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

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20 **Abstract**

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

41

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

43

44 **Introduction**

45 With estimates of several hundred to several thousand containers lost at sea every year from more
46 than 100 million transported (World Shipping Council, 2017), cargo spillages are not particularly
47 common. However, containers themselves can cause significant local physical and ecological damage
48 to the seabed, as well as more specific impacts related to the nature of the cargo (Frey and De
49 Vogelaere, 2014). Regarding plastic cargo, once containers are ruptured, material will escape and
50 settle on the seabed or rise to the surface and disperse, depending on its density, with an abundance
51 of distinct objects of low density or components therefrom washing up at particular locations over a
52 relatively short period of time. Most container loss goes undocumented or is not reported in a
53 systematic manner because, currently, there is no obligation for lost cargo to be declared unless of a
54 hazardous nature. However, using a mean, estimated annual container loss over the last decade of
55 568, coupled with an average capacity of 26.5 tonnes and a plastic cargo content of 70%, Galafassi et
56 al. (2019) suggest that up to 10,500 tonnes of marine plastic litter per year may be derived from this
57 route. This compares with estimates of between 4.8 and 12.7 million tonnes of plastic per annum
58 discharged via the global coastal zone (Jambeck et al., 2015).

59 By tracking or recovering buoyant products, spillages afford an opportunistic means of studying the
60 transport of plastics in the oceans. Moreover, if the date and location of cargo loss are known,
61 information can be potentially useful for improving or calibrating circulation models of floating
62 debris (Iwasaki et al., 2017; Myrhaug et al., 2018; Onink et al., 2019). Among the few plastic spillages
63 gaining media attention, however (and as compiled in Frid and Caswell, 2017), only two appear to
64 have been studied in the scientific literature. Thus, firstly, about 80,000 Nike shoes were lost in the
65 North Pacific Ocean in 1990, and articles subsequently washed ashore provided an important
66 calibration point for a computer model of floatable material in the region (Ebbesmeyer and
67 Ingraham, 1992). Secondly, in 1992 a container of children's bath toys was lost in the center of the
68 North Pacific Ocean and 29,000 articles of unique design were subsequently tracked and retrieved

69 over a range of thousands of km, allowing an orbital period for flotsam in the Pacific Subarctic Gyre
70 of about 3 years to be estimated (Ebbesmeyer et al., 2007). A more recent analogy, but not involving
71 container loss, is the trans-Pacific transport of floating debris resulting from the Tohoku earthquake
72 and tsunami of 2011. Here, observations of a range of distinctive items or fragments thereof (but
73 mainly boats) at sea or after coastal deposition allowed windage values to be estimated for scaling
74 oceanographic models of the Pacific Ocean (Maximenko et al., 2018).

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

86

87 **Materials and Methods**

88 *The spillage*

89 The first beached HP cartridges were reported along the coastline of the Azores archipelago, about
90 1400 km to the west of Portugal, in September 2014. After HP was contacted, the company issued a
91 statement and set up a free phone line and recycling service but was unable (and not obliged) to
92 provide precise details on the number of cartridges or containers lost or the location of the spillage.

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

101 *Cartridge sightings and reporting*

102 Once HP cartridges had started to appear around the south-west coast of England (towards the end
103 of 2015), a call was set up within an international marine beachcombing group on Facebook with
104 55,000 members. Sightings of cartridges that were identifiable from the characteristics and signage
105 indicated below were requested, including any retrospectively, along with the location and date. Of
106 particular significance was the date of first appearance of a cartridge in a specific region or location,
107 which we assume provides the best estimate of the timescale involved in reaching the depositional
108 environment from the spillage.

109 The characteristics and condition of the cartridges were not asked for but were often evident from
110 any photographs or information supplied. The call for the dataset was formally terminated in early
111 2018 but subsequent observations from some participants continue to be recorded. Any cartridges
112 retrieved by the authors and other respondents that were used for subsequent characterisation and
113 analysis were stored (and posted) in individual, sealed cardboard containers.

114

115 *Cartridge characteristics*

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

131 Based on the part numbers, the inkjet cartridges are HP 564 CVP Cyan, HP 564 CVP Magenta, and HP
132 564 Black. According to HP, these products are constructed of about 50% of plastic recycled from
133 older cartridges and 50% of plastic recycled from bottles and apparel hangers (Hewlett-Packard
134 Development Company, 2014). Online HP 564 cartridge installation instructions indicate that the
135 product sold to the consumer is shrink-wrapped in clear plastic and boxed.

136 *XRF analysis and microscopy*

137 The surfaces of about 30 cartridges, retrieved by the authors from south-west England or that had
138 been supplied from other participants in western Europe between December 2015 and August 2016,
139 were analysed by portable, energy-dispersive X-ray fluorescence (XRF) spectrometry using a Niton
140 XL3t He GOLDD+. The instrument was configured, nose-upwards, in a laboratory accessory stand and

141 operated in a low density plastics mode with thickness correction. Regions of the cartridges coded in
142 Figure 1 were placed over the detector window and counted for successive periods of 20 seconds
143 and 10 seconds at 50 kV-40 μA and 20 kV-100 μA , respectively. Elemental concentrations (in $\mu\text{g g}^{-1}$)
144 were derived from secondary X-ray spectral peaks using standardless fundamental parameters
145 software and, for performance checks, polyethylene Niton reference discs impregnated with various
146 elements were analysed at regular intervals throughout each measurement session.

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

149

150 **Results and Discussion**

151 *Geographical distribution of cartridges and relationships with ocean currents*

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

164 in Figure 2, and with the propensity for buoyant plastics to be transported considerable distances in
165 the Atlantic (Cozar et al., 2017; Herrera et al., 2018).

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

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

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

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

208 *Dispersion modeling of cartridges*

209 The dispersion of cartridges was modeled using PlasticAdrift (plasticadrift.org), an online surface
210 drift tool based on an extensive dataset of drogued and undrogued drifter trajectories as aggregated
211 in the NOAA Global Drifting Buoy Program (van Sebille, 2014). Here, the probability distributions of
212 free drifting, neutrally buoyant particles released from the spillage location during a single event

213 were mapped at a spatial resolution of one degree (latitude and longitude), a temporal resolution of
214 two months and a depth of < 15 m over a period of ten years. For the fifteen regions shown in Table
215 1, and because drifter data are lacking near coastlines, modeled locations were selected as grids as
216 close to the coastline of initial observation as possible or at the central entry point of a distinctive
217 body of water (such as the English Channel and southern North Sea) and as indicated in Figure 2. In
218 each grid, data were acquired as a time-series of probabilities of encountering a particle, as
219 exemplified in Figure 4 for the Azores, Bay of Biscay, Bermuda and Irish Sea.

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

231 In contrast, at three locations cartridges were observed in advance of model predictions. Specifically,
232 in the southern North Sea and coastal Florida, cartridges were first reported four months and three
233 years ahead of the onset of model probability, respectively, and while a cartridge was retrieved from
234 Cape Verde 35 months after the spillage occurred, modeled particles did not extend this far south
235 over the ten-year period considered. For the southern North Sea, the discrepancy maybe attributed
236 to lack of drifter data in this region (plasticadrift.org). More generally, however, these observations
237 suggest that floating plastic may reach some locations more rapidly or may deposit in regions where

238 plastic is not predicted on the basis of Lagrangian tracking considerations alone through additional
 239 transport mechanisms such as windage and Stokes drift (that are only partly accounted for in the
 240 model through undrogued drifter data).

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

245

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

region	<i>n</i>	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
252 15. Florida	1	26-Oct-17	1372	8.8	2400

253 *Excluding the Irish coast.

254 **Including NW Spain.

255 > Probability was never returned over the period of simulation.

256

257 *Physical and chemical modifications of cartridges in the environment*

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

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

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

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

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

299 Also shown in Figure 5 (J) is a microscopic image of debris derived from the cleaning and disassembly
300 of three cyan cartridges. The yellow, brown and dark grey particles are grains of silt that had
301 accumulated internally and externally during transportation or beaching, while white and blue

302 particles, of < 100 µm to 1 mm in dimension, are fragments of (micro-) plastic that had readily
303 chalked and flaked off the external cartridge surfaces during manipulation. Thus, aside from the
304 general impacts associated with marine plastic litter, the HP cartridges appear to act as a ready
305 source of microplastics whose chemical and toxicological impacts may be modified by the presence
306 of TiO₂ particulates and traces of BFRs.

307

308 *Regulations relevant to the cartridge spillage*

309 A wide range of instruments exists at regional, national and international levels in order to prevent,
310 reduce and manage marine litter, including plastics, and these have been reviewed by Chen et al.
311 (2015). What is lacking, however, is any specific guidance or instrument on the loss of plastic at sea
312 during its transportation as cargo or, more generally, to plastic waste sourced or encountered
313 outside the jurisdiction of any one nation or group of nations (Gold et al., 2013).

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

323 From a regulatory perspective, the current case involving HP inkjet cartridges is potentially more
324 complex because the products were fitted with electronic chips and are, therefore, classified as
325 electrical and electronic consumables (Environment Agency, 2018). Accordingly, cartridges are

326 subject to the Waste Electrical and Electronic (WEEE) Directive (European Parliament and Council,
327 2012) and the Restriction of Hazardous Substances (RoHS) Directive (European Parliament and
328 Council, 2011). Moreover, according to MARPOL Annex V, cartridges are defined as E-waste
329 consumables which contain material potentially hazardous to human health and/or the environment
330 (Marine Environment Protection Committee, 2017). The element of greatest potential hazard
331 identified on the cartridge chips from XRF analysis is Br, a constituent of brominated flame
332 retardants (BFRs). According to the RoHS Directive, concentrations of certain BFRs (polybrominated
333 diphenyl ethers and polybrominated biphenyls) must not exceed $1000 \mu\text{g g}^{-1}$ by weight on any
334 component of an electrical item that can be separated mechanically. The total Br content, indicative
335 of a lower estimate of total BFR content, exceeded this in all chips analysed but without knowing
336 whether restricted or unrestricted BFRs were used (i.e. the form of Br) it is not possible to ascertain
337 whether or not these components are classified as hazardous.

338 *General Discussion*

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

344

345 **Conclusions**

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

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

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

363

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368

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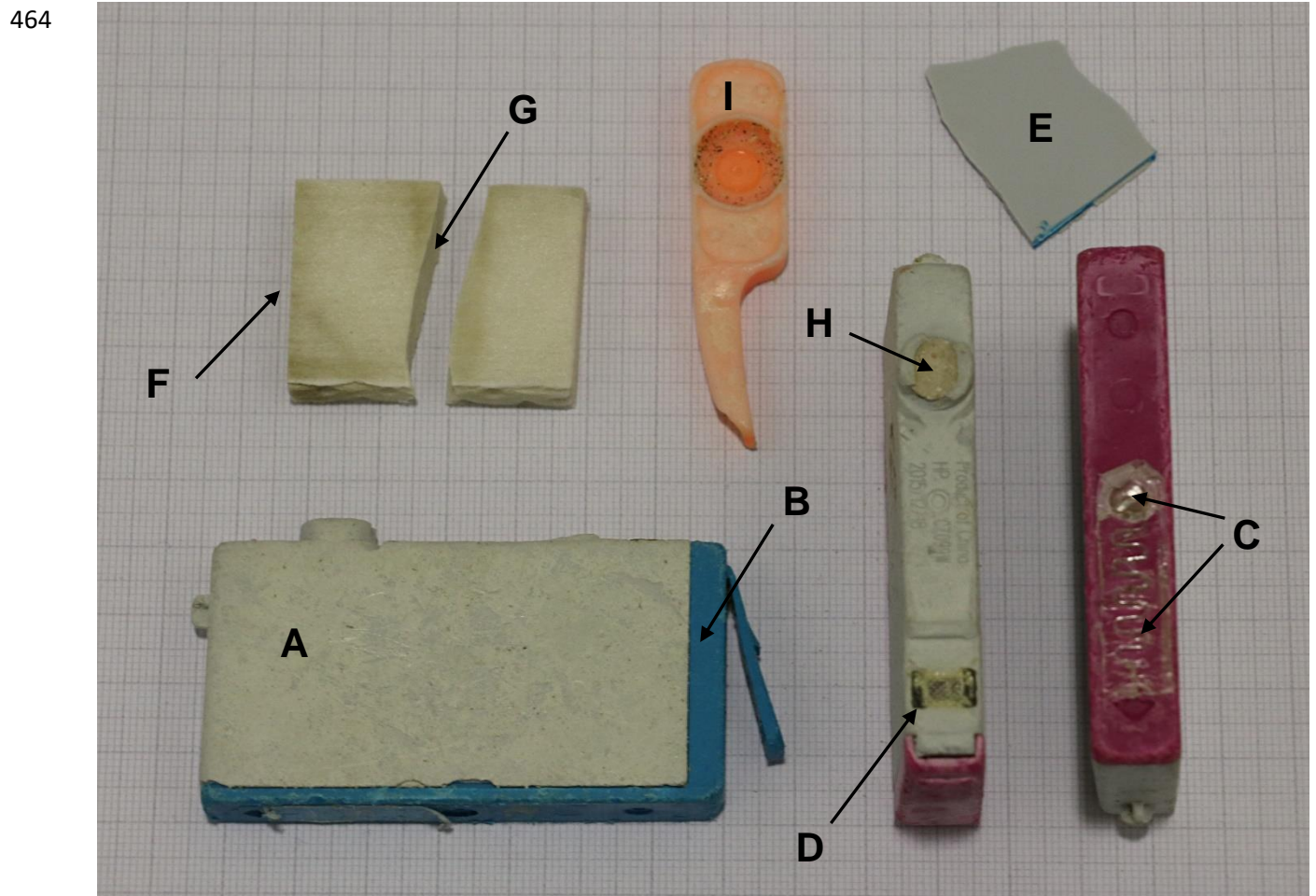
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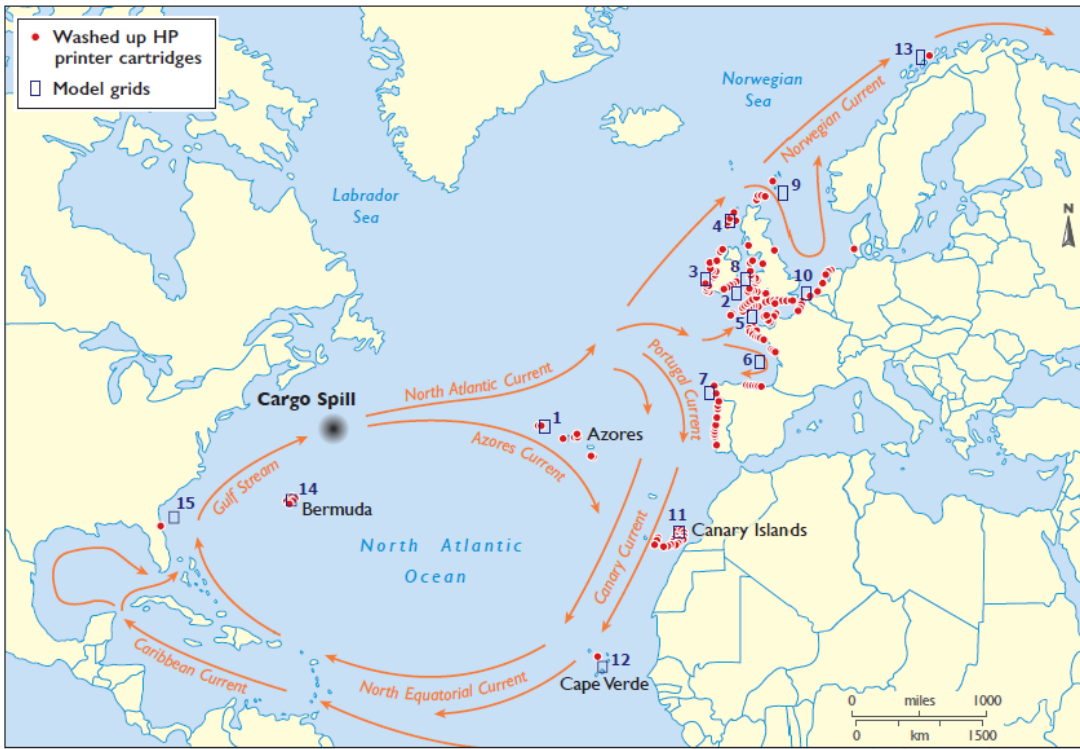
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461 Figure 1: Components of the HP inkjet cartridges, photographed on mm-scaled graph paper. A:
462 plastic shell; B: colored backing; C: vent hole and air channel; D: electronic chip; E: interior shell
463 surface; F: hydrophobic foam exterior; G: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



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



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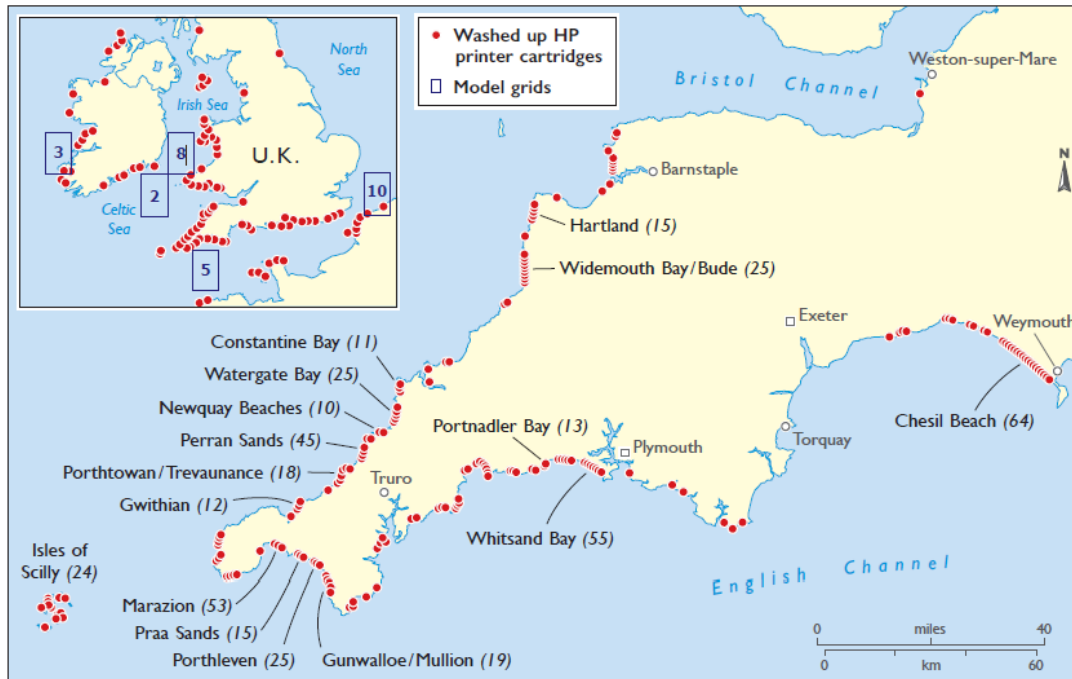
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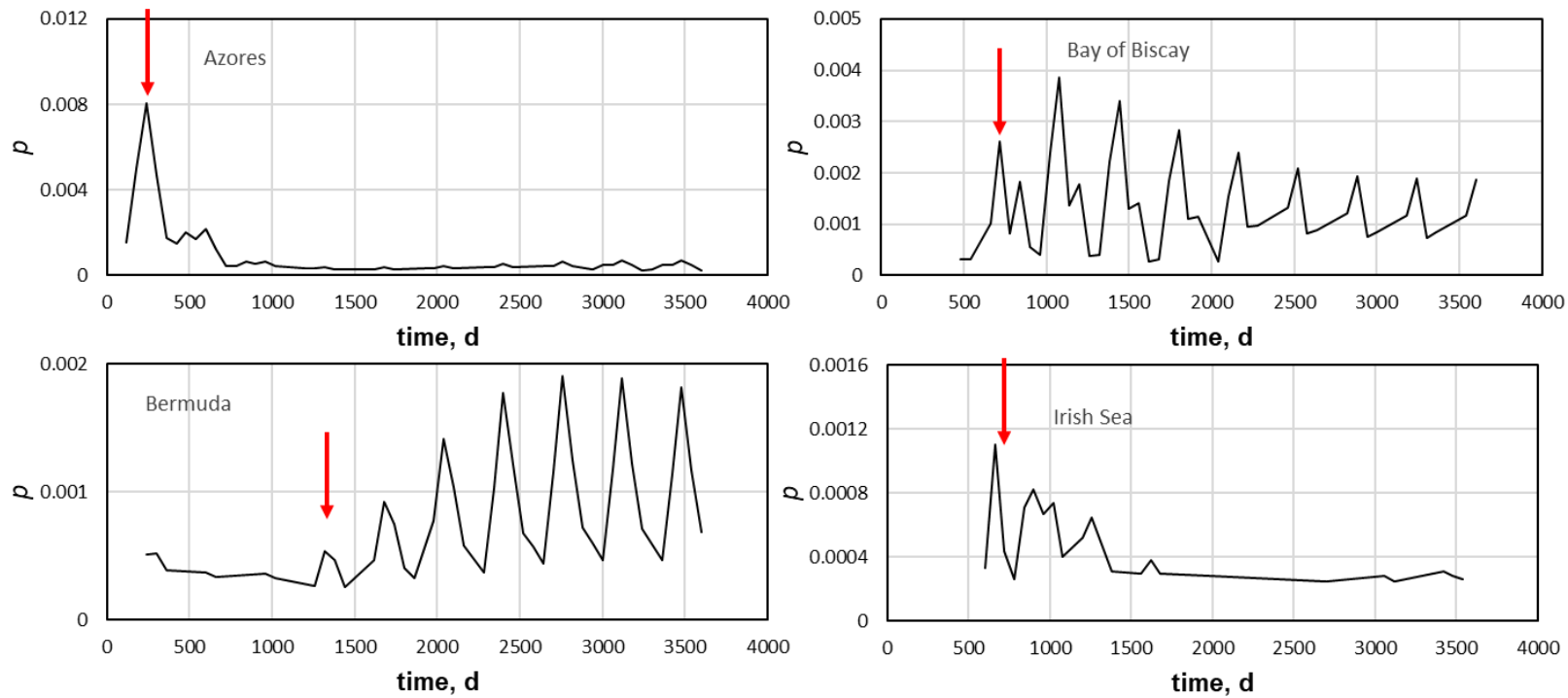
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478 Figure 3: Sightings of beached HP cartridges around the British Isles and, expanded, south-west
 479 England. Note the lack of sightings on eastern coasts and, in south-west England, along the
 480 sheltered, rocky shoreline of the Bristol Channel.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

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488 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
489 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.



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

