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► **To cite this version:**

Fanny Chenillat, Thierry Huck, Christophe Maes, Nicolas Grima, Bruno Blanke. Fate of floating plastic debris released along the coasts in a global ocean model. *Marine Pollution Bulletin*, 2021, 165, pp.112116. 10.1016/j.marpolbul.2021.112116 . hal-03373319

HAL Id: hal-03373319

<https://hal.science/hal-03373319>

Submitted on 11 Oct 2021

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Fate of floating plastic debris released along the coasts in a global ocean model

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submitted to *Marine Pollution Bulletin* – revised version with notes

Abstract

Marine plastic pollution is a global issue, from the shores to the open ocean. Understanding the pathway and fate of plastic debris is fundamental to manage and reduce plastic pollution. Here, the fate of floating plastic pollution discharged along the coasts is studied by comparing two sources, one based on river discharges and the other on coastal populations, using a Lagrangian numerical analysis in a global ocean circulation model. About 1/3 of the particles end up in the open ocean and 2/3 on beaches. The input scenario largely influences the accumulation of particles toward the main subtropical convergence zones, with the South Pacific and North Atlantic being mostly fed by the inputs of the coastal population. The input scenario influences the number of beached particles that end up in several coastal areas. Beaching occurs mainly locally, although a significant number of particles travel long distances, allowing for global connectivity.

1. Introduction

Marine pollution from plastics is a global issue and challenge (persistence of plastics at sea, consequences for marine life and potentially human health) that infests the ocean from coastal

30 regions (e.g., Bergmann et al., 2017; Napper and Thompson, 2020) to the open sea (Barnes et
31 al., 2009; Law et al., 2010; Cozar et al., 2014; van Sebille et al., 2015; Lebreton et al., 2018).
32 According to Geyer et al. (2017), about half of the plastic debris produced is less dense than
33 seawater and, consequently, is expected to float at the sea surface. This floating pollution
34 either accumulates in the center of subtropical gyres (e.g., the Pacific Garbage Patch) or is
35 discharged onto coasts and beaches. Transport of plastic is affected by a variety of physical
36 processes (van Sebille et al., 2020; Dobler et al., 2019) characterized by different temporal and
37 spatial variability. The pathways and fate of plastic debris in the oceans are still uncertain for
38 many reasons, including a misperception of their sources, both in terms of quantity and
39 distribution (Viatte et al., 2020). Indeed, observations are still limited, and the origins of the
40 plastic collected at sea and along coasts remain ~~completely impossible~~ a challenge to identify or
41 assess.

42 Most of the projects on this issue are nowadays oriented toward a particular region or theme
43 (Black et al., 2020), whereas plastic pollution must be considered as a global concern (Maes et
44 al., 2019). Understanding the main pathway and fate of plastic debris remains fundamental to
45 better manage and reduce plastic pollution from an environmental and economic perspective.
46 Indeed, Lau et al. (2020) have shown that if no plastic pollution reduction strategy is
47 undertaken, plastic pollution will triple by 2040. Despite the multiplicity of plastic pollution
48 sources and the large uncertainties about the contribution of land-based plastic pollution
49 (Horton and Dixon, 2017), according to van Sebille et al. (2020), it is today recognized that
50 coastal pollution is one of the largest sources of ocean plastic waste globally, with 5 to 12
51 million tons year⁻¹ (Jambeck et al., 2015). As estimated by Faris and Hart (1994), 80% of marine
52 litter enters the ocean by land, with the remaining 20% assumed to come from marine activities
53 such as commercial and recreational fishing, cruises, and shipping (Lebreton et al., 2012). ~~Given~~
54 ~~the scarcity of available data and observations on marine litter and plastic pollution (Cozar et~~
55 ~~al., 2014), numerical models appear to be one of the most adequate tools for understanding~~
56 ~~the transport and dispersion of plastic in the ocean (Hardesty et al., 2017), especially in a~~
57 ~~Lagrangian framework (van Sebille et al., 2018).~~ Given the scarcity of available data and
58 observations on marine litter and plastic pollution (Galvani et al., 2021), numerical simulation

59 can be used ‘to fill in the gap’ between these observations, and to test hypotheses about how
60 plastic particles behave in the ocean” as explained in van Sebille et al. (2020). Indeed, numerical
61 models are proper tools for understanding the transport and dispersion of plastic in the ocean
62 (Hardesty et al., 2017), especially in a Lagrangian framework (van Sebille et al., 2018).
63 For instance, Lebreton et al. (2012) studied the relative contributions of plastics from
64 impervious watersheds, coastal population and shipping inputs to different accumulation
65 zones. In their study, they estimated that between 28% and 40% of the released particles were
66 beached, depending on the input scenario.

67 Using a similar numerical methodology, we study hereafter the fate of floating plastic pollution
68 in the ocean as discharged along the coasts. We compare two different ~~types~~ scenario of
69 sources in the global ocean: one based on river inputs, and the other based on population
70 density along the coasts and waste management. We use a Lagrangian numerical analysis in
71 conjunction with surface currents from a reanalysis of a global ocean circulation model with a
72 horizontal resolution of $1/12^\circ$. ~~In both scenarios, we find the five persistent convergence zones~~
73 ~~located in the subtropical gyres, also known as garbage patches (Kubota, 1994; Maximenko et~~
74 ~~al., 2012), but with different characteristics. More generally, particles ending up at sea~~
75 ~~represent less than half of the particles released (and less than 20 % in the convergence zones),~~
76 ~~whereas more than 50% end up at the coast.~~ We discuss how the use of different scenarios
77 helps to understand ocean connectivity and plastic pollution on a global scale. This study ~~also~~
78 highlights the importance of considering accurate coastal inputs or sources, in particular
79 littering from coastal populations, and provides insight into future strategies for monitoring and
80 mitigating plastic debris. This study fits well within the main research priorities on marine
81 plastic litter raised by the scientific community (Maximenko et al., 2019), in response to the G7
82 Science Ministers meeting in Berlin in October 2015 (Williamson et al., 2016), such as
83 *understand the pathways* “establishing connections between sources and sinks for different
84 types of debris”, and *understand the sinks*, “including accumulation in remote locations”.

85 Section 2 presents the material and methods. Results for particles ending up at sea and in the
86 convergence zones are given in section 3, whereas the specific analysis of particles ending up
87 along the coast (beaching) is presented in section 4. Section 5 is the concluding section.

88

89 2. **Material and methods**

90

91 2.1. Global surface ocean circulation model

92

93 For this study, we use the sea surface current of the Global Oceanic Circulation Model
94 GLORYS12V1, a leading global reanalysis of ocean circulation and physics (Lellouche et al.,
95 2018). This reanalysis is part of the Copernicus Marine Environment Monitoring Service
96 (CMEMS) with a new global eddy-resolving resolution and an ocean model with 50 vertical
97 levels. The model component is the NEMO platform, forced at its surface by the ERA-Interim
98 atmospheric reanalysis of the European Center for Medium-range Weather Forecast. These
99 products are part of international efforts to give a better estimate of the global state of the
100 oceans (von Schuckmann et al., 2016). This reanalysis covers the 1993-2018 altimetry era with a
101 daily frequency, and provides not only a higher horizontal resolution compared to previous
102 versions, but also improvements and corrections (Lellouche et al., 2018). In the following, we
103 use the daily mean surface currents from the upper layer of the model with a thickness of 1 m,
104 from 1 January 1993 to 31 December 2015 (GLOBAL REANALYSIS PHY_001_030 product
105 downloaded from <https://resources.marine.copernicus.eu>). The products of the Copernicus
106 reanalysis being provided on a regular grid (A-grid in Arakawa and Lamb (1977) classification),
107 we interpolated the velocities on the ORCA 1/12° native C-grid to run the Lagrangian
108 experiments.

109

110 2.2. Coastal plastic source scenarios

111

112 In this study, we compare two distinct scenarios of coastal sources of plastic particles: one
113 based on inputs from the world's main rivers and the other based on the coastal population
114 (Fig. S1), which we will identify as the river scenario and population scenario hereafter.

115 The **river scenario** comes from the model developed by Lebreton et al. (2017). This global
116 model of plastic inputs from rivers into the oceans is based on waste management, population

117 density and hydrological information. It estimates that about 2 million tons of plastic waste
118 enters the ocean every year from 40,760 rivers. The 20 most polluting rivers are mainly located
119 along the western North Pacific and account for 71% of the total (Fig. 1). The North Indian and
120 North Atlantic basins account for 13% and 12% of the river inputs, respectively. Data were
121 downloaded from the global model inputs for annual midpoint estimates in Lebreton et al.
122 (2017) (data are available at figshare.com at doi:10.6084/m9.figshare.4725541).

123 The second scenario is the mismanaged waste from coastal population scenario that we refer
124 to as *population scenario* hereafter. It is actually a proxy of the mismanaged waste released by
125 the coastal population entering the ocean, as described in van Sebille et al. (2015): it is
126 computed as the human population within 200 km of the coast scaled by the amount of
127 mismanaged plastic waste available to enter the ocean by country in 2010 (as referenced in
128 Jambeck et al. (2015) by ‘mismanaged waste’, dependent on the economic level per country)

129 ~~The *population scenario* is described in van Sebille et al. (2015): the coastal source is a proxy of~~
130 ~~the human population within a radius of 200 km from the coast scaled by the amount of plastic~~
131 ~~waste available to enter the ocean by country in 2010, as referenced in Jambeck et al. (2015) by~~
132 ~~‘mismanaged waste’.~~ In this scenario, plastic debris entering the ocean is more widely
133 distributed (Fig. 1 and Fig. S1) over 2633 coastal input positions. The west coast of the North
134 Pacific accounts for 37% of the total population input, i.e., a relative contribution half less than
135 in the river input scenario. The North Atlantic shorelines represent the second-highest source of
136 plastic inputs with 21% of total inputs (43% more than river inputs). The North Indian basin
137 represents 18% of the total input. The Eastern Pacific, South Atlantic (east and west) and the
138 Mediterranean Sea represent larger sources of plastic (5%, 5% and 10%, respectively) than in
139 the river scenario (<1%, 1% and <1%, respectively). Data were provided by Erik van Sebille
140 (pers. comm., 2018) based on the estimate of Jambeck et al. (2015) that 4.8-12.7 million tons of
141 land-based plastic debris entered the ocean in 2010, which is 2-6 times more than the river
142 input on average.

143 Both scenarios are projected and discretized on our model grid. The finite number of total
144 particles released along the experiment, and the rounding-of to an integer number of particles
145 released each month in sources grid cells, reduces the effective number of source points as

146 follows. For the rivers scenario, the finite number of particles released each month (20,000)
147 reduces the effective number of source points to 522 grid cells (Fig. S1). There are very large
148 sources, with about 10 rivers releasing more than 500 particles per month (representing
149 altogether more than 58% of the total), with the Yangtze River peaking at about 5000 particles
150 (25% of the total). For the population scenario, out of the 2633 source points provided by Erik
151 van Sebille (pers. comm., 2018) on a $1^\circ \times 1^\circ$ grid, the finite number of particles released each
152 month reduces the effective number of source grid cells to 1196 in our experiment (i.e., more
153 than twice that of the rivers scenario). There are no sources as extreme as in the rivers
154 scenario, the peak values are about 350 particles per month (barely 2% of the total), with 23
155 sources releasing more than 100 particles per month (representing altogether 19% of the
156 total).

157 Our objective is to diagnose how differences in input scenarios affect the fate of floating plastic
158 debris on a global scale. Thus, to make the two scenarios comparable, we choose to ignore the
159 difference in the total amount of plastic mass released in each scenario. For simplicity, we also
160 choose to ignore the temporal variability of coastal inputs in the two scenarios (e.g., river
161 discharge depends on rainfall variability). Thus, we consider that a mean equivalent amount of
162 plastic is released every month over the 23 years of simulation (1993-2015) from their coastal
163 positions (see next section) in both scenarios (river and population).

164

165 2.3. Lagrangian analysis

166

167 To study the fate and pathway of floating plastic debris in the global ocean, we use a Lagrangian
168 approach with the Ariane methodology (Blanke and Raynaud, 1997). As detailed in Maes et al.
169 (2018) or Dobler et al. (2019), the Ariane tool has been used so that the numerical particles are
170 horizontally advected by surface currents and do not experience vertical motion. The plastic
171 input data for both scenarios were gridded on the ORCA native grid at a resolution of $1/12^\circ$ at
172 the nearest ocean grid point, i.e. each source point is associated with a single grid cell of the
173 model. The initial particle positions are determined randomly within the grid cell. Note that the
174 population density proxy data set was available at a resolution of $1^\circ \times 1^\circ$; for this reason, some

175 final positions on the $1/12^\circ$ grid are not initialized exactly at the coast (as strictly defined by the
176 land-sea mask of the model) but near the coast. Two experiments are run according to the
177 coastal input scenario (see previous section) with equivalent total particle numbers: 5,589,080
178 particles for the river scenario, and 5,571,720 particles for the population scenario (the particle
179 numbers are slightly different due to rounding to an integer number of particles released each
180 month). About 20,000 particles are thus released each month during the 23-year period from
181 1993 to 2015 (i.e., about 240,000 particles released per year). ~~Particles released at the same~~
182 ~~location are subject to turbulent, seasonal and interannual variability of the surface current.~~
183 **Particles released at close locations within the same grid cell are subject to turbulent, seasonal**
184 **and interannual variability of the surface current that will lead to dispersion in their**
185 **trajectories.** The positions of the particles are recorded with a monthly frequency. There are no
186 explicit sinks in our approach i.e., the released particles stay indefinitely at the surface in the
187 model, still moving or stuck along the coasts.

188

189 2.4. Particle behavior

190

191 We have diagnosed that particles can experience a different fate depending on their position
192 and trajectory in the ocean:

- 193 ● *case a*: the particle leaves the coastline and travels within the ocean domain until the
194 end of the experiment;
- 195 ● *case b*: the particle leaves the coastline, travels in the open ocean but ends up along the
196 coast: we will define these particles as “beached”;
- 197 ● *case c*: the particle never leaves the coastline but rather travels alongshore;
- 198 ● *case d*: the particle never leaves its initial grid cell. More precisely, the particle can
199 barely move but never leaves the grid point associated to its initial position. Such
200 behavior results from a conjunction between the initial positioning (indented coastline)
201 and the dynamics (convergence), which creates unfavorable conditions for moving to
202 another grid cell. Note that this behavior concerns a very small fraction of the initialized
203 particles (<1%, see section 3) and will be considered as a “rare cases” category.

204 Note that, in absolute terms, cases b and c could refer to a similar category of beaching and
205 thus to the same local pollution by plastic debris. However, we choose to distinguish these two
206 cases because of the possible role of river mouth dynamics in such behavior.

207

208 **3. Open ocean convergence zones**

209

210 The particles are released continuously in both experiments. ~~After a few years of Lagrangian~~
211 ~~advection, the particles spread almost everywhere in the global ocean, from the coast to the~~
212 ~~open ocean.~~ After a few years of Lagrangian advection, the particles have spread almost all over
213 the global ocean, from the coast to the open ocean. Only a few regions remain free of particles:
214 the Southern Ocean (because of the strong northward Ekman transport), the Atlantic and
215 Pacific equatorial region (because of the strong Ekman transport divergence), and also the
216 northern North Pacific and Chukchi Sea in the Arctic. Figure 2 represents what could be roughly
217 observed in terms of relative surface plastic pollution from space at any given time. The two
218 scenarios have similarities and differences (Fig. 2). In both scenarios, surface plastics cover a
219 large portion of the ocean between 45°S and 45°N. Particles seem to accumulate in bays, gulfs
220 and seas surrounded by high-flow rivers (river inputs) and densely populated coastlines
221 (population inputs), e.g., in the Bay of Bengal, Gulf of Guinea and China Sea (Reisser et al.,
222 2013; Hinojosa and Thiel, 2009; Collignon et al., 2012; Ryan, 2013), similarly in both scenarios.
223 Other regions of accumulation are in the centers of the subtropical gyres, regions known as CVZ
224 (Convergence Zones), where plastic accumulates through Ekman transport (Kubota, 1994;
225 Maximenko et al., 2012; van Sebille, 2015), mainly in the North Pacific and South Indian basins.
226 Concentrations differ strongly between scenarios in the South Atlantic, North Atlantic, South
227 Pacific, and Arctic, but also in some coastal regions (e.g., off Europe and Brazil). Another
228 difference between the scenarios is the lower concentration of particles in the equatorial
229 Pacific and equatorial Atlantic in the river scenario compared to the population scenario. These
230 discrepancies between the scenarios are only due to the relative input of particles (as the
231 dynamics are the same in both experiments). Compared to the in situ observations (see figure 1
232 “standardized data” of van Sebille et al., 2015), the population scenario seems to show better

233 agreement than the river scenario in terms of relative amplitude and global distribution of
234 surface plastic debris, mostly because of the higher concentrations in the North Atlantic, South
235 Atlantic and South Pacific CVZs. It should be mentioned that no scenario exactly satisfies the
236 relative concentrations of particles in the different regions, especially since the syntheses of the
237 observations do not agree with each other. This ~~must~~ might be due to the fact that particles
238 inputs are more widely distributed along the coast in the population scenario than in the river
239 scenario, as described in section 2.2.

240

241 To determine the origins of these discrepancies and to untangle the fate and pathways of the
242 particles, now we modify the standard way of analyzing the fate of our particles. Instead of
243 merely looking at the position of particles at time t , which mixes particles of different ages
244 (such as Fig. 2), we choose to focus on the position of particles as a function of their age, i.e.,
245 the time elapsed since their release. We can thus follow a cohort of particle traveling from their
246 release position to their final position (Fig. 3). For this section, we focus on particles from case
247 a , i.e., particles ending up at sea. Since particles may be released at the same location at
248 different times, they may experience different dynamics; thus, such an analysis provides much
249 more consistent statistics on the plastic fate at the ocean surface. Figure 3 shows both the
250 quasi-initial position of the particles (i.e., one month after their release at the coast), and their
251 position after 22 years. The one-month-old particles have experienced one month of dynamics
252 and are still relatively close to their release position: such a representation gives a good
253 approximation of the initialization of particles in terms of position and concentration. It also
254 explicitly illustrates the main input differences between the scenarios: with the exception of the
255 tropical areas of the West Pacific and Northeast Indian Oceans, all other shores show significant
256 differences. As explained in section 2b, the population scenario is more widely spread,
257 especially in relation to the American, European and African population. Most of the older
258 particles, which have been drifting with the currents for 20 years, aggregate in the centers of
259 the gyres (while a few others are still drifting in highly dynamical regions such as the Agulhas
260 Current or between the subtropical region of the South Indian Ocean and the southwestern
261 Pacific Ocean). After drifting with the currents for 20 years, particles aggregate in the centers of

262 the gyres (while others are still drifting in highly dynamical regions such as the Agulhas Current
263 or between the subtropical region of the South Indian Ocean and the southwestern Pacific
264 Ocean).

265 Figure 3 highlights the importance of sources for accumulation in CVZs and, specifically, the
266 local influence of plastic pollution in the main gyres. By the term "local" we define the particles
267 that originate and end in the same region, as defined in figure S2. Whereas the North Pacific
268 and South Indian CVZs show quite similar concentrations and positions to the first order in both
269 scenarios, the concentration of particles in the South Pacific, North and South Atlantic CVZs is
270 much lower in the river scenario than in the population scenario. Indeed, the sources around
271 the latter basins are much lower in the river scenario (Fig. 1) indicating that particles have
272 mostly a local origin in many regions: particles initialized in one region are likely to stay in this
273 region (e.g., North and South Atlantic, Southeast Pacific and Mediterranean). Outside the CVZs,
274 particle concentrations are much lower (e.g., Maximenko et al., 2012; Law et al., 2014). In all
275 basins, there is a very intense divergence of particles around the equator, due to the poleward
276 Ekman transport associated with trade winds, such that particles from a sub-basin (North or
277 South) are very likely to remain in their region of origin. As already highlighted by Lebreton et
278 al. (2012), because (i) there are little exchanges between hemispheres across the equator
279 (except in few coastal regions), and (ii) the particles are mostly released in the northern
280 hemisphere in the river scenario, there are significantly less particles that end up in the South
281 Atlantic and South Pacific gyres compared to their northern hemisphere counterparts. In the
282 Indian basin, however, there is a seasonal north-south flush of particles along the eastern
283 boundary (van der Mheen et al., 2020).

284

285 In addition to the local contribution of plastic pollution in the main gyres, ~~there is a strong~~
286 ~~remote influence due to~~ there is also a remote contribution allowed by the connectivity
287 between sub-basins. This connectivity depends on the strength and extent of the attraction
288 basins (Froyland et al., 2014). To study this connectivity from coastal regions to the open ocean,
289 we determine the temporal accumulation of particles in the main gyres (Fig. 4) and establish a
290 connectivity matrix from the coastal inputs of particles - i.e., the initial position of the particles -

291 to their final position at sea (Fig. 5) between the sub-regions defined in Fig. S2 (see also the
292 mapped initial positions given in Figs. S3 and S4). To better capture the open-ocean signal of
293 the particles attracted (Fig. 4), we limit the extension of the CVZs to their core - where particles
294 accumulate over time (van Sebille et al., 2020) – and focus on the five main CVZs (see the
295 colored boxes in Fig. 3). The slope of the curve indicates whether particles accumulate mostly in
296 an attractive CVZ (positive slope), whether particles escape mostly from a leaky CVZ (negative
297 slope), or whether an equilibrium is reached between sources and sinks in an attractive but still
298 leaky CVZ (null slope). Sinks may represent particles that move to other regions or that beach.
299 The rate at which a CVZ attracts particles provides an indication of the origin of the particles:
300 the faster the early rate, the younger the particles are, the less they travel (and vice versa for a
301 slower rate).

302 In both *rivers and population* scenarios, the *Indian* CVZ is the region where plastics accumulate
303 the most and very rapidly: in 10 years up to 5.0% and 5.9% accumulate in the river and
304 population scenarios, respectively, with concentrations that continue to increase up to 15 years
305 of simulation. This results from the multiplicity of large sources converging to the Indian basin
306 (see IND.S in Figs. 5, S3 and S4), from local sources (all Indian) to remote sources (from the
307 Pacific and Atlantic shores). This is in line with Lebreton et al. (2012) who found that in the
308 Indian CVZ, the main contributors are Southeast Asia/Indonesia, Africa and India. Overall, the
309 South Indian is the most heterogeneously and widely impacted region, with particles coming
310 from all origins with the population inputs (except the Mediterranean) and from all over the
311 North Pacific and South Atlantic with the river inputs (Fig. 5). *In this case, particles likely crossed
312 the equator, e.g. between the South and the North Indian during the intermonsoon season as
313 recently documented by van der Mheen et al. (2020).* This result contrasts with that of Lebreton
314 et al. (2012) who identified the greatest diversity of particle origins in the Southeast Pacific. This
315 discrepancy ~~must~~ *might* be due to differences in input scenarios. Interestingly, the North Indian
316 feeds the Southeast Pacific (Fig. 5). This connection has already been documented as the
317 surface “superconvergence” pathway linking the south Indian Ocean to the subtropical south
318 Pacific gyre through the Great Australian Bight (Maes et al., 2018).

319 The *North Pacific* is the second region where plastics are accumulating the most and very
320 rapidly. The North Pacific CVZ starts to significantly attract particles after 2 years of simulation
321 and accumulates approximately the same number of particles in both scenarios, up to ~4% in
322 about 5 years (Fig. 4). Particles traveled for 2 years from the Pacific and Indian shores before
323 ending up in the CVZ (see PAC.NE in Figs. 5, S3 and S4). An equilibrium is reached between
324 sources and sinks in the population scenario. However, in the river scenario, the equilibrium
325 shows a dip from year 7 to year 15 (i.e., 2000 to 2008), which is not observed in the population
326 scenario. This difference may be due to interannual variability in the dynamics linking one of
327 the sources to the CVZ. Indeed, in the river scenario, some of the sources involved in the
328 feeding of the North Pacific CVZ in the population scenario must be missing (e.g., from the
329 Eastern Pacific). Toward the end of the simulation, after 15 years (i.e., from 2008), there is a
330 second increase in both scenarios, showing that the dynamics have favored the accumulation of
331 common sources – i.e., from North Pacific or South Indian - in the North Pacific CVZ.
332 Interestingly, the period 2000 to 2015 corresponds to a cool phase of the Pacific Decadal
333 Oscillation (PDO) and a positive phase of the North Pacific Gyre Oscillation (NPGO). Such
334 interannual variability is beyond the scope of this paper, but additional attention could be given
335 to linking particle accumulation to different modes of climate indices in future research
336 projects.

337 In the *South Atlantic*, there is a rapid accumulation of particles, followed by a slower increase
338 over the rest of the simulation with the population scenario (Fig. 4), due to the larger sources
339 all around the basin, mostly from Southeastern America (Figs. 3, S1 and S3). However, with
340 river inputs, the particle concentration in the South Atlantic CVZ increases slowly over the
341 whole period because particles come from very remote sources, from all over the Indian and
342 NW Pacific (see ATL.S. in Figs. 5 and S4).

343 Accumulations in the *North Atlantic* CVZ vary significantly according to the input scenario, as in
344 Lebreton et al. (2012). In the river scenario, very few particles accumulate, and an equilibrium
345 of ~0.1% is rapidly reached (Fig. 4), with particles being attracted only from the local shores
346 (see ATL.N in Fig. 5). In the population scenario, a maximum is rapidly reached (1% in less than a
347 year), followed by a decrease and a further increase toward an equilibrium of ~1.1% in 5 years

348 (Fig. 4). In this case, there is a clear balance between the sources (North and South Atlantic
349 shores) and the open waters of the North Atlantic (Fig. 5), with the dispersion of particles from
350 the core in the *North Atlantic* waters.

351 In the *South Pacific* CVZ, particles accumulate very slowly and the maximum concentration of
352 about 0.1 and 1% is reached in 15 years (ten times slower than in the North Atlantic CVZ) with
353 rivers and population inputs, respectively. This is consistent with Lebreton et al. (2012) who
354 identified that “particles originating from South Atlantic and identified in the South Pacific Gyre
355 took more than 15 years to make the journey”. In both scenarios, the locations of sources are
356 similar, but the concentration of inputs from the Eastern and Southwestern Pacific shores is
357 higher in the population scenario (see the PAC.SE position in Fig. 5), as in Lebreton et al. (2012).
358 ~~In terms of the contribution of coastal sources to open ocean pollution, we evaluate that 28%~~
359 ~~(~470,000 particles) and 49% (~1,200,000 particles) of the particles ending at sea have a local~~
360 ~~origin in the river and population scenarios, respectively (these figures are computed as the~~
361 ~~sum of the diagonal terms in the connectivity matrix, Fig. 5). Thus, 72% and 51% of the particles~~
362 ~~ending at sea have a remote origin in the river and population scenarios, respectively, with our~~
363 ~~definition of regions.~~
364 ~~In terms of open ocean pollution (particles in case a, ending at sea), we~~
365 ~~evaluate that 28% (~470,000 particles) have a local origin in the river scenario, against 49%~~
366 ~~(~1,200,000 particles) in the population scenario (these numbers are computed as the sum of~~
367 ~~the diagonal terms in the connectivity matrix, Fig. 5). Thus, the remaining portions of the~~
368 ~~particles have a remote origin (with our definition of regions), respectively 72% in the river and~~
369 ~~51% in population scenarios.~~
370 ~~The NW Pacific shores represent the largest source of pollution at~~
371 ~~sea in both scenarios (Fig. 1): particles reach mostly the South Indian ($4.5 \cdot 10^5$ and $3.8 \cdot 10^5$~~
372 ~~particles, i.e., 8% and 6.8% of released particles) and the NE Pacific ($4.0 \cdot 10^5$ and $3.0 \cdot 10^5$~~
373 ~~particles, i.e., 7.2% and 5.4% of released particles), then the South Atlantic ($6.0 \cdot 10^4$ and $5.8 \cdot 10^4$~~
374 ~~particles, i.e., 1.1% and 1.0% of released particles) (numbers are given for river and population~~
375 ~~inputs, respectively). Within these regions are the three main CVZ in terms of total number of~~
376 ~~particles in cores. The NW Pacific is also a significant source of local pollution with $1.9 \cdot 10^5$ and~~
377 ~~$1.2 \cdot 10^5$ particles (i.e., 3.4% and 2.2% of released particles) for the river and population inputs,~~

376 respectively. The remaining number of particles ($3.7 \cdot 10^4$ and $1.8 \cdot 10^4$ particles, i.e., 0.7% and
377 0.3% of released particles) ends up in the South Pacific (E and W) and North Indian.

378 In summary, these results emphasize the importance of the input of coastal sources in the total
379 accumulation and composition of the 5 CVZ, and the possible exchanges between these
380 regions. Our results show similarities and differences with those of Lebreton et al. (2012) (see
381 above for more details) who performed a similar analysis. Although we found the same 5 CVZ,
382 one of the most divergent results is that they find that northern CVZs accumulate more
383 particles than southern CVZs (~25% in northern hemisphere CVZs compared to ~10% in
384 southern hemisphere CVZs), which is not our case (we find that 5% of the particles accumulates
385 in northern hemisphere CVZs versus ~8% in southern hemisphere CVZs). This discrepancy may
386 be due to differences in the input scenarios, the numerical tools (from surface current products
387 to Lagrangian experiments), and the methodology (definition of regions). However, it remains
388 difficult to validate the most realistic solution due to the lack of in situ observations in these
389 regions, especially in the southern hemisphere.

390 In total, in both scenarios, CVZs do not attract more than 20% of the total particles released at
391 the coast after a few years of simulation (Fig. 4). While the defined CVZs cover only a fraction of
392 the patches in the gyres, i.e., the core, we found that only 29/45% of the particles end up in the
393 open ocean, away from the coast, for the river and population scenarios, respectively (Fig. 6).
394 The majority of the particles thus end up along the coast, 71/55% respectively, and we now
395 examine in detail the behavior of these beached particles.

396

397 **4. Beaching**

398

399 As noted in many previous studies (e.g., Maximenko et al., 2012; van Sebille et al., 2015),
400 coastal deposit of plastic debris represents an important reservoir in the total budget. In the
401 present estimation of the model dispersion, a significant proportion of the particles released at
402 the coast does not end up in the open ocean (*case a*). Indeed, 36 and 43 % of them end up on
403 beaches (*case b*) while 34 and 11 % travel alongshore (*case c*), in the river and population
404 scenarios, respectively (Fig. 6). In total, 70% and 54% of the particles end up on the coasts (sum

405 of *case b* and *case c*) in the river and population scenarios, respectively. This is in good
406 agreement with Lebreton et al. (2019) who showed that 67% of the world's plastic washed up
407 on the coasts. Note that a small proportion of particles, ~1%, do not move from the grid cell
408 where they were released. Details on these categories are given hereafter. Overall, the broad
409 spatial spreading of beachings along the coasts (Fig. 7) is not strikingly different between the
410 two scenarios (except for a few areas), especially when compared to the very contrasted input
411 functions (Fig. S1).

412 In terms of sources, in both scenarios, coastal pollution originates mainly from the NW Pacific,
413 North Indian and North Atlantic shorelines, mainly because these are the main sources of
414 particles (Fig. 6). ~~In the population scenario, the Mediterranean also represents a major source~~
415 ~~of beached particles.~~ **In the population scenario, most of particles released from the**
416 **Mediterranean shores actually beached.** Depending on the region, the balance of *open-ocean-*
417 *fate (case a)* and *coastal-fate (case b and c)* is variable (Fig. S5). ~~Some regions are mainly~~
418 ~~sources of coastal pollution for cases b and c (i.e., they contribute to >50% of the total~~
419 ~~pollution).~~ **The following regions contribute to more than 50% of the total coastal pollution, as**
420 **diagnosed in cases b and c:** North Indian (56%), NW and SE Pacific (70% and 96%), North
421 Atlantic (93%) and Mediterranean (97%) with the river scenario; and NW Pacific (57%), North
422 Atlantic (65%) and Mediterranean (96%) with the population scenario (Fig. S5).

423 The origin of the particles that accumulate along the coast is mostly local (Figs. 7, 8, S6 and S7),
424 i.e., the initial and final positions are in the same region (this is also true for the particles that
425 stay on the coast in *case c*, Fig. S8). In both scenarios, we estimate that 85% (~2,000,000
426 particles) of the beached particles have a local origin (this number is computed as the sum of
427 the diagonal terms of the connectivity matrix, Fig. 8) likely due to coastal retention and coastal
428 recirculation. That is especially true for the NW Pacific, North Indian and North Atlantic in both
429 scenarios, and additionally for the Mediterranean in the population scenario. It is not surprising
430 that in the river scenario, the positioning of local beaching pollution corresponds to the river
431 areas, i.e., the Niger, the Amazon, the Ganges and rivers of the NW Pacific region (Mekong,
432 Yangtze, etc.) (Figs. 7 and S6). Rivers also appear to be hotspots for particle retention on coasts
433 (with 34% of particles in *case c*, Fig. 6 and S8). With regard to the population scenario, where

434 sources are more widely distributed, beaching locations appear to be widespread along the
435 shores and, to a lesser extent, even in divergent regions such as coastal upwelling areas like
436 California, Peru or NW Africa (Fig. 7).

437 Coastal pollution is not, exclusively and totally, local, and the beaching process may in fact
438 occur after a long distance traveled. In both scenarios, we find that ~27% of the beached
439 particles traveled less than 500 km, ~66% between 500 km and 5000 km, and ~7% more than
440 5000 km (Fig. 9). This highlights the *shore-to-shore* connectivity between remote regions (Fig. 8
441 and S9). For example, particles from the NW Pacific, which is the main source of coastal
442 pollution, can reach the Pacific, Indian or South Atlantic. Conversely, in the population scenario,
443 particles from the Atlantic shores can reach the West Pacific, South Indian, and also Arctic
444 shores. The Indian shores are also a source of beaching for older particles in the West Pacific, in
445 both scenarios.

446 To summarize, the impact of local pollution on beaching is even greater with population inputs
447 rather than with river inputs. [This result deserves more attention and, due to uncertainties and
448 gaps in the observations of plastic waste, it remains challenging to predict plastic sources and
449 fate in coastal systems as mentioned recently by Galgani et al. \(2021\).](#) As for the particles at
450 sea in the CVZs, the differences between the two scenarios appear mainly in the North Atlantic
451 and SE Pacific, where the sources are very different (Fig. S1). In the North Atlantic, river inputs
452 tend to stay locally on the coast (mostly from the Amazon and Niger), whereas population
453 inputs represent a high source of beached and offshore pollution (from Europe and North
454 America). In the SE Pacific, this local pollution is represented by a significant proportion of
455 offshore pollution with population inputs. The Mediterranean and NE Atlantic are largely
456 affected by beaching and coastal retention (Fig. 6 and Fig. S8) with population inputs.

457 Interestingly, these results highlight the disparity between regions in terms of plastic pollution:
458 some regions are strongly affected by coastal pollution (e.g., the North Pacific), due to coastal
459 retention and coastal recirculation, while others have a significant proportion of particles
460 staying offshore (e.g., North Indian and NW Pacific). In contrast to local pollution, there are a
461 significant number of beached particles that have traveled long distances in both scenarios and
462 this study highlights the main pathways of plastic debris between coastal regions and their

463 ability to travel long distances before ending up at the coast. Note that the geographic
464 differences found in the final positions of particles between the two scenarios are directly
465 related to the location of input sources and differences in concentration. Given these
466 differences between the input scenarios, the particles may encounter different oceanographic
467 features and dynamics that are likely to influence their final positions. However, the statistical
468 robustness of our approach relies on the use of several million particles to diagnose the main
469 pathways from the initial positions to the final positions, overcoming the effect of small scales.
470 Moreover, ~~Note, however, that~~ in our simulations, the particles do not sink, whereas in reality,
471 such old particles would most likely fall down the water column (Egger et al., 2020; Pabortsava
472 and Lampitt, 2020) under the action of biology (biofouling, ingestion, or aggregation) (e.g., Kooi
473 et al., 2017; van Sebille et al., 2020).

474 A qualitative comparison with global beaching patterns, as compiled for instance in the
475 LITTERBASE database (<https://litterbase.awi.de/litter>, Tekman et al., 2018), generally shows
476 relatively good agreement, except for some regions. For instance, the database reports no
477 beachings along the east coast of Africa from Somalia to Mozambique, and along the coasts of
478 Oman and Yemen, probably due to a lack of observations.

479 A striking difference between the 2 scenarios is the complete absence of beachings along the
480 Pacific coast of South America. Coastal plastic and other debris reported along the Chilean coast
481 suggest that the river input scenario is not sufficient to supply plastic particles to the South
482 Pacific, and in this respect the population scenario is more satisfactory (as reported in
483 LITTERBASE from Thiel et al. 2003; Hinojosa and Thiel, 2009; Hinojosa et al., 2011; Thiel et al.,
484 2013; Miranda-Urbina et al., 2015, Hidalgo-Ruiz et al., 2018). Similarly, the 2 scenarios differ
485 greatly along the East coast of America, where the river scenario leads to almost no beaching
486 north of Florida. This is not the case in LITTERBASE, confirming once again the need for
487 population inputs. Beaching patterns around the Indian basin and along the West Pacific coasts
488 are not significantly different between the 2 scenarios, and are in good agreement with
489 previously published results (van der Mheen et al., 2020). Beaching patterns around Australia
490 (PAC. SW in Fig. 8) differ from the 2 scenarios and the population scenario is in better

491 agreement with recent studies (Galaiduk et al. 2020) with significant input from local and
492 northwest Pacific shores.

493

494 **5. Conclusions**

495

496 The aim of this study is to investigate the pathway and fate of floating plastic debris, a key issue
497 that remains fundamental to better manage and reduce plastic pollution. We diagnose the fate
498 of plastic pollution discharged along the coasts by comparing two different types of sources in
499 the global ocean: one based on rivers and the other on the population density along the coasts.
500 We use a Lagrangian numerical analysis (forward particle tracking) based on surface currents
501 from reanalysis of a global ocean circulation model with a resolution of $1/12^\circ$. Our results
502 highlight the importance of the input scenario for the concentration of dispersed particles in
503 the open ocean, in specific subtropical convergence zones for instance, and the number of
504 particles beaching around oceanic basins, such as the Mediterranean Sea. The concentration of
505 particles at sea in certain convergence zones is particularly sensitive to the input scenario. More
506 precisely, population-related inputs are critical to feed convergence zones of the South Pacific
507 and North Atlantic. Connectivity between coastal sources and open ocean regions also indicates
508 that the Indian region is the most heterogeneous in terms of pollution with population-related
509 inputs. *More generally, particles ending up at sea represent less than half of the particles
510 released (and less than 20 % in the convergence zones), whereas more than 50% end up at the
511 coast.*

512 A large fraction of the total particles released ends up along the coast, between 54% in the
513 population scenario and 70% in the river scenario. The number of particles that beach in certain
514 areas also depends particularly on the input scenario, such as the European West Coast, the
515 Mediterranean Sea, and African East Coast with the population input. Rivers represent a large
516 source of local coastal pollution, probably due to the retention and recirculation of coastal
517 waters. Regardless the input scenario, some regions are more subject to offshore pollution such
518 as the South Atlantic and the NE Pacific, while others are more largely affected by coastal
519 pollution (beaching) such as the NW Pacific, North Atlantic and Mediterranean shores. We have

520 found that particles can travel up to several thousand kilometers, allowing remote connectivity
521 between coastal regions. This property is of interest for the application to other types of
522 floating pollution or any conservative biogeochemical properties, or viruses and pathogens.
523 Our study remains an idealized case from several aspects, and from our point of view, the main
524 approximations are the “oversimplified” beaching process and the related dynamical processes.
525 Indeed, beaching of plastics is a complex process that is strongly influenced by small-scale
526 coastal ocean dynamics (Isobe et al., 2014), and by the local morphology of the coastline
527 (Zhang, 2017). Including Stokes-drift, waves or tides can also influence the number of particles
528 stuck to the coast, and increase it by more than three times (Dobler et al., 2019). Another key
529 point is the definition that can be given to the term “beaching”. Using a 1/12° eddy-resolving
530 ocean model, our definition is purely probabilistic since we define as beached particles those
531 that are at a certain distance from the coast (i.e., one grid point) (as similar studies e.g., van der
532 Mheen et al. (2020)).

533 Although this study is still based on available scenarios for plastic sources, it provides new
534 insights on connectivity between regions, on offshore pollution with CVZ composition and on
535 coastal pollution in terms of beaching. There are many ways to add complexity to these
536 processes. Indeed, for the sake of simplicity, we have neglected many key factors such as the
537 temporal/seasonal variability of coastal inputs that could change with rainfall (e.g., Lebreton et
538 al., 2017; van der Mheen et al., 2020), and also the significant worldwide increase in plastic
539 inputs to the sea in relation to population growth and the rapid increase in plastic production
540 (Ostle et al., 2019). We have also ignored ~~sources~~ [contribution of](#) of pollution from maritime
541 inputs on global shipping route or fishery activities (e.g., Lebreton et al., 2012). With the 1/12°
542 eddy-resolving ocean model used, one might have expected to find particles crossing the
543 Antarctic Polar Front and reaching the Southern Ocean (Fraser et al., 2018), but it is likely that
544 the absence of extreme events and Stokes drift ([driven by surface winds](#)) does not allow such
545 connectivity. Finally, we focus on floating debris that could experience vertical motion in
546 response to physical or biological processes (van Sebille et al., 2020). It could be interesting to
547 implement models that allow interaction with the marine ecosystem – e.g., processes such as
548 ingestion by plankton and fish, sedimentation by biofouling (Kooi et al., 2017) which could

549 represent an important sink for particles toward the deep ocean (van Sebille et al., 2020).
550 Indeed, it has recently been documented by Egger et al. (2020) that we can find below the
551 surface (5 m depth) to 2,000 meters about 56%-80% of what is seen at the surface.
552 Marine plastic pollution represents an increasing threat to the environment. Because of their
553 serious detrimental effects on marine ecosystems (see examples in Napper and Thomson,
554 (2020)) and given the huge cost of removing this pollution from beaches (e.g., Burt et al., 2020;
555 Cruz et al., 2020; Napper and Thomson, 2020), it is today fundamental to understand the fate
556 and pathway of marine plastic debris. Such studies are needed to better inform and guide the
557 stakeholders involved in the reduction of plastic pollution and waste management decision
558 makers. However, a consensus is needed among researchers and a major step forward will be
559 to improve the quality of information available on beached marine debris, which would require
560 standardization of data sets (e.g., reporting metrics and sampling methods) (Serra-Gonçalves et
561 al., 2019; Galgani et al., 2021).

562

563 **Acknowledgements**

564 FC was supported by postdoctoral funding from CNRS/INSU. We thank gratefully Laurent
565 Lebreton and Erik van Sebille for providing their data sets for the source scenarios.

566

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