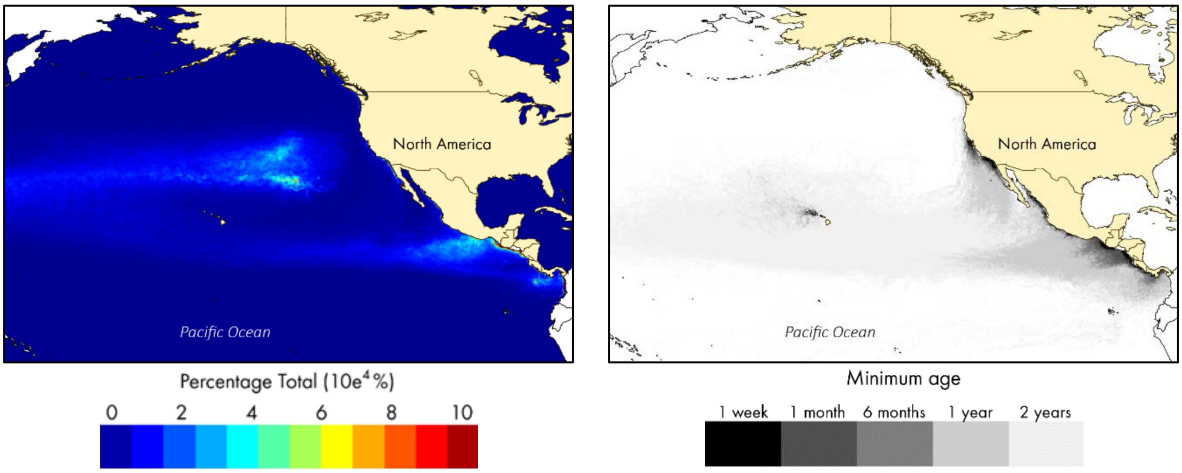

Figure 23. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from North and Central America's Pacific coastline to the ocean.

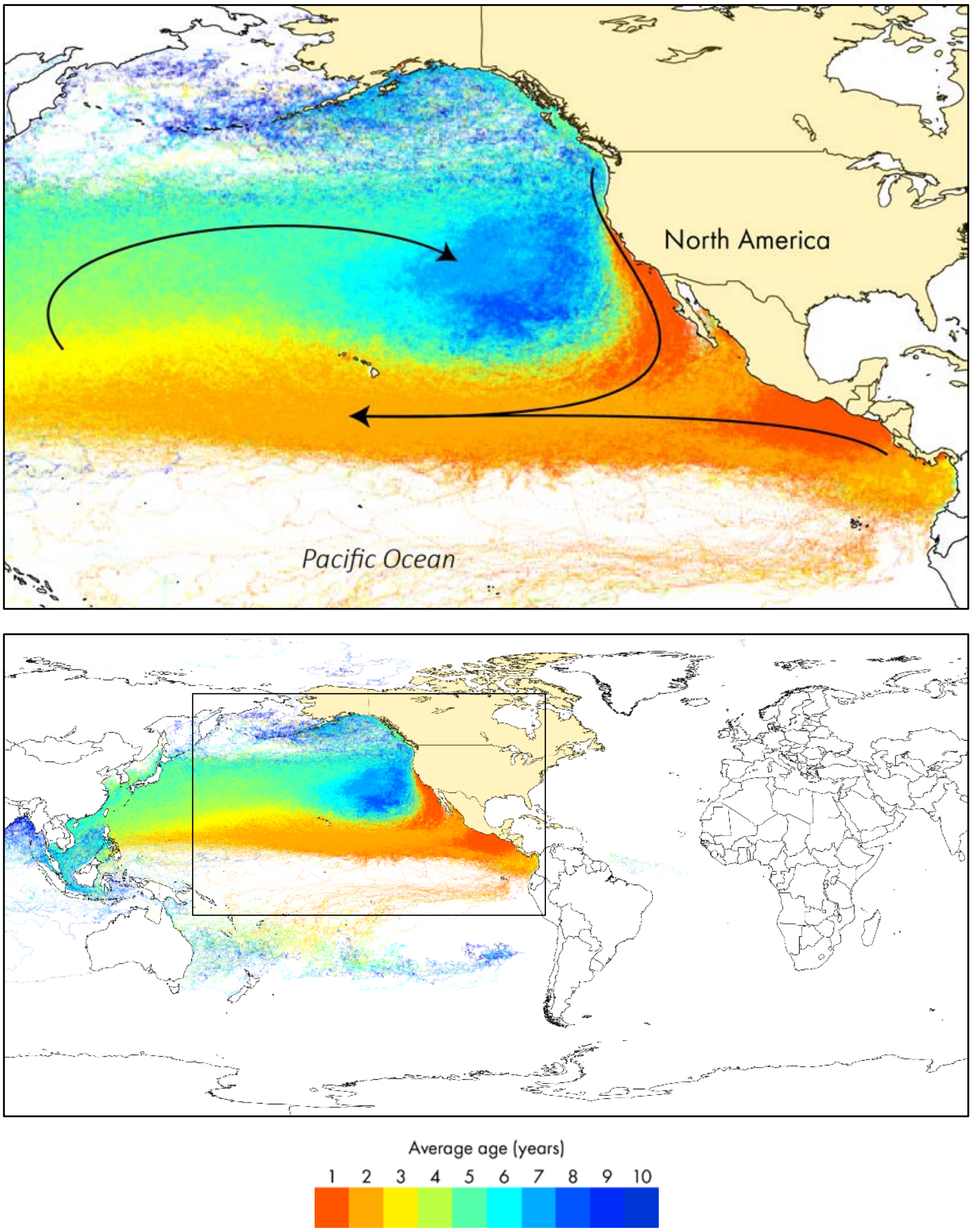

Figure 24. Average age in years of particles originating from North and Central America's Pacific coastline (1994-2014) in the North Pacific Ocean (top) and globally (bottom).

North and Central America (Atlantic coastline)

Countries of North and Central America sharing a stretch of coastline inside the Caribbean Sea, the Gulf of Mexico or the Atlantic Ocean were selected for this scenario, including Mexico, Belize, Guatemala, Honduras, Nicaragua, Costa Rica, Panama, Colombia, Venezuela, Bahamas, Barbados, Cuba, Dominican Republic, Guadeloupe, Haiti, Jamaica, Martinique, Trinidad and Tobago, Guam, Puerto Rico, the USA and Canada. For these countries, Jambeck et al (2015) reports an annual plastic litter input between 171 and 457 thousand tonnes for 2010 with the major regional producers being the USA (41 to 110 thousand tonnes, Pacific and Atlantic coastline), Haiti (22 to 59 thousand tonnes) and the Dominican Republic (18 to 47 thousand tonnes).

Most model particles released inside the Caribbean Sea and the Gulf of Mexico eventually escape the region through the Gulf Stream along the coast of Florida. Particles can reach the North Atlantic Ocean within one year and finally accumulate inside the subtropical convergence zone known as the Sargasso Sea (Figure 25). Some particles however never leave the marginal seas of the Caribbean Region. Regional hotspots were identified in the eastern part of the Gulf of Mexico and the Bay of Honduras. In the Caribbean islands, the model usually predicts higher accumulation in the southern side of an island. Far away from the North American continent, the Bay of Biscay in Europe shows a relatively high rate of particle frequency suggesting a potential accumulation of marine debris in this area.

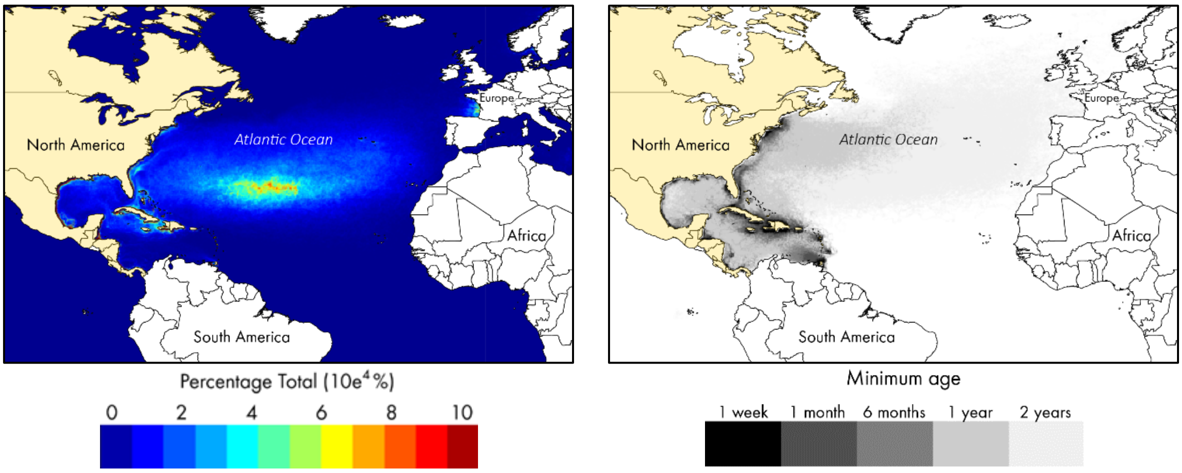

Figure 25. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from North and Central America's Atlantic coastline to the ocean.

Modelled particles usually resides in the Caribbean Sea and the Gulf of Mexico between one to two years and leave the region by entering the Atlantic Ocean within three years. From there and within four years, it follows the Gulf Stream towards northern Europe and circulate either north along the Scandinavian Peninsula and the Arctic or south along the

Iberian Peninsula, West Africa and back into the subtropical convergence zone. The model shows a significant proportion of old particles in the southeast part of the Gulf of Mexico suggesting an important accumulation rate in this area (Figure 26).

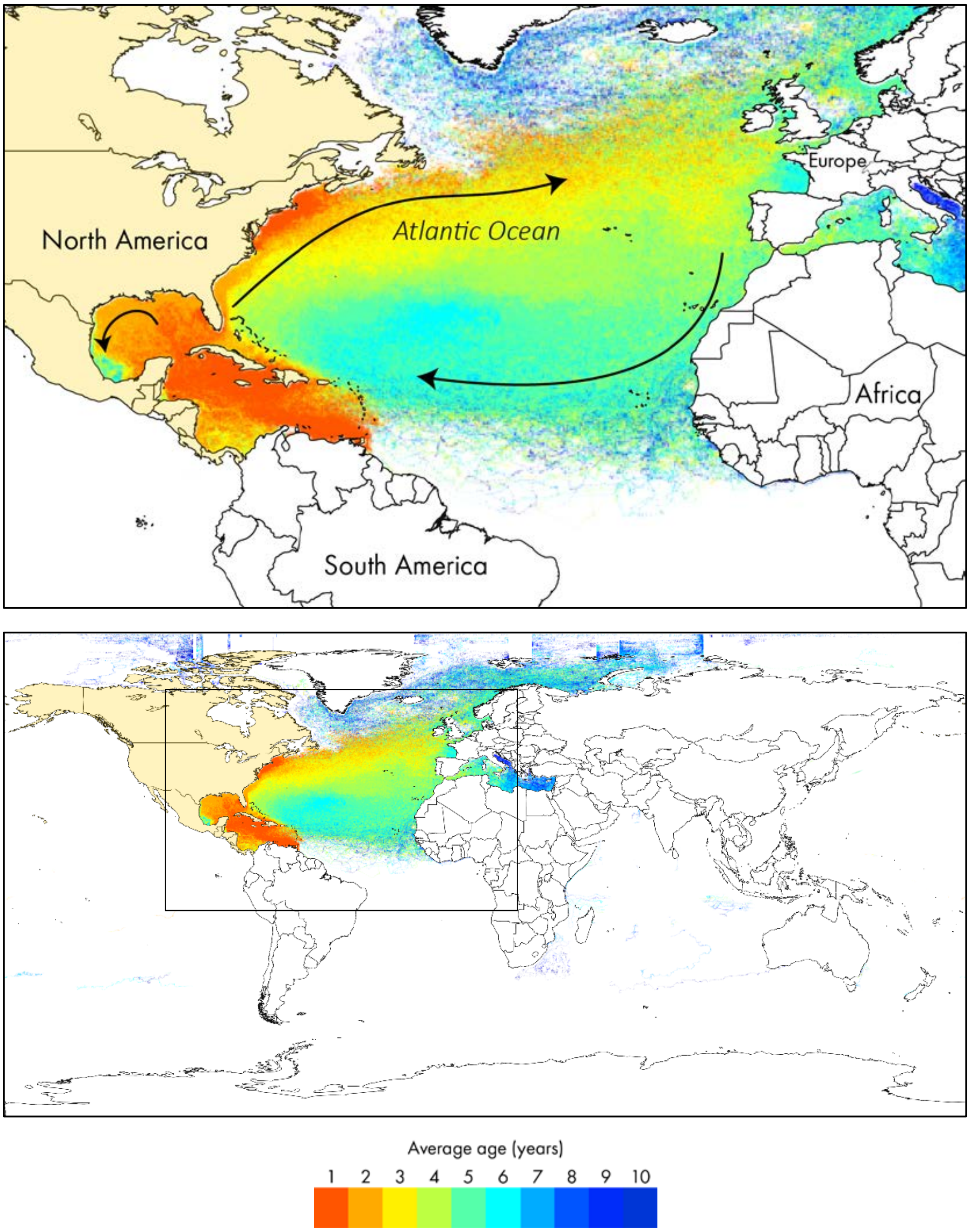

Figure 26. Average age in years of particles originating from North and Central America's Atlantic coastline (1994-2014) in the North Atlantic Ocean (top) and globally (bottom).

South America

Nearly 150 million people live within 50 km of the ocean in South America. According to Jambeck et al. (2015), the largest emitter of marine litter in the region is Brazil with an estimated 71 to 189 thousand tonnes of mismanaged plastic entering the ocean every year. Brazil is followed by Peru (29 to 78 thousand tonnes per year) and Argentina (24 to 63 thousand tonnes per year).

Model particles released from South Africa where found in all five main oceans of the world and predominantly in the South Atlantic and South Pacific Oceans.

On the west coast, particles are transported equatorward with the Humboldt Current. When reaching equatorial latitudes, the particles migrate towards the west with the South or North Equatorial Current and accumulate in the Pacific Ocean. Similarly to the North and Central America's pacific coastline scenario, the particles can reach Southeast Asia or Oceania within 1 to 2 years.

On the east coast, model particles released north of the Equator are likely to drift northward into the Caribbean Sea and later in the North Atlantic (after 3 years in average). Particles released south of the Equator will be transported south, along the continent with the Brazil Current and eventually accumulate in the South Atlantic convergence zone.

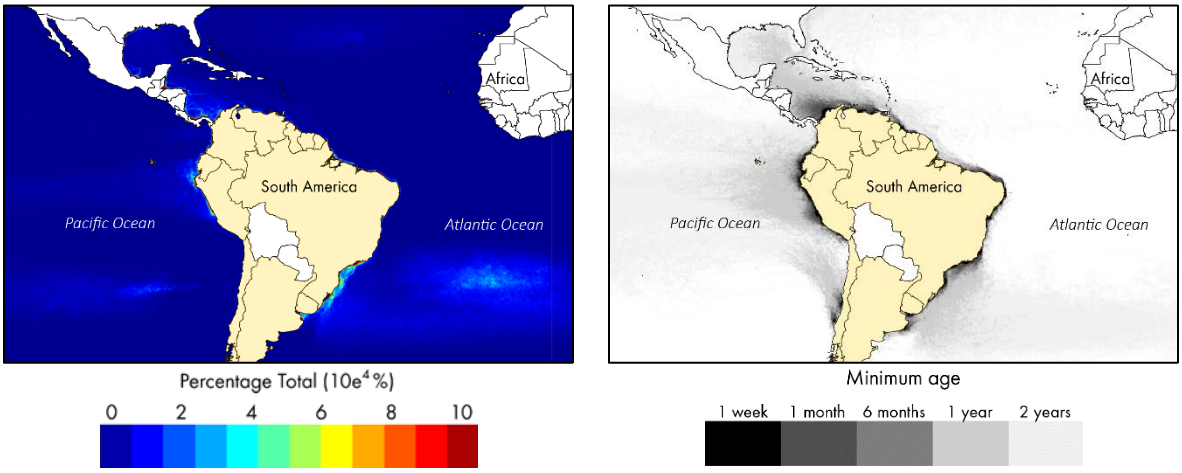

Figure 27. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from the South America's coastline to the ocean.

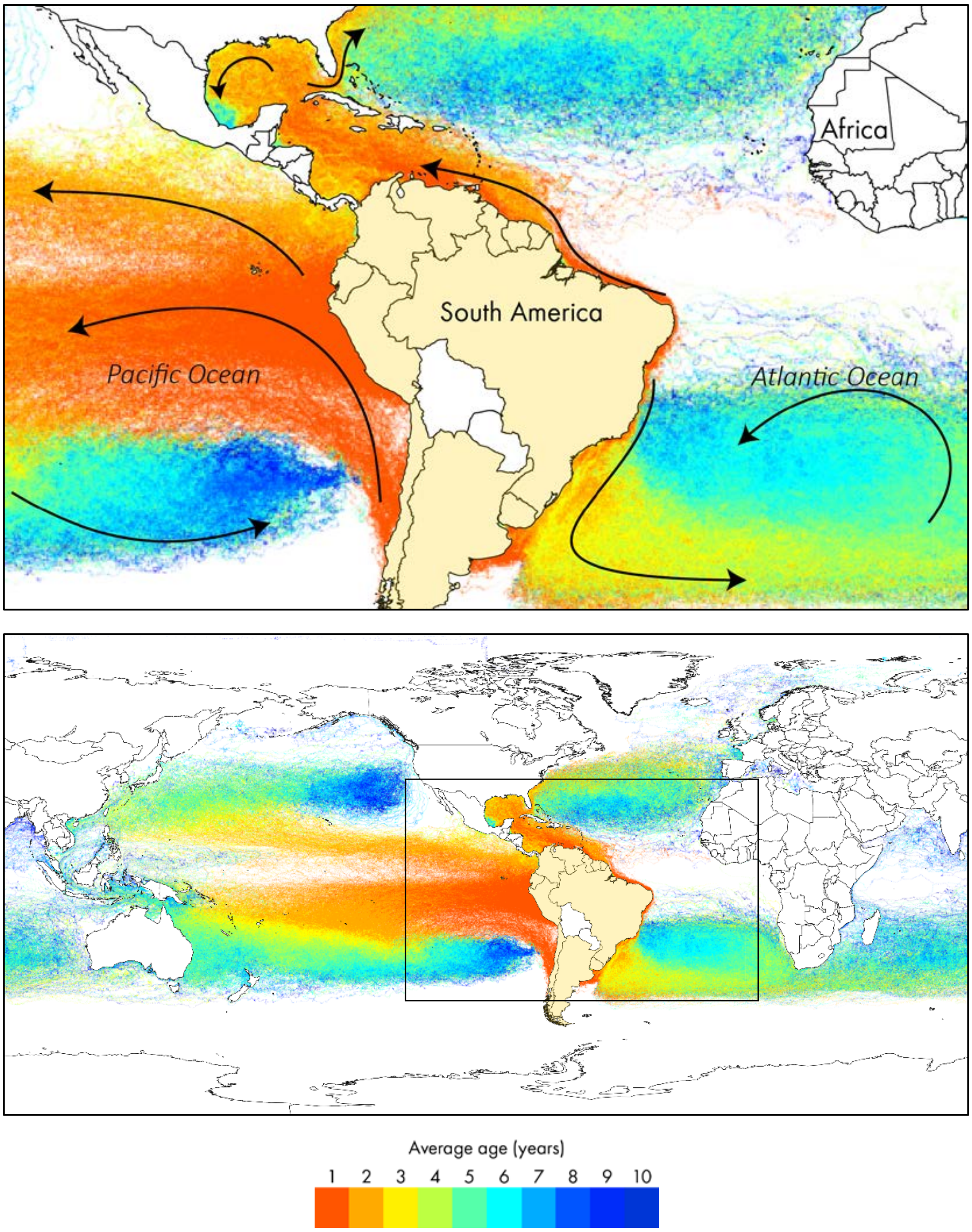

Figure 28. Average age in years of particles originating from South America (1994-2014) in the Pacific and Atlantic Oceans (top) and globally (bottom).

West Africa

The region of West Africa from Morocco to Namibia represents more than 92 million people living at less than 50 km of the Atlantic Ocean. The largest emitter of mismanaged litter is Nigeria with a predicted 128 to 341 thousand tonnes of plastic entering the marine environment for 2010 (Jambeck et al, 2015), followed by Morocco with 47 to 124 thousand tonnes. Other significant contributions in Sub Saharan Africa are those of Senegal (38 to 102 thousand tonnes per year) and Ivory Coast (29 to 78 thousand tonnes per year)

Surprisingly the dispersal model shows that West Africa has a relatively low impact on the South Atlantic Ocean but rather affects the North Atlantic Ocean. Most model particles released in West Africa leave the continent within one year and travel west towards the South American coastline. Because most particles arrive in South America north of the equator, they follow the Caribbean current and enter the Gulf of Mexico within 3 years and eventually leak into the North Atlantic gyre after 5 years in average.

Noticeably, the model predicts the Gulf of Guinea as a local hotspot for marine litter accumulation. A significant amount of particles remains trapped by the Guinea Current that flows eastward and can reside between five to ten years in the region.

The dispersal model shows that particles from West Africa can reach the Arctic Circle within ten years.

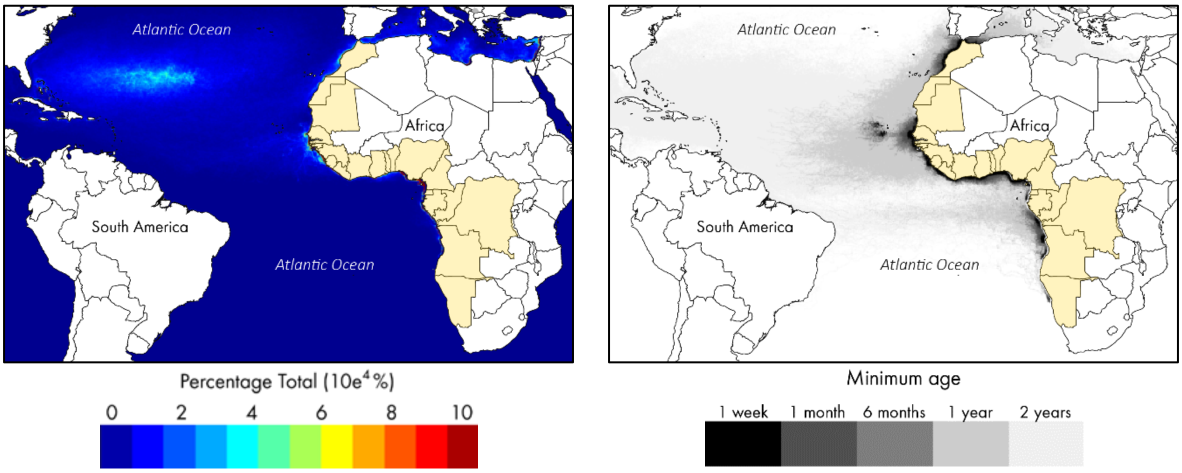

Figure 29. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from West Africa's coastline to the ocean .

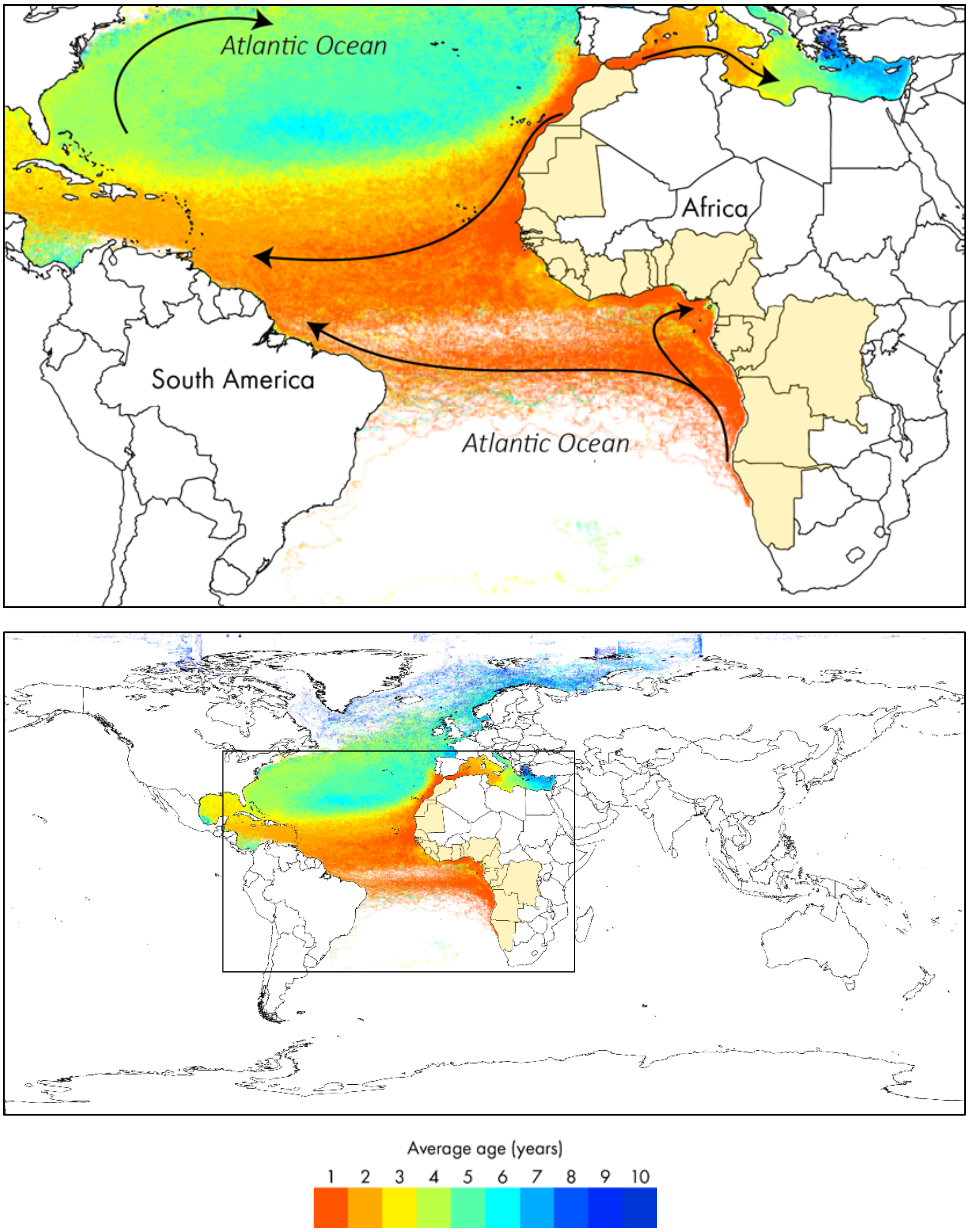

Figure 30. Average age in years of particles originating from West Africa (1994-2014) in the Atlantic Ocean (top) and globally (bottom).

East Africa

More than 46 million people live in the coastal areas of East Africa. Data on mismanaged waste for Djibouti, Somalia, Kenya, Tanzania, Mozambique, South Africa, Madagascar, Mauritius and the island of La Reunion suggest an annual marine litter input from East Africa between 135 and 361 thousand tonnes for 2010 (Jambeck et al., 2015). The largest plastic litter producer in the region is South Africa with 95 to 252 thousand tonnes per year.

In East Africa, the dispersal model predicts that particles released south of Kenya including Madagascar will likely be transported by the warm Agulhas Current at the southern tip of the African continent. From there, they either follow the west wind drift and enter the Indian Ocean or enter the Atlantic Ocean through the colder Benguela Current. However, particles released north of the equator are more likely to drift in the Arabian Sea and later in the Gulf of Bengal. The model predicts a significant probability of accumulation along the eastern coastline of Africa and Madagascar, particularly the sections that face south like in Somalia, Kenya and Mozambique (Figure 31). Particles in the area are transported by the south easterly trade winds and remain very close to the shoreline.

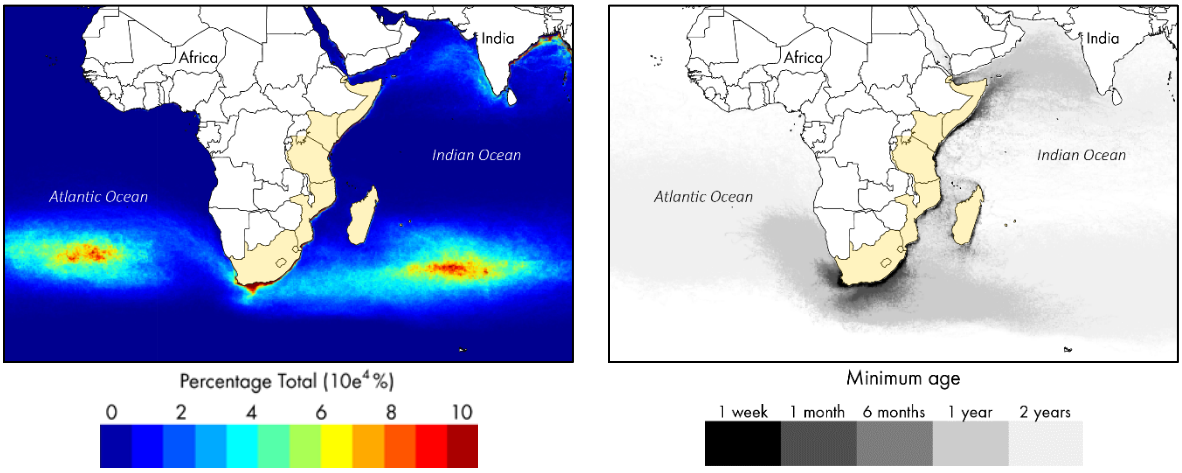

Figure 31. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from East Africa's coastline to the ocean.

Modelled particles in East Africa usually leave the region within one to two years. When not stranded, they escape the continent at the southern tip where Indian and Atlantic Oceans meet or at the north, in the Arabian Sea. Within five years, most drifting particles have reached the subtropical convergence zones in the Indian and South Atlantic Oceans or the Bay of Bengal that appears as a regional hotspot for accumulation. Within ten years, the model predicts that marine litter from East Africa could travel as far as the North Atlantic and the South Pacific's eastern side (Figure 32).

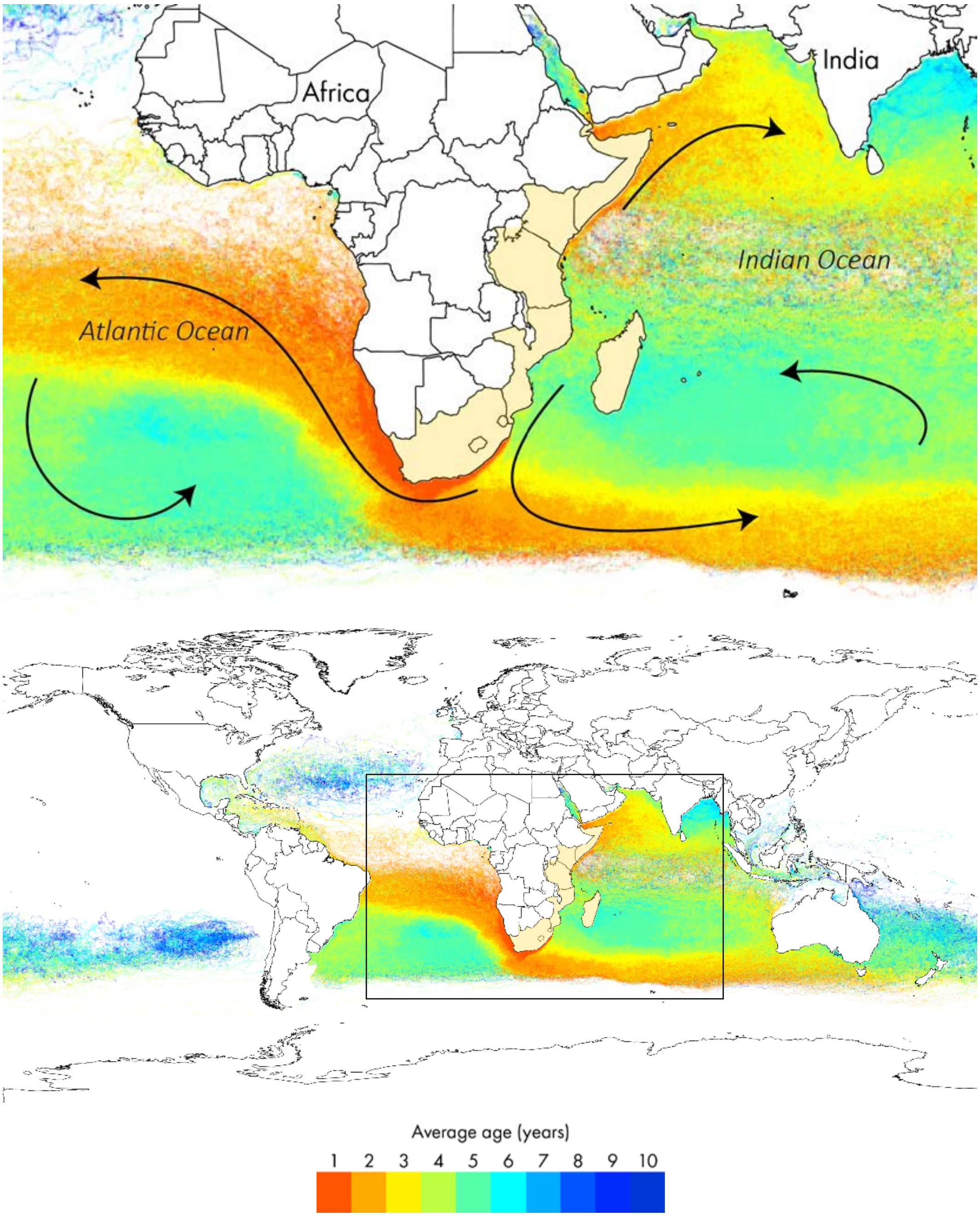

Figure 32. Average age in years of particles originating from East Africa (1994-2014) in the Indian and Atlantic Oceans (top) and globally (bottom).

India, Bangladesh, Sri Lanka and the Arabic Peninsula

According to data on waste management and coastal population density (Jambeck et al., 2015), Sri Lanka ranks first in countries emitter of marine litter for this region with an estimated annual input between 239 and 636 thousand tonnes. Overall, this region could leak from 594 to 1,585 thousand tonnes of marine plastic litter every year with significant contributions also from Bangladesh (118 to 315 thousand tonnes per year) and India (90 to 240 thousand tonnes per year). Countries of the Arabic Peninsula that faces the Indian Ocean (Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, UAE and Yemen) would produce between 71 and 189 thousand tonnes of litter each year.

Of all regions covered in this modelling assessment, the Indian subcontinent and Arabic Peninsula is the less dispersive scenario. Model particles mostly remain in the area between the strong westward equatorial current and the landmass. Periodic episodes of monsoon conditions constantly push the material back to shore particularly on the west side of India and inside the Bay of Bengal.

Some particles eventually finds their way in the Southern Hemisphere with the Agulhas current along the eastern side of Africa. During the ten years of simulation, some model particles were recorded in the South Atlantic and the Pacific Oceans.

The model also suggests that while the Persian Gulf is leaking material (average particle age below one year), the Arabian Sea is a distinct accumulation zone (average particle age up to 10 years).

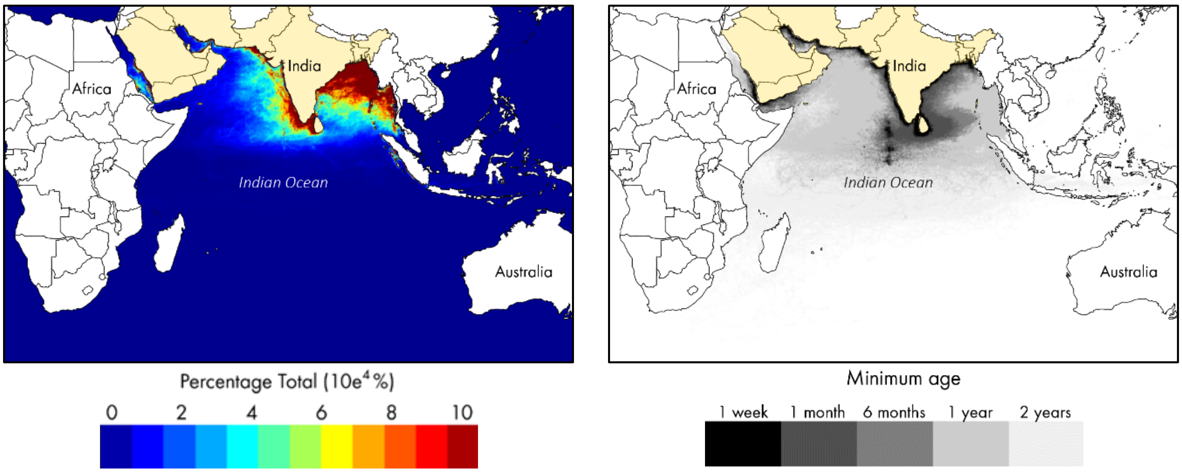

Figure 33. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time (right) for particles from India, Bangladesh, Sri Lanka and the Arabic Peninsula's coastline to the ocean.

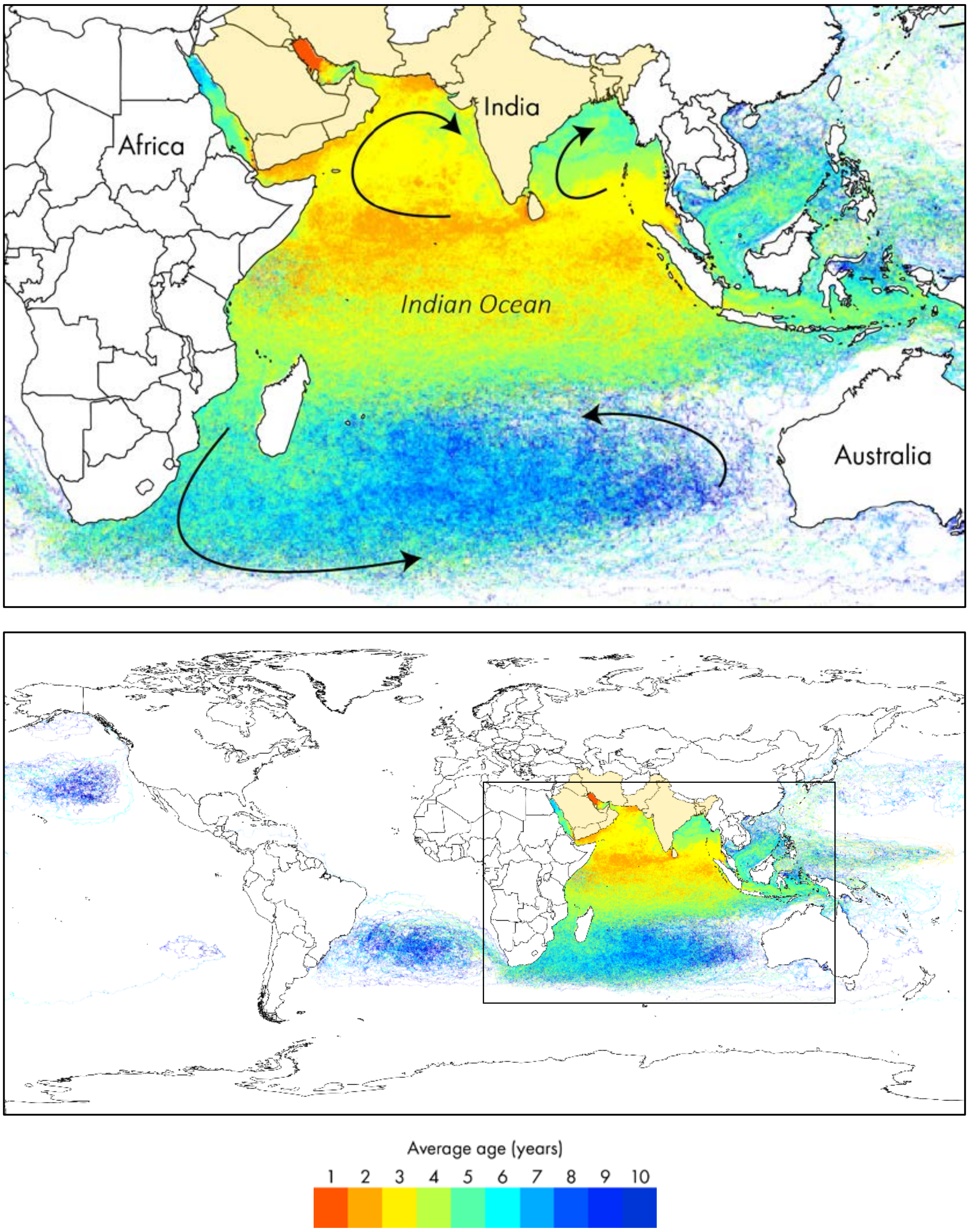

Figure 34. Average age in years of particles originating from India, Bangladesh, Sri Lanka and the Arabic Peninsula (1994-2014) in the Indian Ocean (top) and globally (bottom).

Western and Northern Europe

Western and Northern Europe with over 130 million coastal inhabitants from Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Norway, Portugal, Spain, Sweden, the Netherlands and the United Kingdoms, released in the marine environment an estimated 37 to 98 thousand tonnes of plastic litter for the year 2010 (Jambeck et al., 2015). Countries of Northern and Western Europe present in average a relatively low rate of mismanaged waste production per inhabitant resulting from modern municipal solid waste management infrastructures. The lowest rate is found in Denmark and Sweden with 1 g per coastal inhabitant and per day. Germany shows the highest rate with 10 g per person and per day.

The dispersal model describes the Gulf of Biscay in the South West of France, the western shores of the United Kingdoms and Northern Europe from Belgium to Norway as local hotspots for frequency of marine litter. A significant amount of material however leak into the North Atlantic Ocean and accumulates in the Sargasso Sea. In the Mediterranean, particles from Spain, France but also other western countries accumulate around the African coasts (see more details on the Mediterranean Sea in next section).

Particles from Western and Northern Europe regularly reach the Arctic Circle within 3 to 4 years in average.

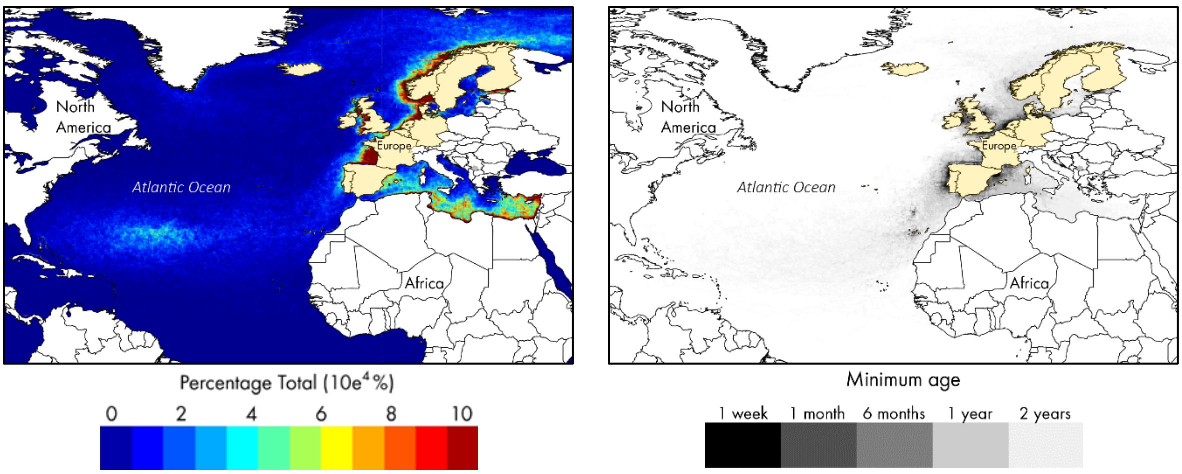

Figure 35. Frequency of particle visits as a percentage of total particle number for the year 1994-2014 (left) and minimum travel time for particles (right) from Western and Northern Europe's coastline to the ocean.

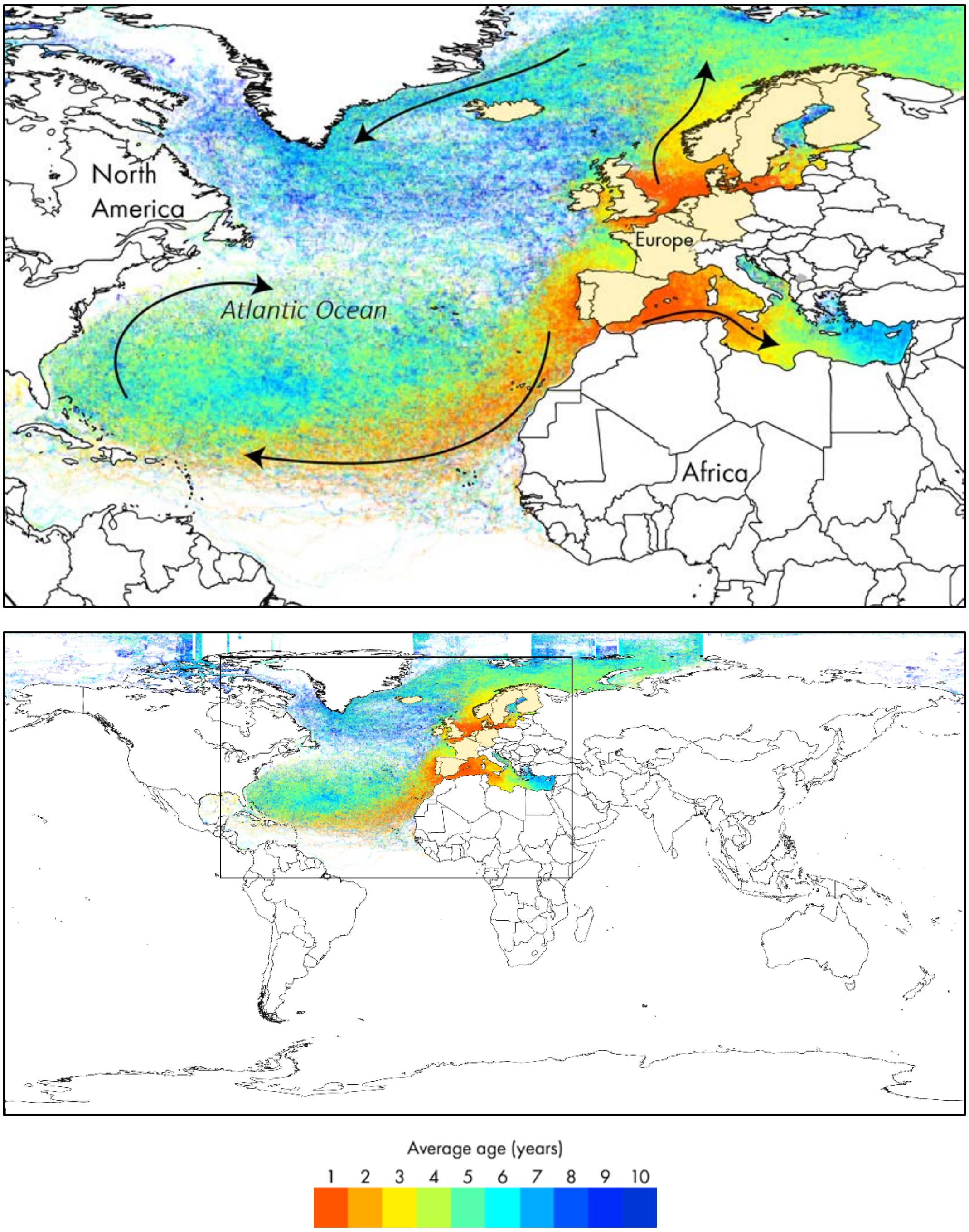

Figure 36. Average age in years of particles originating from Western Europe (1994-2014) in the Atlantic Ocean (top) and globally (bottom).

The Mediterranean

The Mediterranean Sea has been described as one of the most affected areas by marine litter in the world. Some of the largest quantities of municipal solid waste (MSW) are generated annually per person in the Mediterranean Sea (208-760 kg/year; http://www.atlas.d-waste.com/). Because of urbanization, tourism, shore use, important riverine inputs (from the Nile, Po, Rhose and Ebre rivers, 30% of the world maritime traffic (http://www.unep.org/regionalseas/marinelitter/about/distribution/) and no possible outflow at Gibraltar for items less dense than the surrounding seawater, the Mediterranean situation appears particularly sensitive to debris accumulation. Semi-arid climates in the south with annual rainfall concentrated into just a few months (and the associated spreading of litter during periods of intense rainfall) mean that river transport and uncontrolled discharges act as major sources of litter entering the marine environment.

Surveys conducted to date show considerable spatial variability with the highest densities of marine litter stranded on the sea floor, sometimes reaching more than 100,000 items/km^2 (Galgani et al. 2000) and floating microplastics, reaching mean values of 1,050,000 particles /km^2 in the southern Adriatic Sea (maximum of 4,680,000/km^2; Suaria et al. 2015).

In the Mediterranean, report (Galgani 2015; in review) classify land-based (up to 69% of liter) and vessel-based (up to 26%) as the two predominant sources of litter in the region. The variability of surface circulation in the region is high, as instabilities occur in the basin. No global data set on floating marine debris currently exists, though scenarios can be hypothesised to evaluate realistic distributions of litter. To date, only a few large sub-basins appear as potential retention areas (e.g the north-western Mediterraean and the Tyrrhenian sub-basins, the southern Adriatic and the Gulf of Syrt (Poullain et al 2012, Mansui et al. 2014). These regions lose their retention character for longer duration journeys, however, as no permanent gyres exist in the region (local sub-gyres typically persist for months with seasonal and inter-annual variability altering water movements and litter distribution.

If the western Mediterranean coasts suggest regions of low impact, the southern coastal strip of the eastern Mediterranean basin appears to be a preferential beaching destination with marine litter stagnating along the Tunisian and Libyan coasts that may result from accumulation in the Gulf of Syrt (Erikssen et al. 2014; Mansui et al 2014). In contrast, the Levantine sub-basin appears as a more local and potential source for the nearby coast there (Mansui et al. 2014).

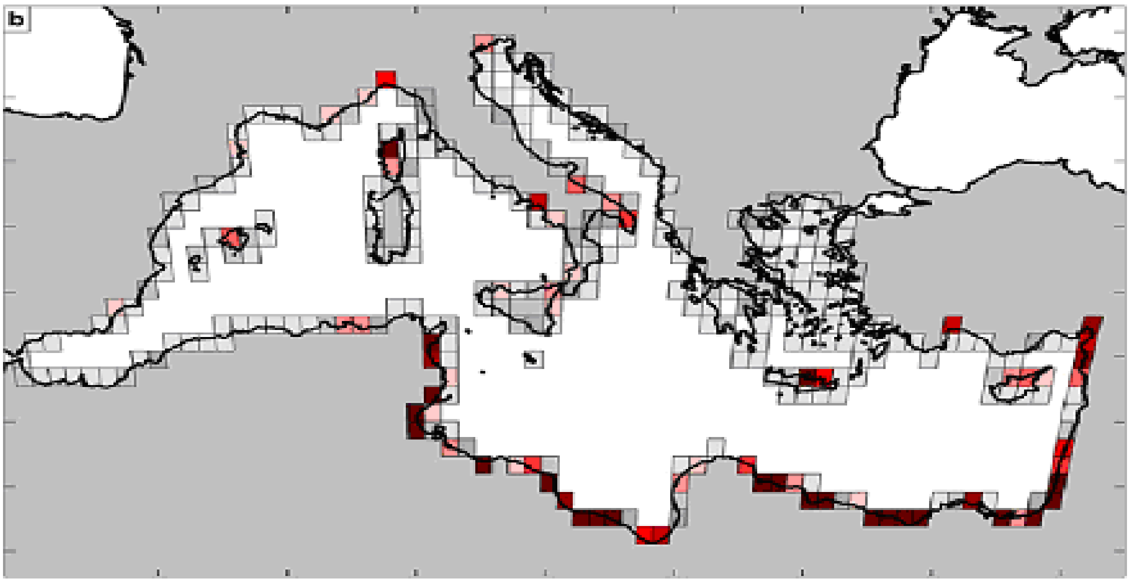

Figure 37. General predictive scheme of litter stranding on Mediterranean Beaches (Mansui et al., 2014)

Identifying knowledge gaps in critical regions

Litter generation: source distributions

The modelling assessment presented above relies heavily on the accuracy of the particle source distribution. For this example, a proxy based on coastal population density grids (Yetman *et al.*, 2004) and estimates of mismanaged waste generation per country (Jambeck *et al.*, 2015) was used. However, to fully understand litter generation, other source proxies should be proposed in parallel to reflect the contribution of specific sectors of human activity such as:

- fishing
- aquaculture
- tourism
- shipping
- transportation

Riverine input, not considered in this assessment should be represented in the future. There is no global estimate to date of global riverine inputs of macro and microplastics into the ocean. Following a similar approach than for the coastal population scenario, global and regional riverine input of marine litter in the ocean could be derived from hydrographic modelling and waste mismanagement data on land.

Methods to monitor and estimate socioeconomic activities and resulting waste streams must be developed and implemented in targeted countries to allow a rigorous analysis of litter generation at regional scale. Monitoring of coastal and urban centres could be particularly informative and may provide critical baseline data if and as infrastructure investment changes. Similarly, to the work presented by Jambeck and colleagues (2015), further efforts in assessing the contribution of individual socioeconomic sector must be carried out at national and regional scales. This would imply building capacities in developing countries and implement systematic and accurate monitoring of socioeconomic indicators per countries or regions.

Litter deposition: model uncertainties

Identifying regional hotspot for regional deposition using a dispersal model requires accurate environmental forcing components. The forcing terms used in the framework presented above are derived from archive products of numerically modelled sea surface current, wave and wind data. There is a certain amount of uncertainties associated with these theoretical models. Particularly, understanding the issue from a global to regional or national scale requires different tools, models and assumptions. Time scale dependency is also an important factor. For instance, global geostrophic current model with time scales between 3 to 24 hours, as used in this example, do not consider tidal circulation. Coastal circulation processes are rather complex and site specific. They are best understood at smaller time scales (one hour or less) and spatial scales (metres to kilometres). Therefore while global models are useful to draw probabilistic conclusions, regional models at higher resolution (both in time and space) should be implemented while conducting a deterministic analysis. There are many existing options for environmental forcing data and circulation models at both global and regional scales. In any case, the accuracy of dispersal forcing components should be validated against observations. The main source of validation for these circulation models is location data collected by drifting buoys such as the global drifter program. While drifting buoys provide very useful information, other technologies to better understand dispersal of debris are available (high resolution imagery, SAR, LiDAR, Doppler scattering). Further research and investment in monitoring debris displacement should be conducted in targeted regions. The type of polymer, the size and shape of a debris have an impact on its floatability. High floatability items such as packaging products, bottles or fishing buoys will be much more subject to wind forcing than less buoyant items such as fishing nets or plastic bags. The dispersal model shows that the windage coefficient (set at a standard 0.5% for this assessment) has a very significant impact over time on debris mass transport and connectivity between the different accumulation zones worldwide. A rigorous assessment should consider different type of debris with windage coefficient gradually varying between no forcing (0%, fully submerged) to strong wind forcing (2-3 %, semi submerged). Ideally, windage coefficient should vary in time to reflect the change in floatability overtime (e.g. degradation, biofouling…). A framework integrating this component would require empirical formulations based on observations and experiments for different types of polymer, debris shapes, water biochemistry, solar radiation etc.

The modelling approach presented here has other limitations. For instance, the model only treats the sea surface which is considered as a sink for marine debris. However, no interaction with other sinks such as the shoreline (stranding), the water column and sea bed (sinking) or the biota (ingestion) are considered. There is still room to improve the various models of marine litter presented to date, particularly in regards to long term fate of plastic material in the ocean.

Recommendations for priority actions and target areas for monitoring efforts

There remain a number of ongoing challenges with respect to monitoring marine litter in the ocean and along the coastline. Some of these challenges are associated with the various methodologies that are used to sample litter and may include where litter is sampled, how frequently, what approach, whether data are collected, whether litter is left in situ or removed and other related issues. There are also challenges that arise due to infrastructure, support, facilities and waste management resources and there are further sensitivities with respect to how, when, and what approach to use for engagement with the wider community (keeping in mind cultural, historical, and societal differences).

In spite of numerous challenges, there are tremendous opportunities that currently exist and new opportunities arising. The increase in awareness of the plastic pollution issue from media, experiential learning, scientific information and other means provides exciting prospects for engagement, data collection, dissemination and synthesis. Plastic is ubiquitous in the ocean, increasing rapidly, and affecting wildlife, economies, and potentially human health. Recent modelling suggests that approximately 8.4 million tons of plastic flow to the ocean each year, primarily from major urban centers, particularly in Asia. However, there has been very little data collected to document the existence of these extensive plastic plumes around major urban centers. Understanding the transport of plastics from land into marine systems is critical for modelling the distribution and trends of plastic in the ocean, estimating its impact on regional economies near sources, and clarifying the magnitude of this pollution to the public, industry, and policy-makers.

The need to provide a consistent framework and toolkit for priority actions and action areas cannot be overstated. Some suggested priority actions include:

1) Harmonization of data collection approaches at local, regional, and global scales (including web based support or a repository where methods, analytical approaches and outreach approaches can be shared);

2) Consistent data collection and repeated sampling for litter and microplastics at coastal, upstream, inland, nearshore and offshore sites. This would include standardized, repeatable surveys to allow comparisons between regions;

3) Apply a statistical design to sampling, ensure the inclusion of not only ‘hotspots’ but non-hotspot sites, particularly focusing on inputs in the Asia Pacific, Caribbean, African, European and North American regions;

4) Development and integration of watershed, coastal, sea-surface and sediment sampling established as co-occurring or concurrent monitoring programs. Such programs would ideally be carried out in different countries simultaneously and with shared methodologies;

5) Coupled with (4) above is the establishment of rubbish traps on waterways (up and downstream) to help identify sources and community contribution. Coupling such data collection strategies also has tremendous opportunities for outreach/ community engagement activities. One recent example is the Baltimore Waterwheel (though simpler approaches may be just as effective).

6) Compilation of a comprehensive data set on plastics at the coastal margin on land and at sea near and away from urban centers for countries identified in recent literature (Jambeck *et al.* 2015) as having significant inputs to the marine environment.

7) Combine empirical data and statistical models to produce maps of plastic plumes generated from urban centers (with inclusion of covariates such as population density, infrastructure and other potentially important correlates);

8) Well-designed studies that quantify sea-based litter, particularly from aquaculture-sourced gear and including gear types, target species and impacts. Ideally, such studies would compare high/low aquaculture sites and would consider a number of variables including infrastructure, local climate conditions, rates of production, consumption, and human attitudes. Some regions to carry out such studies would include Asia Pacific, Australia, Africa, USA, the Mediterranean and the Caribbean;

9) Modelling efforts that identify biodiversity impact hotspots – or economic, aesthetic, or other criteria deemed to be of interest/priority;

10) Public and open sharing of baseline data generated from 1-9 through visual, report and social media streams;

11) A global library or repository (with map) which includes contributors, initiatives, contacts and sources, data holders and others. This repository would not necessarily require the inclusion of the data itself, but would be a place whereby information, approaches, methodologies, and other information would be shared on an open-source platform. It could also include upcoming events, conferences and information sharing opportunities (such as the MOOC). Ideally, such a platform or repository could be hosted by UNEP for its authority and in order to engage more people to contribute. Sustained commitment to such a resource would be critical.

12) Build capacity in developing/data-poor countries to monitor ocean health at the regional level

13) Quantification of economic losses to tourism and other industries that results from plastic pollution. This might be achieved by pilot projects in paired sites and would

provide opportunities for outreach and campaigns to increase awareness of local economic costs of littering;

14) Extend research efforts to consider land-based waste management efforts to inform government and non-governmental bodies for improved decision making and to drive change;

15) Carry out a rigorous evaluation of waste management infrastructure and needs for small island nations; and

16) Combine scientific knowledge with outreach, education and policy to achieve greatest impact. This includes development of outreach and awareness raising campaigns that are flexible and can be responsive to the public (simple, useful examples include water stations in airports that show how many plastic water bottles have been saved [increases with each ‘fill’]);

17) Ensure appropriate communication and harmonization occurs with other land-based waste management programs (particularly those that are not ‘marine litter’ focused);

18) Identify potential charismatic or iconic fauna to serve as State of Environment or community target taxa in specific regions. This may include threatened and endangered species for which there may be opportunities to apply additional policy levers as risk assessments identify high-risk geographic regions for impact;

19) Quantification of the impacts of litter on maritime navigation, human injuries on beaches, for divers and for fishers’ safety; and

20) A sustained investment in litter movement in the ocean, particularly utilizing technological opportunities such as space-based monitoring to identify and monitor macro-debris movement in the coastal and marine environment (through satellite imagery and analyses).

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