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Transport, weathering and pollution of plastic from container losses at sea: Observations from a spillage of inkjet cartridges in the North Atlantic Ocean

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Abstract

Observations of beached polypropylene inkjet cartridges, spilled from a ship container lost in the North Atlantic Ocean, have been compiled through calls on social media. Within a period of four years from the spillage, a total of about 1500 cartridges were reported in locations as far apart as Florida and northern Norway. The distribution of cartridges reflected the principal surface currents in the ocean, with some carried by the Canary current, via the Azores and Portugal currents, around the North Atlantic Gyre, and others transported northwards with the North Atlantic and Norwegian currents. Along the shorelines of the UK and Ireland, there was a clear, preferential accumulation of cartridges on west- and south-facing coasts, consistent with the direction of the North Atlantic current and the heading of the principal winds. Dates of first sightings in various regions throughout the North Atlantic suggested that cartridges traveled on average at around 6 to 13 cm s^{-1}. These observations and estimates were largely consistent with simulations of the dispersion of free floating, neutrally buoyant particles from the spillage site derived from an empirical model based on drifter tracking data. Microscopic and X-ray fluorescence analyses of selected cartridges revealed a high degree of exterior weathering, resulting in chalking and embrittlement of the polypropylene and the formation of microplastics rich in Ti, chemical fouling of interior ink foams (where still present) by Fe oxides, and, in some cases, the presence of an electronic chip containing Cu, Au and brominated compounds. Significantly, the latter characteristic renders cartridges as electrical and electronic waste and means that current, conventional regulations on plastic cargo lost at sea are not applicable here. More generally, the study highlights inadequacies in the relevance and robustness of instruments and conventions that deal with plastic waste in the ocean.

Keywords: marine plastic; spillages; transport modeling; weathering; microplastics

Introduction

With estimates of several hundred to several thousand containers lost at sea every year from more than 100 million transported (World Shipping Council, 2017), cargo spillages are not particularly common. However, containers themselves can cause significant local physical and ecological damage to the seabed, as well as more specific impacts related to the nature of the cargo (Frey and De Vogelaere, 2014). Regarding plastic cargo, once containers are ruptured, material will escape and settle on the seabed or rise to the surface and disperse, depending on its density, with an abundance of distinct objects of low density or components therefrom washing up at particular locations over a relatively short period of time. Most container loss goes undocumented or is not reported in a systematic manner because, currently, there is no obligation for lost cargo to be declared unless of a hazardous nature. However, using a mean, estimated annual container loss over the last decade of 568, coupled with an average capacity of 26.5 tonnes and a plastic cargo content of 70%, Galafassi et al. (2019) suggest that up to 10,500 tonnes of marine plastic litter per year may be derived from this route. This compares with estimates of between 4.8 and 12.7 million tonnes of plastic per annum discharged via the global coastal zone (Jambeck et al., 2015).

By tracking or recovering buoyant products, spillages afford an opportunistic means of studying the transport of plastics in the oceans. Moreover, if the date and location of cargo loss are known, information can be potentially useful for improving or calibrating circulation models of floating debris (Iwasaki et al., 2017; Myrhaug et al., 2018; Onink et al., 2019). Among the few plastic spillages gaining media attention, however (and as compiled in Frid and Caswell, 2017), only two appear to have been studied in the scientific literature. Thus, firstly, about 80,000 Nike shoes were lost in the North Pacific Ocean in 1990, and articles subsequently washed ashore provided an important calibration point for a computer model of floatable material in the region (Ebbesmeyer and Ingraham, 1992). Secondly, in 1992 a container of children’s bath toys was lost in the center of the North Pacific Ocean and 29,000 articles of unique design were subsequently tracked and retrieved over a range of thousands of km, allowing an orbital period for flotsam in the Pacific Subarctic Gyre of about 3 years to be estimated (Ebbesmeyer et al., 2007). A more recent analogy, but not involving container loss, is the trans-Pacific transport of floating debris resulting from the Tohoku earthquake and tsunami of 2011. Here, observations of a range of distinctive items or fragments thereof (but mainly boats) at sea or after coastal deposition allowed windage values to be estimated for scaling oceanographic models of the Pacific Ocean (Maximenko et al., 2018).

In January 2014, plastic Hewlett-Packard (HP) inkjet cartridges were lost from a container ship in the middle of the North Atlantic Ocean. After cartridges were first spotted washing up on beaches, calls were put up on social media in order to catalogue and map subsequent observations, with preliminary findings reported in the media (BBC, 2016). Since these reports, however, the dataset has expanded considerably both in terms of number of items recovered and their geographical extent. Accordingly, the present study provides a more critical examination of the full dataset in relation to ocean transport and coastal deposition, and compares observations with simulations of the spillage derived from an empirical (drogue-tracking) model. We also determine the physical and chemical composition of the products and components thereof by suitable analytical techniques in order to gain an understanding of how the material has weathered and address the findings of the study in terms of international laws and conventions.

Materials and Methods

The spillage

The first beached HP cartridges were reported along the coastline of the Azores archipelago, about 1400 km to the west of Portugal, in September 2014. After HP was contacted, the company issued a statement and set up a free phone line and recycling service but was unable (and not obliged) to provide precise details on the number of cartridges or containers lost or the location of the spillage.

HP cartridges were, however, washed up with items that had been spilled from containers aboard the "Suez Canal Bridge", where events and cargo loss had been documented as part of various lawsuits filed (Stamford, 2014). From this information, we assume that containers containing HP cartridges were lost from this ship or one close by in the North Atlantic Ocean between the Azores and the US Coast on 23 January 2014. After requesting more specific information about the movements and anchorage of the "Suez Canal Bridge" from Alphaliner, an internet-based information source on liner shipping, we established a more accurate position for the ship on this date that was some 1500 km east of New York.

Cartridge sightings and reporting

Once HP cartridges had started to appear around the south-west coast of England (towards the end of 2015), a call was set up within an international marine beachcombing group on Facebook with 55,000 members. Sightings of cartridges that were identifiable from the characteristics and signage indicated below were requested, including any retrospectively, along with the location and date. Of particular significance was the date of first appearance of a cartridge in a specific region or location, which we assume provides the best estimate of the timescale involved in reaching the depositional environment from the spillage.

The characteristics and condition of the cartridges were not asked for but were often evident from any photographs or information supplied. The call for the dataset was formally terminated in early 2018 but subsequent observations from some participants continue to be recorded. Any cartridges retrieved by the authors and other respondents that were used for subsequent characterisation and analysis were stored (and posted) in individual, sealed cardboard containers.

Cartridge characteristics

Visual inspection and disassembly of a number of beached cartridges (exemplified in Figure 1) enabled us to establish the characteristics and components of the original products. Thus, they consist of a grey plastic shell (coded A in Figure 1) with the HP logo embossed on the two largest faces, and a magenta cyan or, less frequently, black plastic backing on two edges denoting the color of the ink (B). A tab is attached to the shorter length of the backing, and on the longer length there is a vent hole-air channel configuration (C) that was originally taped over and an electronic chip (D). Intact colored cartridges are about 70 x 37 x 11 mm in size and weigh about 15 g when dry, while black cartridges are notably thicker (about 15 mm) and weigh about 20 g. Densities when dry and sealed are, therefore, calculated to be about 0.5 g cm^{-3}. Cartridge interiors, whose surfaces were evident or readily accessed (E), contain a hydrophobic foam through half of the volume (F, G) which, according to HP, is filled with water-soluble dye ink. The ink outlet port (H), of about 7 mm in diameter on coloured cartridges and about 12 mm on black cartridges, is opposite to the longer edge of the backing and was originally covered with an orange plastic cap of about 55 mm in length and 2 g in mass (I). Markings on the exterior indicate that the plastic shell is polypropylene, and that cartridges were manufactured in China with an expiry date of December 2015.

Based on the part numbers, the inkjet cartridges are HP 564 CVP Cyan, HP 564 CVP Magenta, and HP 564 Black. According to HP, these products are constructed of about 50% of plastic recycled from older cartridges and 50% of plastic recycled from bottles and apparel hangers (Hewlett-Packard Development Company, 2014). Online HP 564 cartridge installation instructions indicate that the product sold to the consumer is shrink-wrapped in clear plastic and boxed.

XRF analysis and microscopy

The surfaces of about 30 cartridges, retrieved by the authors from south-west England or that had been supplied from other participants in western Europe between December 2015 and August 2016, were analysed by portable, energy-dispersive X-ray fluorescence (XRF) spectrometry using a Niton XL3t He GOLDD+. The instrument was configured, nose-upwards, in a laboratory accessory stand and operated in a low density plastics mode with thickness correction. Regions of the cartridges coded in Figure 1 were placed over the detector window and counted for successive periods of 20 seconds and 10 seconds at 50 kV-40 μA and 20 kV-100 μA, respectively. Elemental concentrations (in $\mu g\ g^{-1}$) were derived from secondary X-ray spectral peaks using standardless fundamental parameters software and, for performance checks, polyethylene Niton reference discs impregnated with various elements were analysed at regular intervals throughout each measurement session.

Cartridge components were also examined under an Olympus SZ40 microscope and photographed using a Canon EOS 7D operated with Canon EOS Utility software.

Results and Discussion

Geographical distribution of cartridges and relationships with ocean currents

The sightings of HP cartridges over the four-year survey period specified above are mapped out in Figure 2, along with the best estimate of the spillage location, and the cartridge data are summarized according to region and date of initial sighting in Table 1. Thus, a total of 1467 cartridges was observed by 279 respondents on sandy and pebble beaches and boulder shorelines throughout the North Atlantic Ocean with a range of 7700 km from Tromsø (Norway) in the north-east to Florida in the south-west. More than 50% of cartridges were recorded in the English Channel and Celtic Sea regions of north-west Europe where significant accumulation of marine plastic waste is known to take place (Nelms et al., 2017). It is important to bear in mind, however, that regional differences in cartridge density more generally do not necessarily reflect variations in true geographical abundance because neither the distribution of respondents nor accessibility to the coastal zone are constant. Nevertheless, the overall distribution of cartridges is consistent with the principal wind- and thermohaline-driven surface currents in the North Atlantic Ocean, also indicated in Figure 2, and with the propensity for buoyant plastics to be transported considerable distances in the Atlantic (Cozar et al., 2017; Herrera et al., 2018).

Thus, the best estimate of the source of cartridges is on the northern fringes of the anticyclonic subtropical gyre and in the region where the Gulf Stream bifurcates into the North Atlantic Current and the Azores Current. The latter current transports cartridges towards the Azores archipelago where they were first observed, with subsequent sightings made on the Canary Islands and Cape Verde as the Canary current heads southwards along the coast of North Africa. Cartridges are then transported west with the north equatorial current and northeast with the Gulf Stream, accounting for strandings reported on Bermuda and Florida towards the end of the period of investigation. Meanwhile, the North Atlantic Current carries cartridges in a north-easterly direction towards Ireland and Scotland and, as the Norwegian Current, along the coast of Norway. Branches of the North Atlantic Current head along the coast of Portugal as the broad but often poorly-defined Portugal current, around the Bay of Biscay, and into the Irish Sea via the Celtic Sea and into the North Sea via the English Channel to the south and Norwegian Sea to the north.

In regions impacted by the North Atlantic Current, the accumulation of cartridges is distinctly greater on west- and south-facing coasts in accordance with the general circulation described above. This effect is also evident from the distribution of cartridges retrieved from the UK and Ireland and, on a finer scale, from south-west England (Figure 3). Here, predominantly south-westerly winds and wind-driven residual currents heading east and north-east (Uncles and Stephens, 2007) result in a distinct lack of samples on eastern coasts, despite an abundance of sandy beaches along these sections of shoreline. Thus, local wave dynamics (for example, long- and cross-shore drift), tidal pumping and windage, which are critical to the precise depositional location of buoyant plastics (Zhang, 2017), are unable to sufficiently deviate floating material from its predominantly north-easterly heading into more sheltered embayments.

The dates of initial cartridge observations are also consistent with these patterns of circulation, with the earliest reports being closest oceanographically (i.e. according to the surface current trajectories) to the spillage (Azores) and the latest initial sightings generally recorded at the greatest distances; namely, Florida, Bermuda and northern Norway. Subsequent sightings of cartridges in the same region, which spanned a period of two years in some cases, may be attributable to deposition in areas that evade ready access or plastic detection, cycling and retention in the local coastal zone or entrapment in oceanic and coastal eddies (Brach et al., 2018). It is also possible that the release of some cartridges may have been hindered by their position or packing relative to container rupturing.

Assuming that timescales involved in beaching and participant detection are small relative to timescales involved in oceanic transport, the dates of initial sightings were used to estimate the times taken to travel along their trajectories from the spillage to their depositional locations and, coupled with distances evaluated from surface current patterns, mean speeds of transportation (Table 1). Values of the latter are rather consistent but are greatest and above 9.5 cm s^{-1} for trajectories to the Azores and regions directly impacted by the North Atlantic Current (Celtic Sea, W Scotland and N North Sea) and are lowest and about 6 cm s^{-1} for trajectories to the islands along the eastern boundary Canary Current. By comparison, mean, near-surface advection speeds computed from satellite-tracked Lagrangian drogue drifter data range from 1.6 m s^{-1} in the Portugal current and 10 to 15 m s^{-1} in the Azores, Canary and North Equatorial currents to more than 30 cm s^{-1} for the Gulf Stream and the North Atlantic and Norwegian currents (Lumpkin and Johnson, 2013; University of Miami, 2013).

Dispersion modeling of cartridges

The dispersion of cartridges was modeled using PlasticAdrift (plasticadrift.org), an online surface drift tool based on an extensive dataset of drogued and undrogued drifter trajectories as aggregated in the NOAA Global Drifting Buoy Program (van Sebille, 2014). Here, the probability distributions of free drifting, neutrally buoyant particles released from the spillage location during a single event were mapped at a spatial resolution of one degree (latitude and longitude), a temporal resolution of two months and a depth of < 15 m over a period of ten years. For the fifteen regions shown in Table 1, and because drifter data are lacking near coastlines, modeled locations were selected as grids as close to the coastline of initial observation as possible or at the central entry point of a distinctive body of water (such as the English Channel and southern North Sea) and as indicated in Figure 2. In each grid, data were acquired as a time-series of probabilities of encountering a particle, as exemplified in Figure 4 for the Azores, Bay of Biscay, Bermuda and Irish Sea.

Of significance are the times elapsed (since the spillage) at which the model first predicted the regional passage of a particle, regardless of its probability, relative to the times when HP cartridges were first sighted (Table 1). Thus, despite the precise observational and modeled locations not always being coincident, model results being constrained by a rather coarse resolution, coastal processes that are not factored into the simulations (e.g. wave and tidal action; Fauziah et al., 2015; Naidoo et al., 2015), and beachcombing not being a continuous process, agreement within 20% occurs in the Celtic and Irish Seas, along the coast of Portugal and in the Canaries. In the majority of the remaining cases, initial cartridge observations are delayed relative to the onset of modeled probability. However, a closer examination of the simulated time series reveals that, in most of these regions, initial cartridge sightings, annotated on the examples shown in Figure 4, coincide with or are close to a single peak or the first of a number of recurring, seasonal peaks in probability.

In contrast, at three locations cartridges were observed in advance of model predictions. Specifically, in the southern North Sea and coastal Florida, cartridges were first reported four months and three years ahead of the onset of model probability, respectively, and while a cartridge was retrieved from Cape Verde 35 months after the spillage occurred, modeled particles did not extend this far south over the ten-year period considered. For the southern North Sea, the discrepancy maybe attributed to lack of drifter data in this region (plasticadrift.org). More generally, however, these observations suggest that floating plastic may reach some locations more rapidly or may deposit in regions where plastic is not predicted on the basis of Lagrangian tracking considerations alone through additional transport mechanisms such as windage and Stokes drift (that are only partly accounted for in the model through undrogued drifter data).

Overall, outputs as animated maps and timed predictions revealed a net reduction in probability over the ten-year period that was most rapid in the Azores and most protracted in Bermuda and the Bay of Biscay. That is, eventually, cartridges are predicted to become trapped in the North Atlantic Gyre and the anticyclonic circulation of the Bay of Biscay.

Table 1: Number of HP cartridge sightings (*n*) ordered by the date of first sighting in different regions of the North Atlantic. (Note that initial sightings on the Azores were reported as a range of dates in September 2014.) Also shown are the times elapsed from the spillage to the first sightings, estimates of the mean speed of travel from the spillage to the locations of deposition, and the onset of probability of a cartridge occurring in the regional grids shown in Figure 2 as predicted by the empirical model, PlasticAdrift.

region	*n*	date of first sighting	time elapsed since first sighting, d	mean speed, cm s^{-1}	onset of modeled probability, d
1. Azores	150	Sep-14	230-250	12.3-13.4	120
2. Celtic Sea*	342	01-Nov-15	647	9.7	660
3. Ireland	84	09-Dec-15	685	8.6	480
4. W Scotland	91	11-Dec-15	687	9.7	420
5. English Channel	440	13-Dec-15	689	9.4	480
6. Bay of Biscay	145	16-Dec-15	692	9.0	480
7. Portugal**	74	19-Dec-15	695	8.5	660
8. Irish Sea	43	23-Dec-15	699	8.8	600
9. N North Sea	1	26-Feb-16	764	10.5	600
10. S North Sea	11	28-Feb-16	766	9.0	900
11. Canaries	20	03-May-16	831	6.0	720
12. Cape-Verde	1	10-Dec-16	1052	6.0	>
13. Norway	1	04-Jun-17	1228	8.3	900
14. Bermuda	63	16-Sep-17	1322	8.9	240
15. Florida	1	26-Oct-17	1372	8.8	2400

*Excluding the Irish coast.

**Including NW Spain.

> Probability was never returned over the period of simulation.

Physical and chemical modifications of cartridges in the environment

Among the cartridge sightings, there was no evidence of shrink-wrapping residue. This suggests that that packaging material (presumably low density polyethylene) deteriorates or degrades at sea significantly more rapidly than the cartridges themselves or that the shrink-wrapping is not readily identified from beach cleans amongst a broader array of packaging waste. The majority of cartridges reported or photographed were largely intact but usually without the plastic cap attached, although some exhibited significant fracturing and had shed the internal hydrophobic foam.

In order to evaluate more closely their physical and chemical characteristics and any changes incurred during oceanic transportation and beaching, different components of selected cartridges were examined under a microscope and analysed by XRF spectrometry. The components are photographed and coded in Figure 5 and examples of XRF spectra are given in Figure S1. In some cases, external surfaces (A) exhibited evidence of fouling by oil and rust, with the latter returning a high Fe signal. However, apart from visible goose barnacles and algal deposits on some cartridges, there was no microscopic evidence of biofouling. The grey shells returned high concentrations of Ti (~ 10,000 $\mu g\ g^{-1}$), reflecting pigmentation of the polypropylene by titanium dioxide, TiO_2, as an opacifier, and compared with the internal surfaces (E), external surfaces (A) were whiter, more brittle and chalky, and exhibited pits, cracks, fissures and notches resulting from photo-oxidation and mechanical weathering. Chalkiness displayed by cartridge exteriors may be attributed to the ability of TiO_2 to absorb UV radiation and, with a product not designed for exterior use, lack of any protective treatment to the pigment (McKeen, 2013).

The cartridge backings (C) displayed similar characteristics to the shells, with (less) chalky external surfaces that were paler and more weathered than internal surfaces; backings exhibited a weaker Ti signal but additional elements were detected reflecting the presence of coloured pigments (e.g. Cu in blue material).

The internal structure of the hydrophobic foam (G) was highly porous and usually rather homogeneous in appearance, and the most notable fluorescent signals were associated with Cl (up to 30,000 $\mu g\ g^{-1}$) and Ca (not quantified in the low density plastics mode) that, presumably, reflect residues of seawater salt trapped in the structure. The external surfaces of foam (F) that were facing the empty ink reservoirs were discolored and contained particulates of varying size and shape. Here, Fe was usually present (in addition to Cl) up to concentrations of a few thousand $\mu g\ g^{-1}$ resulting from fouling of areas directly exposed to seawater through lithogenous particle capture and aqueous ion adsorption or precipitation. Where hydrophobic foam was exposed through the ink outlet port (H), there was sometimes evidence of residual coloured ink and usually an accumulation of particulates that included both lithogenous grains and paler (off-white) microplastics that had flaked off the exterior surface of the deteriorating shell.

The electronic chips (D) that were still adhered to the backing of many cartridges exhibited variable degrees of damage and states of degradation. Here, high but variable concentrations of both Cu and Br (1000 to 5000 $\mu g\ g^{-1}$ and 1000 to 13,000 $\mu g\ g^{-1}$, respectively) were measured by the XRF, along with lower concentrations of Au (a few hundred $\mu g\ g^{-1}$). The presence of these elements results from wire bonding, brominated flame retardants (BFRs) and plating that are characteristic in integrated circuitry (Pecht, 1994), with variable concentrations among chips likely reflecting differences in the degree of weathering.

Also shown in Figure 5 (J) is a microscopic image of debris derived from the cleaning and disassembly of three cyan cartridges. The yellow, brown and dark grey particles are grains of silt that had accumulated internally and externally during transportation or beaching, while white and blue particles, of < 100 μm to 1 mm in dimension, are fragments of (micro-) plastic that had readily chalked and flaked off the external cartridge surfaces during manipulation. Thus, aside from the general impacts associated with marine plastic litter, the HP cartridges appear to act as a ready source of microplastics whose chemical and toxicological impacts may be modified by the presence of TiO_2 particulates and traces of BFRs.

Regulations relevant to the cartridge spillage

A wide range of instruments exists at regional, national and international levels in order to prevent, reduce and manage marine litter, including plastics, and these have been reviewed by Chen et al. (2015). What is lacking, however, is any specific guidance or instrument on the loss of plastic at sea during its transportation as cargo or, more generally, to plastic waste sourced or encountered outside the jurisdiction of any one nation or group of nations (Gold et al., 2013).

The United Nations Convention on the Law of the Sea (UNCLOS) (United Nations, 1982) prohibits the dumping of wastes from ships at sea but excludes matter incidental to or derived from the 'normal' operations of vessels. The latest iteration of Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL) seeks to reduce the amount of garbage being discharged at sea from ships but exempts the accidental loss of waste arising from damage to a ship or its equipment (International Maritime Organization, 2020). Although these conventions appear to classify cargo lost overboard as garbage or derived from normal operations, the IMO has since established an action plan for 2025 that will consider a compulsory means of declaring plastic litter derived from containers lost at sea

From a regulatory perspective, the current case involving HP inkjet cartridges is potentially more complex because the products were fitted with electronic chips and are, therefore, classified as electrical and electronic consumables (Environment Agency, 2018). Accordingly, cartridges are subject to the Waste Electrical and Electronic (WEEE) Directive (European Parliament and Council, 2012) and the Restriction of Hazardous Substances (RoHS) Directive (European Parliament and Council, 2011). Moreover, according to MARPOL Annex V, cartridges are defined as E-waste consumables which contain material potentially hazardous to human health and/or the environment (Marine Environment Protection Committee, 2017). The element of greatest potential hazard identified on the cartridge chips from XRF analysis is Br, a constituent of brominated flame retardants (BFRs). According to the RoHS Directive, concentrations of certain BFRs (polybrominated diphenyl ethers and polybrominated biphenyls) must not exceed 1000 $\mu g\ g^{-1}$ by weight on any component of an electrical item that can be separated mechanically. The total Br content, indicative of a lower estimate of total BFR content, exceeded this in all chips analysed but without knowing whether restricted or unrestricted BFRs were used (i.e. the form of Br) it is not possible to ascertain whether or not these components are classified as hazardous.

General Discussion

Although plastics are ubiquitous throughout the global ocean, their precise origin and age is often difficult to establish. This is because, through fragmentation and erosion, original objects or defining characteristics may not be recognizable, sources of a given plastic may be diffuse, multiple or poorly defined, and there may be a significant (years to decades) time interval between terrestrial emissions and accumulation in offshore waters (Welden and Lusher, 2017; Lebreton et al., 2019).

Conclusions

The current study is both novel and significant in that inkjet cartridges having a distinct signage (product code and use by date) and source have been widely reported on beaches throughout the North Atlantic by a large, international network of volunteers through calls on social media. Locations and dates of these observations are consistent with the broad surface circulation of the

North Atlantic and with model outputs based on Lagrangian drift from the spill site, suggesting that, in general, the transport and fate of buoyant plastic can be predicted well from empirical tracking data. However, in some regions cartridges were observed significantly in advancement of model simulations or at locations where the model failed to predict surface transport, highlighting the potential importance of oceanic processes like windage that are not completely factored into the model and that act to modify the speed and direction of floating material. Observations in areas where drifter tracking data are sparse, such as the southern North Sea and English Channel, could prove useful for improving the calibration of plastic transport models in marginal seas.

The particular product under study has also indicated how readily plastics not designed for external exposure breakdown and act as a ready source of microplastics in the environment. Moreover, the complex, multicomponent (electronic) nature of the product has questioned the relevance and robustness of current instruments and conventions that deal with plastic waste and its accidental loss at sea.

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Figure 1: Components of the HP inkjet cartridges, photographed on mm-scaled graph paper. A: plastic shell; B: colored backing; C: vent hole and air channel; D: electronic chip; E: interior shell surface; F: hydrophobic foam exterior; G: hydrophobic foam interior; H: ink outlet port; I: plastic tab.

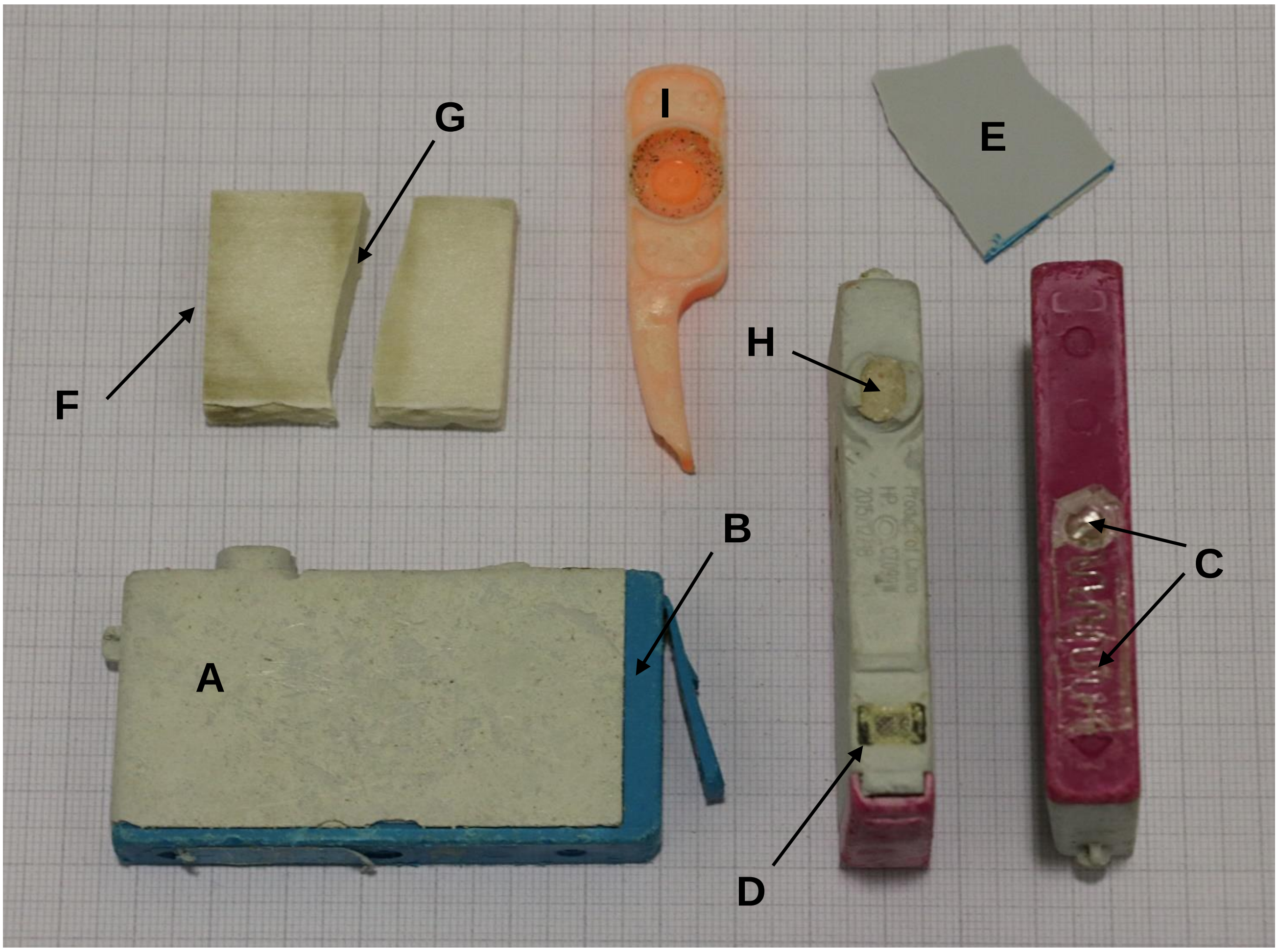

Figure 2: Sightings of beached HP inkjet cartridges in the North Atlantic. (Note that individual dots represent multiple sightings in some locations.) Also annotated are the spillage site, surface currents relevant to the discussion, and grid locations modeled using plasticadrift.org and as numbered in Table 1. Note that the scale bar is indicative only.

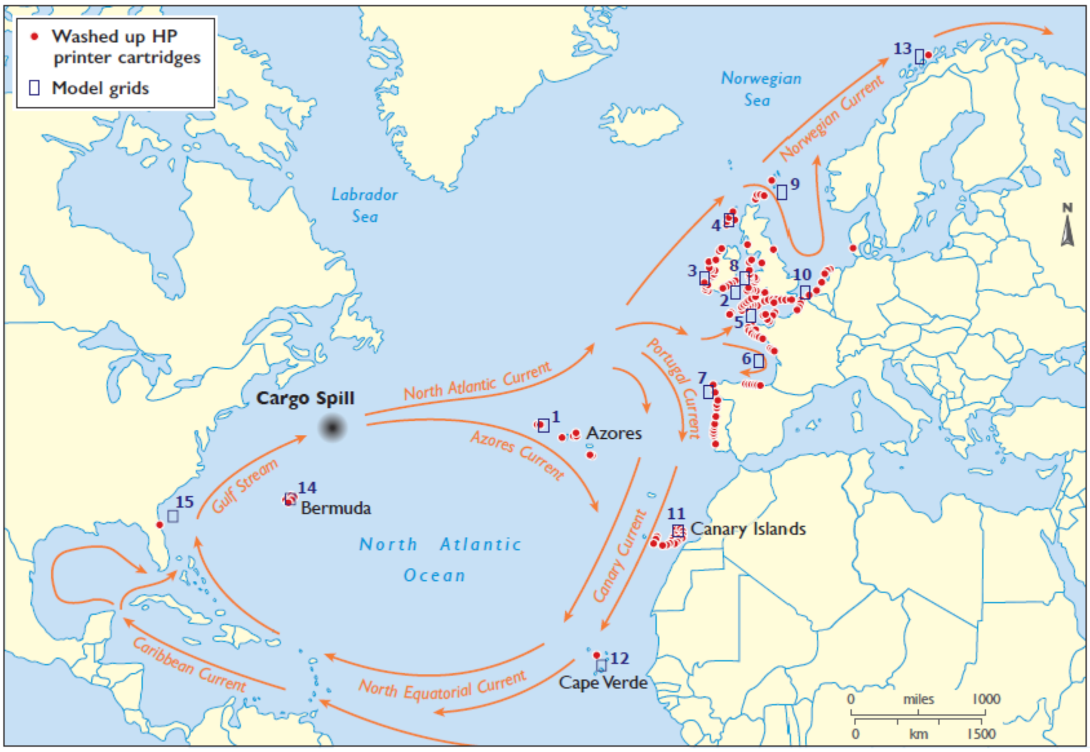

Figure 3: Sightings of beached HP cartridges around the British Isles and, expanded, south-west England. Note the lack of sightings on eastern coasts and, in south-west England, along the sheltered, rocky shoreline of the Bristol Channel. Also shown and as numbered in Table 1 are grid locations used in the plastic.adrift simulation.

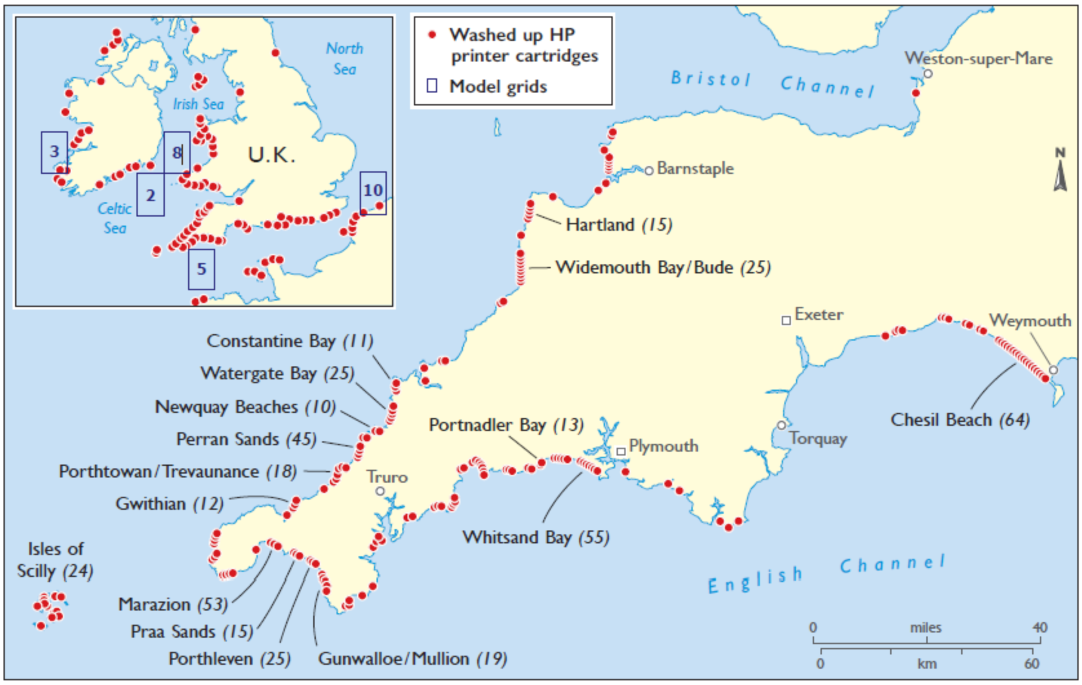

Figure 4: Modeled ten-year time-series of the probability (p) of encountering a free drifting, neutrally buoyant particle emitted from the spillage site at four different grid locations (see Figures 2 and 3). Red arrows denote the times since the spillage at which beached cartridges were first observed in each region.

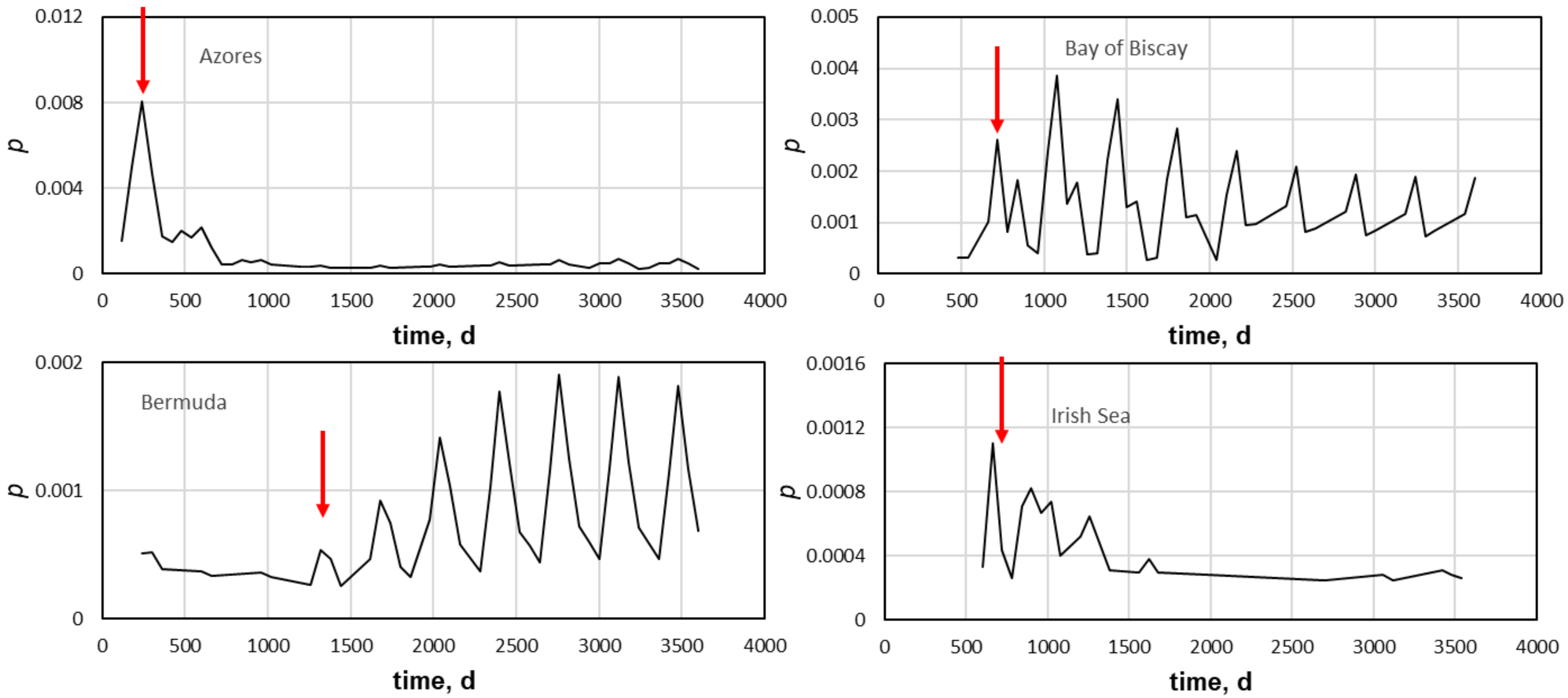

Figure 5: Microscopic images of different components of various HP cartridges. A: inner plastic shell; E: outer plastic shell; G: inner face of hydrophobic foam; F: outer face of hydrophobic foam; D: electronic chips; H: ink outlet port; J: debris arising from sample manipulation. Note that the scale bar is 1 mm.