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

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

Most of the projects on this issue are nowadays oriented toward a particular region or theme (Black et al., 2020), whereas plastic pollution must be considered as a global concern (Maes et al., 2019). Understanding the main pathway and fate of plastic debris remains fundamental to better manage and reduce plastic pollution from an environmental and economic perspective. Indeed, Lau et al. (2020) have shown that if no plastic pollution reduction strategy is undertaken, plastic pollution will triple by 2040. Despite the multiplicity of plastic pollution sources and the large uncertainties about the contribution of land-based plastic pollution (Horton and Dixon, 2018), according to van Sebille et al. (2020), it is today recognized that coastal pollution is one of the largest sources of ocean plastic waste globally, with 5 to 12 million tons year^{-1} (Jambeck et al., 2015). As estimated by Faris and Hart (1994), 80% of marine litter enters the ocean by land, with the remaining 20% assumed to come from marine activities such as commercial and recreational fishing, cruises, and shipping (Lebreton et al., 2012).

Given the scarcity of available data and observations on marine litter and plastic pollution (Galgani et al., 2021), numerical simulation can be used "'*to fill in the gap*' *between these observations, and to test hypotheses about how plastic particles behave in the ocean*" as explained by van Sebille et al. (2020). Indeed, numerical models are proper tools for understanding the transport and dispersion of plastic in the ocean (Hardesty et al., 2017), especially in a Lagrangian framework (van Sebille et al., 2018). For instance, Lebreton et al. (2012) studied the relative contributions of plastics from impervious watersheds, coastal population and shipping inputs to different accumulation zones. In their study, they estimated that between 28% and 40% of the released particles were

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beached, depending on the input scenario.

Using a similar numerical methodology, we study hereafter the fate of floating plastic pollution in the ocean as discharged along the coasts. We compare two different source scenarios in the global ocean: one based on river inputs, and the other based on mismanaged waste by the coastal population. We use a Lagrangian numerical analysis in conjunction with surface currents from a reanalysis of a global ocean circulation model with a horizontal resolution of 1/12°. We discuss how the use of different scenarios helps to understand ocean connectivity and plastic pollution on a global scale. This study highlights the importance of considering accurate coastal inputs or sources, in particular littering from coastal populations, and provides insight into future strategies for monitoring and mitigating plastic debris. This study fits well within the main research priorities on marine plastic litter raised by the scientific community (Maximenko et al., 2019), in response to the G7 Science Ministers meeting in Berlin in October 2015 (Williamson et al., 2016), such as *understand the pathways* “establishing connections between sources and sinks for different types of debris”, and *understand the sinks*, “including accumulation in remote locations”. Section 2 presents the material and methods. Results for particles ending up at sea and in the convergence zones are given in Section 3, whereas the specific analysis of particles ending up along the coast (beaching) is presented in Section 4. Section 5 is the concluding section.

2. Material and methods

2.1. Global surface ocean circulation model

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

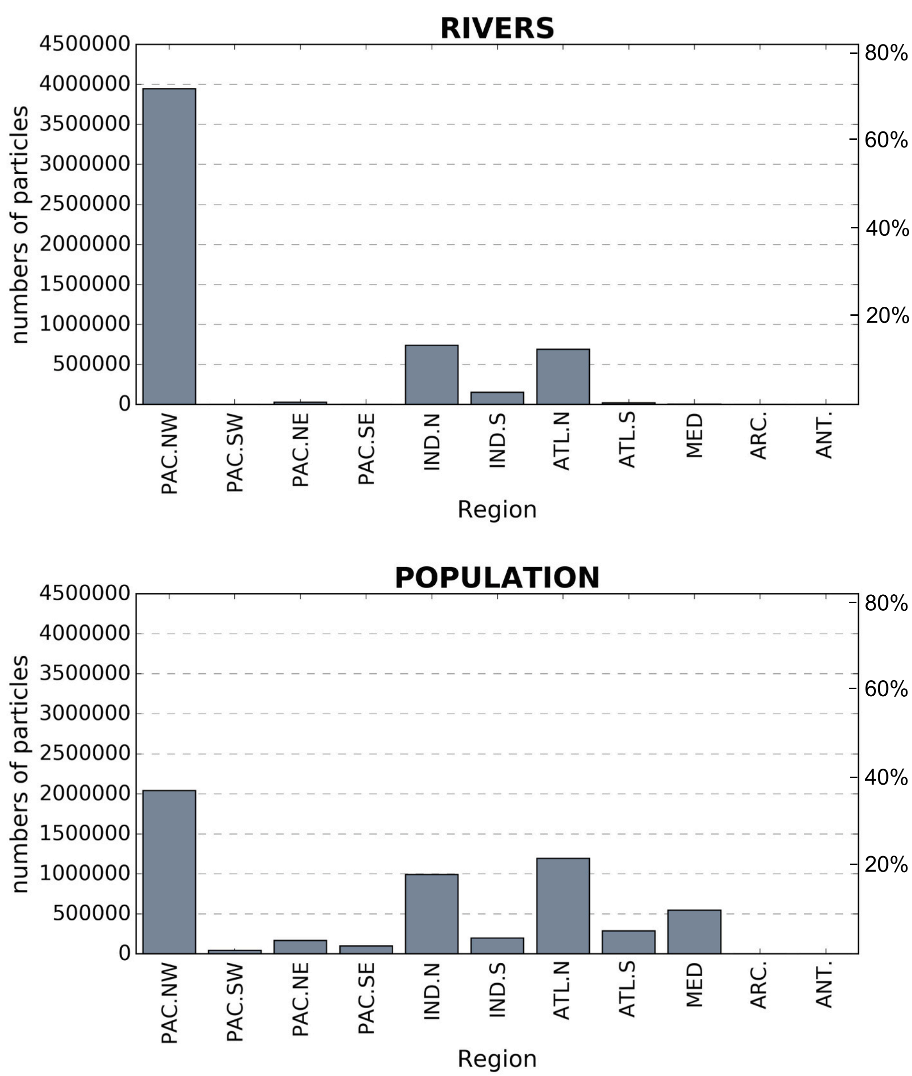

Fig. 1. Total number of particles released in each region in the Lagrangian experiments in the river scenario (top) and the population scenario (i.e., mismanaged waste from the coastal population) (bottom) (maps of the input positions are given in Fig. S1 and oceanic regions are defined in Fig. S2). A total of 5,589,080 and 5,571,720 particles are released in the river and population scenarios, respectively. Percentages on the right are given relatively to the total particles released.

the velocities on the ORCA 1/12° native C-grid to run the Lagrangian experiments.

2.2. Coastal plastic source scenarios

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

The ***river scenario*** comes from the model developed by Lebreton et al. (2017). This global model of plastic inputs from rivers into the oceans is based on waste management, population density and hydrological information. It estimates that about 2 million tons of plastic waste enters the ocean every year from 40,760 rivers. The 20 most polluting rivers are mainly located along the western North Pacific and account for 71% of the total (Fig. 1). The North Indian and North Atlantic basins account for 13% and 12% of the river inputs, respectively. Data were downloaded from the global model inputs for annual midpoint estimates in Lebreton et al. (2017) (data are available at figshare.com at doi:https://doi.org/10.6084/m9.figshare.4725541).

The second scenario is that of mismanaged waste from the coastal population, which we refer to as the ***population scenario*** hereafter. This is actually a proxy of the mismanaged waste released by the coastal population entering the ocean, as described in van Sebille et al. (2015): it is computed as the human population within 200 km of the coast, scaled by the amount of mismanaged plastic waste available to enter the ocean by country in 2010 (as referenced in Jambeck et al. (2015) as 'mismanaged waste', based on the economic level of the countries). In this scenario, plastic debris entering the ocean is more widely distributed (Figs. 1 and S1) over 2633 coastal input positions. The west coast of the North Pacific accounts for 37% of the total population's input, a relative contribution that is half that of the river input scenario. The North Atlantic shorelines represent the second-highest source of plastic inputs with 21% of total inputs (43% more than river inputs). The North Indian basin represents 18% of the total input. The Eastern Pacific, South Atlantic (east and west) and the Mediterranean Sea represent larger sources of plastic (5%, 5% and 10%, respectively) than in the river scenario (<1%, 1% and <1%, respectively). Data were provided by Erik van Sebille (pers. comm., 2018) based on the estimate of Jambeck et al. (2015) that 4.8–12.7 million tons of land-based plastic debris entered the ocean in 2010, which is 2–6 times more than the river input on average.

Both scenarios are projected and discretized on our model grid. The finite number of total particles released over the course of the experiment, and rounding to an integer number of particles released each month in the source grid cells, reduces the effective number of source points as follows. For the river scenario, the finite number of particles released each month (about 20,000) reduces the effective number of source points to 522 grid cells (Fig. S1). There are very large sources, with about 10 rivers releasing more than 500 particles per month (representing altogether more than 58% of the total), with the Yangtze River peaking at about 5000 particles (25% of the total). For the population scenario, out of the 2633 source points provided by Erik van Sebille (pers. comm., 2018) on a 1° × 1° grid, the finite number of particles released each month reduces the effective number of source grid cells to 1196 in our experiment (i.e., more than twice that of the river scenario). There are no sources as extreme as in the river scenario; the peak values are about 350 particles per month (barely 2% of the total), with 23 sources releasing more than 100 particles per month (representing altogether 19% of the total).

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

2.3. Lagrangian analysis

To study the fate and pathway of floating plastic debris in the global ocean, we use a Lagrangian approach with the Ariane methodology (Blanke and Raynaud, 1997). As detailed in Maes et al. (2018) or Dobler et al. (2019), the Ariane tool has been used so that the numerical particles are horizontally advected by surface currents and do not experience vertical motion. The plastic input data for both scenarios were gridded on the ORCA native grid at a resolution of 1/12° at the nearest ocean grid point, i.e., each source point is associated with a single grid cell of the model. The initial positions of the particles are determined randomly within the grid cell. Note that the population density proxy data set was available at a resolution of 1° × 1°; for this reason, some final positions on the 1/12° grid are not initialized exactly at the coast (as strictly defined by the land-sea mask of the model) but near the coast. Two experiments are run according to the coastal input scenario (see previous section) with equivalent total particle numbers: 5,589,080 particles for the river scenario, and 5,571,720 particles for the population scenario (the particle numbers are slightly different due to rounding to an integer number of particles released each month). About 20,000 particles are thus released each month during the 23-year period from 1993 to 2015 (i.e., about 240,000 particles released per year). Particles released at close locations within the same grid cell are subject to turbulent, seasonal and interannual variability in the surface current that will lead to dispersion in their trajectories. The positions of the particles are recorded with a monthly frequency. There are no explicit sinks in our approach i.e., the released particles stay indefinitely at the surface in the model, still moving or stuck along the coasts.

2.4. Particle behavior

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

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

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

3. Open ocean convergence zones

3.1. General aspects

The particles are released continuously in both experiments. After a few years of Lagrangian advection, the particles have spread almost all over the global ocean, from the coast to the open ocean. Only a few regions remain free of particles: the Southern Ocean (due to the strong northward Ekman transport), the Atlantic and Pacific equatorial regions (due to the strong Ekman transport divergence), and the northern North Pacific and Chukchi Sea in the Arctic. Fig. 2 represents what could be roughly observed in terms of relative surface plastic pollution from space at any given time. The two scenarios have similarities and differences (Fig. 2). In both scenarios, surface plastics cover a large portion of the ocean between 45°S and 45°N. Particles seem to accumulate in bays, gulfs and seas surrounded by high-flow rivers (river inputs) and densely populated coastlines (population inputs), e.g., in the Bay of Bengal, Gulf of Guinea and China Sea (Reisser et al., 2013; Hinojosa and Thiel, 2009; Collignon et al., 2012; Ryan, 2013), similarly in both scenarios. Other regions of accumulation are in the centers of the subtropical gyres, regions known as CVZs (Convergence Zones), where plastic accumulates through Ekman transport (Kubota, 1994; Maximenko et al., 2012; van Sebille, 2015), mainly in the North Pacific and South Indian basins. Concentrations differ strongly between scenarios in the South Atlantic, North Atlantic, South Pacific, and Arctic, but also in some coastal regions (e.g., off Europe and Brazil). Another difference between the scenarios is the lower concentration of particles in the equatorial Pacific and equatorial Atlantic in the river scenario compared to the population scenario. These discrepancies between the scenarios are only due to the relative input of particles (as the dynamics are the same in both experiments). Compared to the in situ observations (see Fig. 1 "standardized data" of van Sebille et al., 2015), the population scenario seems to show better agreement than the river scenario in terms of relative amplitude and global distribution of surface plastic debris, mostly because of the higher concentrations in the North Atlantic, South Atlantic and South Pacific CVZs. It should be mentioned that no scenario exactly satisfies the relative concentrations of particles in the different regions, especially since the syntheses of observations do not agree with each other. This might be due to the fact that particles inputs are more widely distributed along the coast in the population scenario than in the river scenario, as described in Section 2.2.

3.2. Details of particles ending at sea

To determine the origins of these discrepancies and to untangle the fate and pathways of the particles, now we modify the standard way of

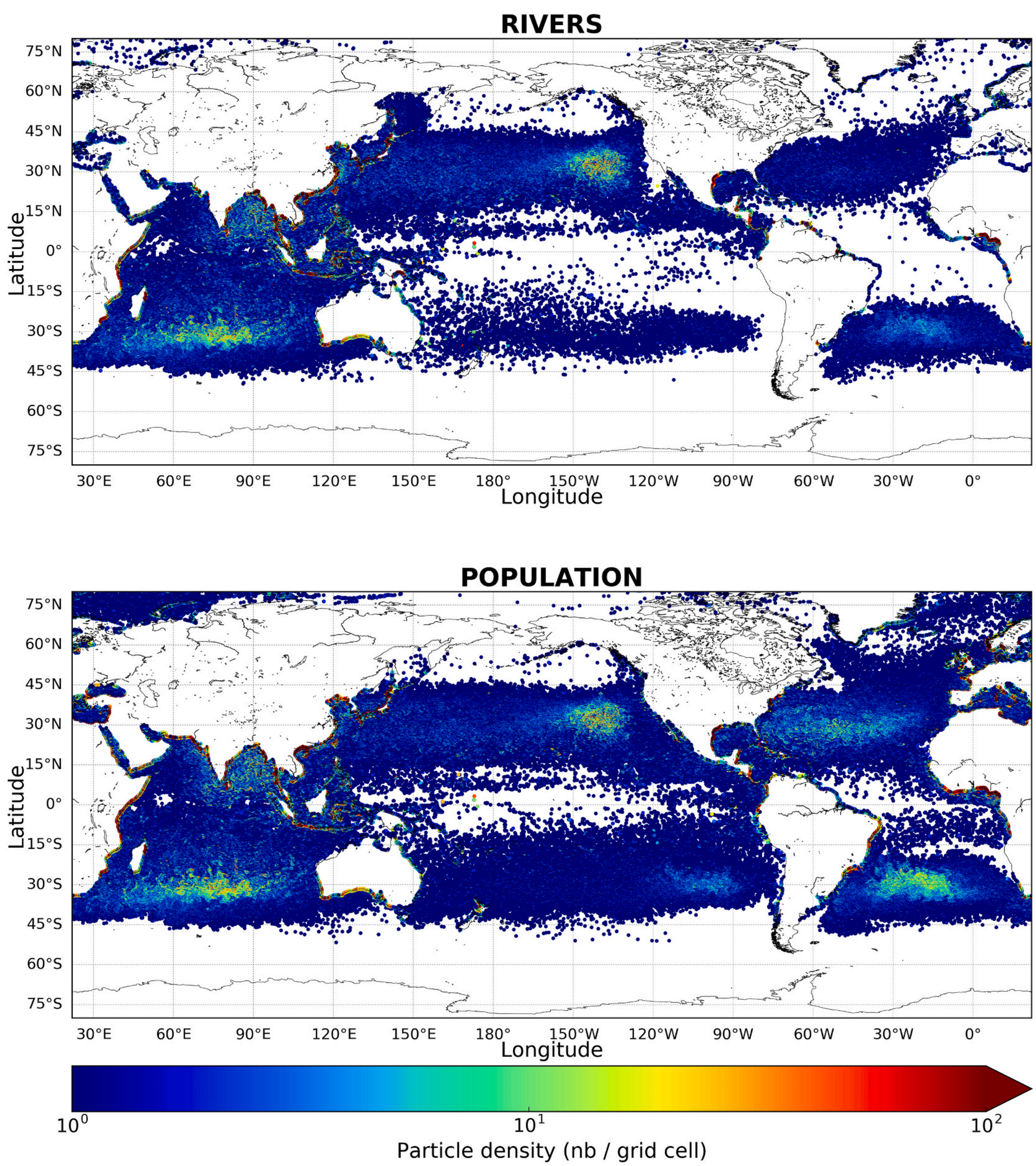

Fig. 2. Number of particles per model grid cell at the end of the model simulations (year 23) in the river scenario (top) and the population scenario (i.e., mismanaged waste from the coastal population) (bottom).

analyzing the fate of our particles. Instead of merely looking at the position of particles at time *t*, which mixes particles of different ages (such as Fig. 2), we choose to focus on the position of particles as a function of their age, i.e., the time elapsed since their release. We can thus follow a cohort of particle traveling from their release position to their final position (Fig. 3). For this section, we focus on particles from *case a*, i.e., particles ending up at sea. Since particles may be released at the same location at different times, they may experience different dynamics; thus, such an analysis provides much more consistent statistics on the plastic fate at the ocean surface. Fig. 3 shows both the quasi-initial position of the particles (i.e., one month after their release at the coast), and their position after 22 years. The one-month-old particles have experienced one month of dynamics and are still relatively close to their release position: such a representation gives a good approximation of the initialization of particles in terms of position and concentration. It also illustrates the main input differences between the scenarios: with the exception of the tropical areas of the West Pacific and Northeast Indian Oceans, all other shores show significant differences. As explained in section 2b, the population scenario is more widely spread, especially in relation to the American, European and African population. After drifting with the currents for 20 years, the particles aggregate in the center of the gyres (while others still drift in highly dynamical regions

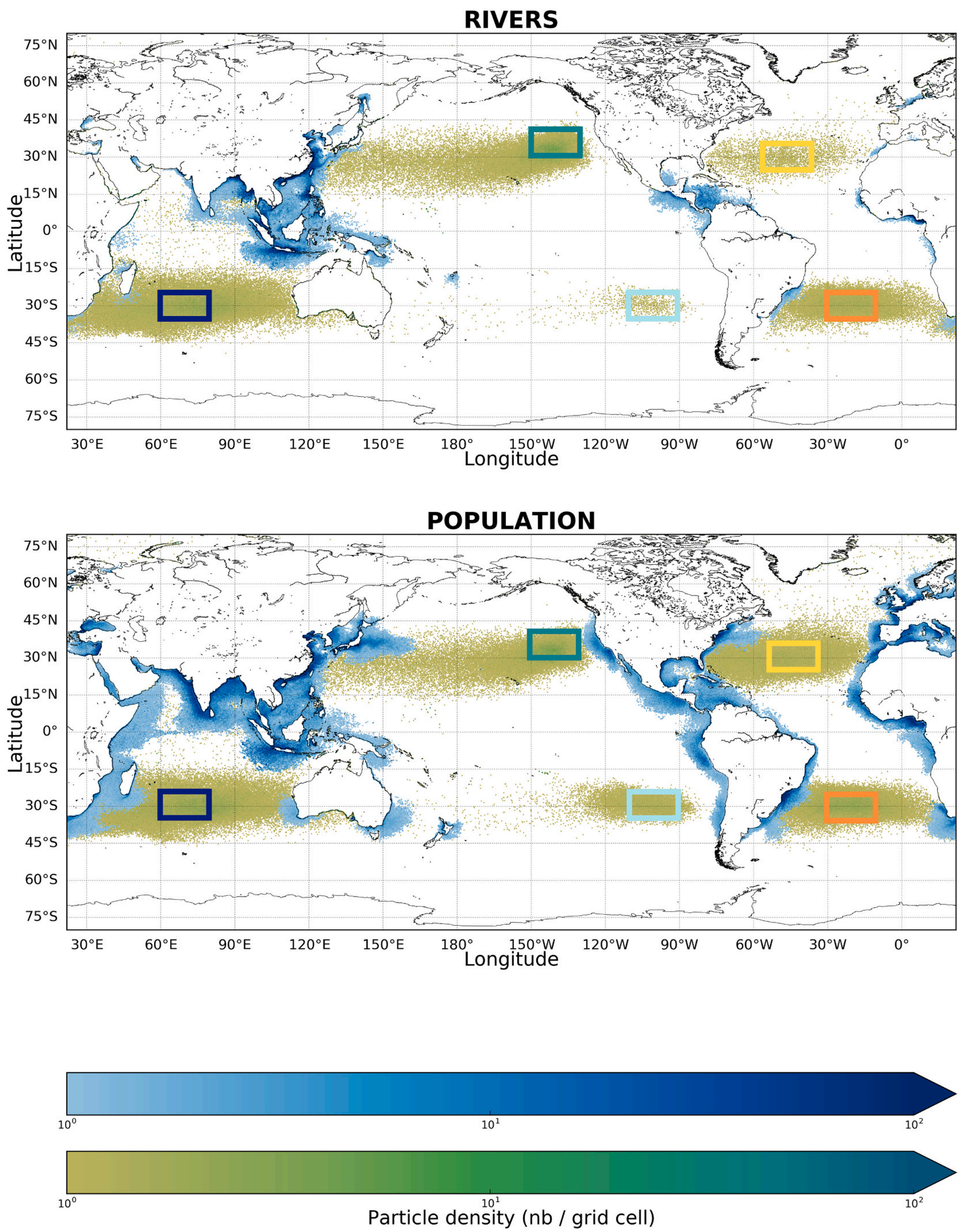

Fig. 3. Number of particles per model grid cell at different ages in the river scenario (top) and the population scenario (i.e., mismanaged waste from the coastal population) (bottom): particles aged 1 month (blue colorbar) and particles aged 22 years (green colorbar). Note that the total number of 1-month-old particles is 22 times higher than the number of 22-year-old particles (released during the first year of the Lagrangian experiment). The colored boxes represent the center of the five main convergence zones (CVZs). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

such as the Agulhas Current or between the subtropical region of the South Indian Ocean and the southwestern Pacific Ocean).

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

In addition to the local contribution of plastic pollution in the main gyres, there is also a remote contribution allowed by the connectivity between sub-basins. This connectivity depends on the strength and extent of the attraction basins (Froyland et al., 2014). To study this connectivity from coastal regions to the open ocean, we determine the temporal accumulation of particles in the main gyres (Fig. 4) and establish a connectivity matrix from the coastal inputs of particles - i.e., the initial position of the particles - to their final position at sea (Fig. 5) between the sub-regions defined in Fig. S2 (see also the mapped initial positions given in Figs. S3 and S4). To better capture the open-ocean signal of the particles attracted (Fig. 4), we limit the extension of the CVZs to their core - where particles accumulate over time (van Sebille et al., 2020) – and focus on the five main CVZs (see the colored boxes in Fig. 3). The slope of the curve indicates whether particles accumulate mostly in an attractive CVZ (positive slope), whether particles escape mostly from a leaky CVZ (negative slope), or whether an equilibrium is reached between sources and sinks in an attractive but still leaky CVZ (null slope). Sinks may represent particles that move to other regions or that beach. The rate at which a CVZ attracts particles provides an indication of the origin of the particles: the faster the early rate, the younger the particles are, the less they travel (and vice versa for a slower rate). The description of each accumulation zones follows:

- In both *river* and *population* scenarios, the *Indian* CVZ is the region where plastics accumulate the most and very rapidly: in 10 years up to 5.0% and 5.9% accumulate in the river and population scenarios, respectively, with concentrations that continue to increase up to 15 years of simulation. This results from the multiplicity of large sources converging to the Indian basin (see IND·S in Figs. 5, S3 and S4), from local sources (all Indian) to remote sources (from the Pacific and Atlantic shores). This is in line with Lebreton et al. (2012) who found that in the Indian CVZ, the main contributors are Southeast Asia/Indonesia, Africa and India. Overall, the South Indian is the most heterogeneously and widely impacted region, with particles coming from all origins with the population inputs (except the Mediterranean) and from all over the North Pacific and South Atlantic with the river inputs (Fig. 5). In this case, the particles likely crossed the equator, for instance between the South and the North Indian during the intermonsoon season, as recently documented by van der Mheen et al. (2020). This result contrasts with that of Lebreton et al. (2012) who identified the greatest diversity of

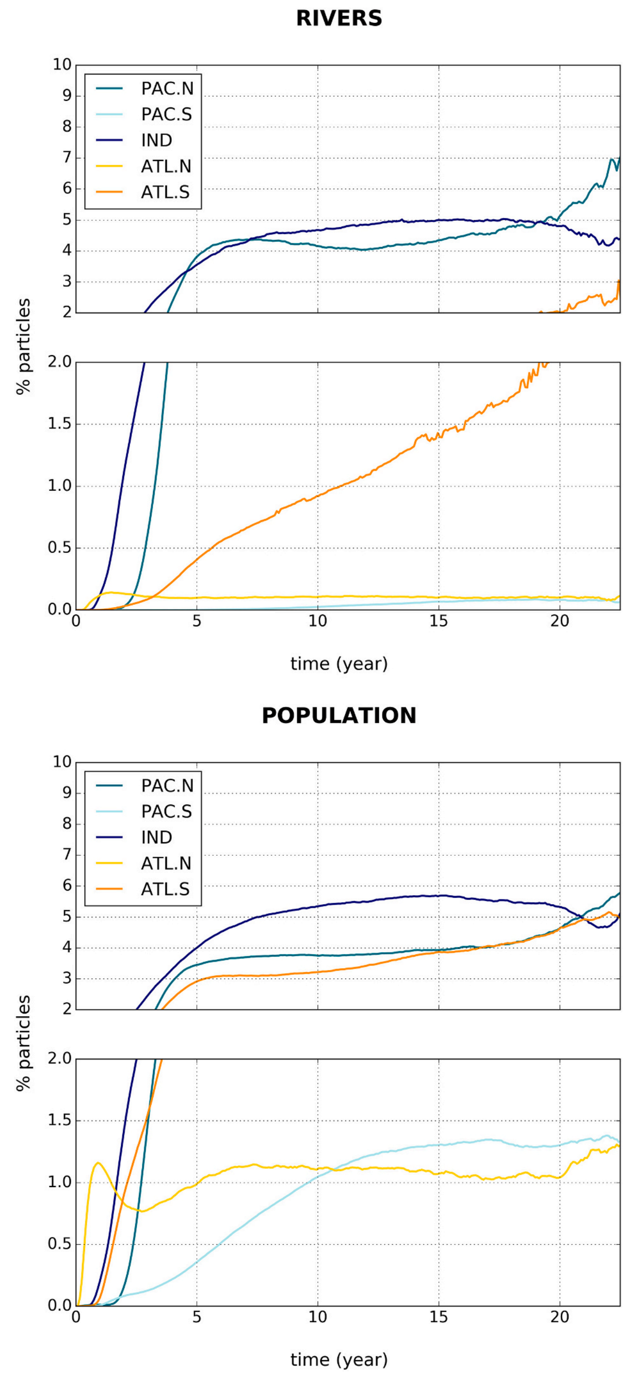

Fig. 4. Percentage of particles in each CVZ center, as a function of simulation time in the river scenario (two upper panels) and the population scenario (i.e., mismanaged waste from the coastal population) (two lower panels). The percentage represents the number of particles in each CVZ normalized by the number of active particles, i.e., the number of particles released at time t since the beginning of the simulation (note that this number of active particles increases each month, as explained in section 2b).

particle origins in the Southeast Pacific. This discrepancy might be due to differences in input scenarios. Interestingly, the North Indian feeds the Southeast Pacific (Fig. 5). This connection has already been documented as the surface "superconvergence" pathway linking the south Indian Ocean to the subtropical south Pacific gyre through the Great Australian Bight (Maes et al., 2018).

- The *North Pacific* is the second region where plastics are accumulating the most and very rapidly. The North Pacific CVZ starts to

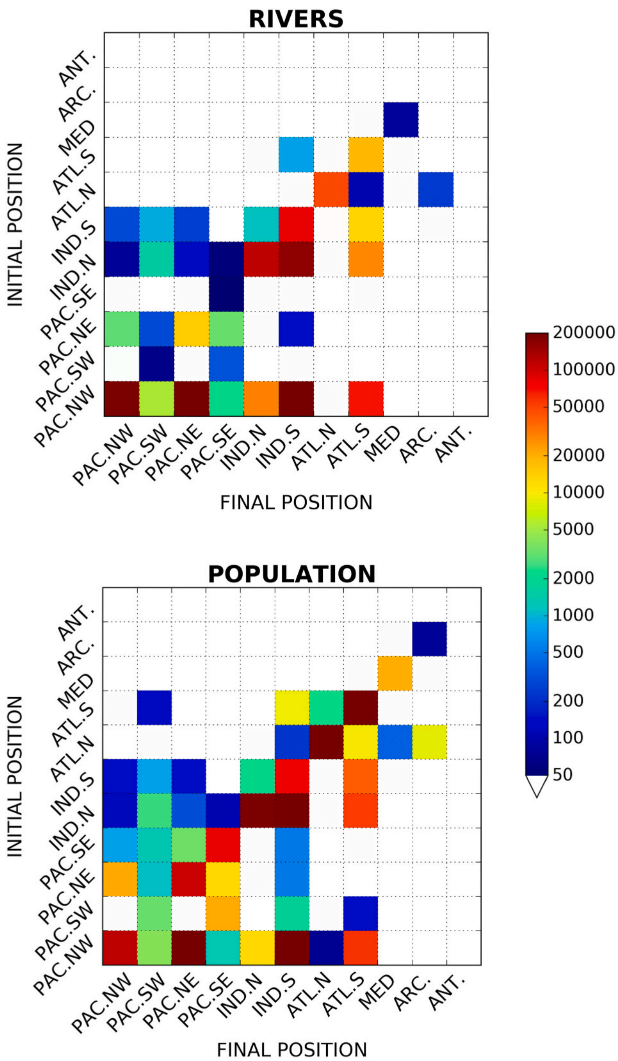

Fig. 5. Connectivity matrix for particles that end up in the sea (case a), in the river scenario (top) and population scenario (i.e., mismanaged waste from the coastal population) (bottom). The cells are colored according to the number of particles originating from the region indicated on the y-axis and ending up in the region indicated on the x-axis. White cells indicate low connectivity (fewer than 50 particles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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

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

- Accumulations in the *North Atlantic* CVZ vary significantly according to the input scenario, as in Lebreton et al. (2012). In the river scenario, very few particles accumulate, and an equilibrium of ~0.1% is rapidly reached (Fig. 4), with particles being attracted only from the local shores (see ATL.N in Fig. 5). In the population scenario, a maximum is rapidly reached (1% in less than a year), followed by a decrease and a further increase toward an equilibrium of ~1.1% in 5 years (Fig. 4). In this case, there is a clear balance between the sources (North and South Atlantic shores) and the open waters of the North Atlantic (Fig. 5), with the dispersion of particles from the core in the *North Atlantic* waters.

- In the *South Pacific* CVZ, particles accumulate very slowly and the maximum concentration of about 0.1 and 1% is reached in 15 years (ten times slower than in the North Atlantic CVZ) with river and population inputs, respectively. This is consistent with Lebreton et al. (2012) who identified that "particles originating from South Atlantic and identified in the South Pacific Gyre took more than 15 years to make the journey". In both scenarios, the locations of sources are similar, but the concentration of inputs from the Eastern and Southwestern Pacific shores is higher in the population scenario (see the PAC.SE position in Fig. 5), as in Lebreton et al. (2012).

In terms of open ocean pollution (particles in case a, ending at sea), we evaluate that 28% (~470,000 particles) have a local origin in the river scenario, against 49% (~1,200,000 particles) in the population scenario (these numbers are computed as the sum of the diagonal terms of the connectivity matrix, Fig. 5). Thus, the remaining portions of the particles have a remote origin (with our definition of regions), respectively 72% in the river scenario and 51% in the population scenario. The NW Pacific shores represent the largest source of pollution at sea in both scenarios (Fig. 1): particles reach mostly the South Indian (4.5 10^5 and 3.8 10^5 particles, i.e., 8% and 6.8% of the released particles) and the NE Pacific (4.0 10^5 and 3.0 10^5 particles, i.e., 7.2% and 5.4% of the released particles), then the South Atlantic (6.0 10^4 and 5.8 10^4 particles, i.e., 1.1% and 1.0% of the released particles) (numbers are given for river and population inputs, respectively). Within these regions are the three main CVZs in terms of total number of particles in cores. The NW Pacific is also a significant source of local pollution with 1.9 10^5 and 1.2 10^5 particles (i.e., 3.4% and 2.2% of released particles) for the river and population inputs, respectively. The remaining number of particles (3.7 10^4 and 1.8 10^4 particles, i.e., 0.7% and 0.3% of released particles) ends up in the South Pacific (E and W) and North Indian.

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

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

4. Beaching

As noted in many previous studies (e.g., Maximenko et al., 2012; van Sebille et al., 2015), coastal deposit of plastic debris represents an important reservoir in the total budget. In the present estimation of the model dispersion, a significant proportion of the particles released at the coast does not end up in the open ocean (*case a*). Indeed, 36 and 43% of them end up on beaches (*case b*) while 34 and 11% travel alongshore (*case c*), in the river and population scenarios, respectively (Fig. 6). In total, 70% and 54% of the particles end up on the coasts (sum of *case b* and *case c*) in the river and population scenarios, respectively. This is in good agreement with (Lebreton et al., 2019) who showed that 67% of the world's plastic washed up on the coasts. Note that a small proportion of particles, ~1%, do not move from the grid cell where they were released. Details on these categories are given hereafter. Overall, the broad spatial spreading of beachings along the coasts (Fig. 7) is not strikingly different between the two scenarios (except for a few areas), especially when compared to the very contrasted input functions (Fig. S1).

In terms of sources, in both scenarios, coastal pollution originates

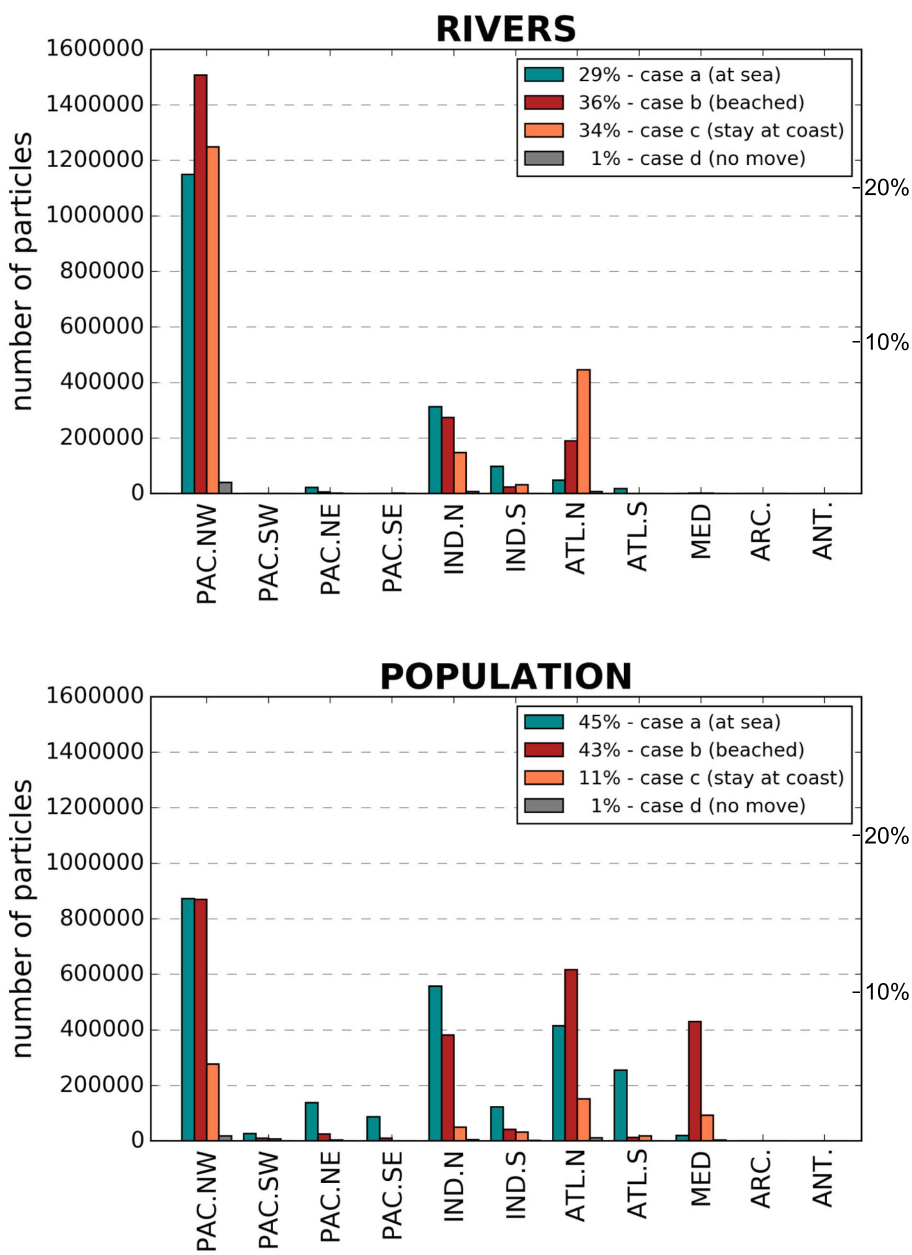

Fig. 6. Histogram of the fates of particles according to their initial region in the Lagrangian experiments (as in Fig. 1): particles ending at sea (cases a), beached particles (case b), particles remaining along the coast (case c) or particles that do not move (case d), in the river scenario (top) and the population scenario (i.e., mismanaged waste from the coastal population) (bottom). Percentages on the right are given relatively to the total particles released.

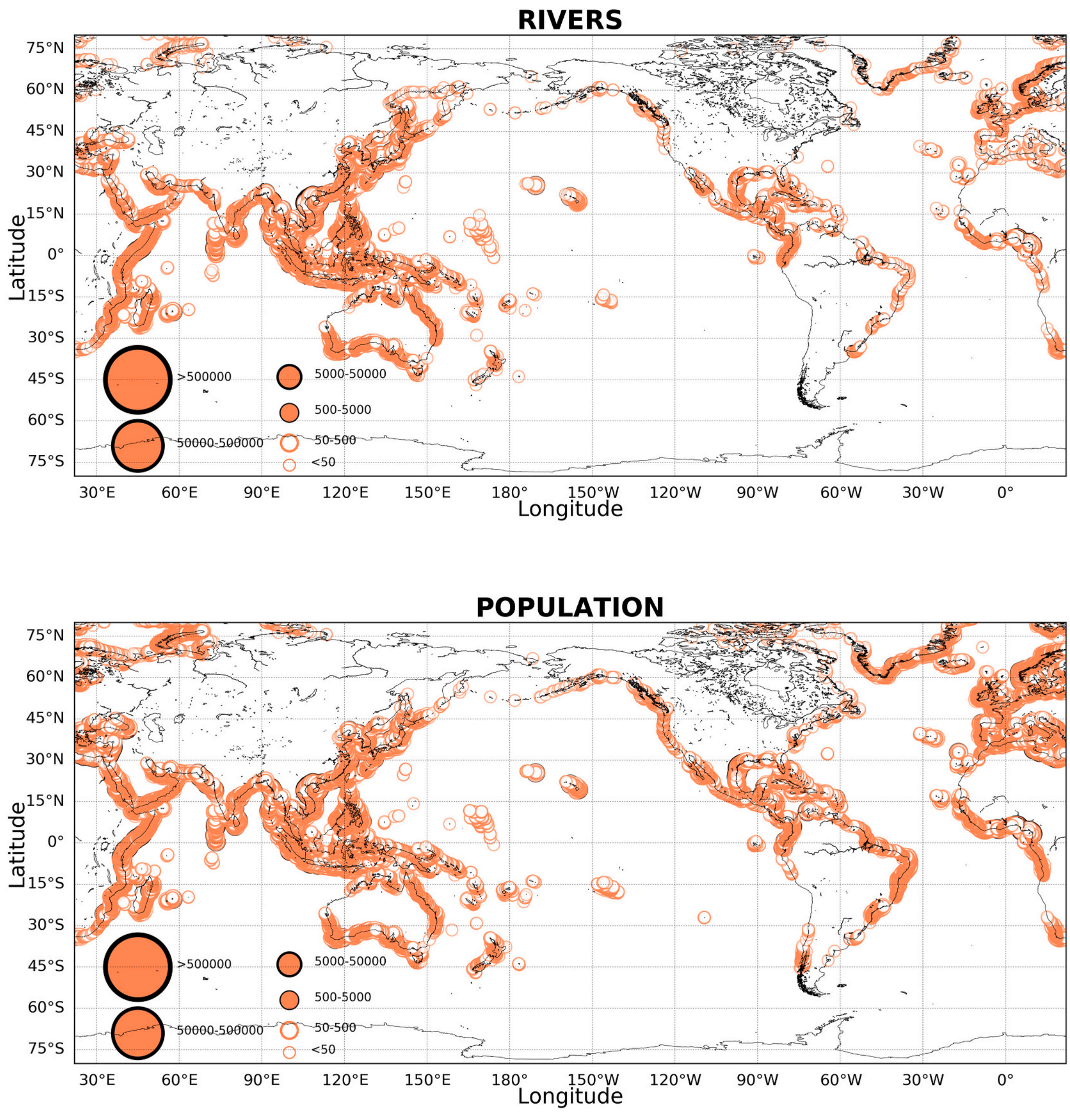

Fig. 7. Number of beached particles (case b) in each coastal grid cell at the end of the simulation (year 23) in the river scenario (top) and the population scenario (i.e., mismanaged waste from the coastal population) (bottom).

mainly from the NW Pacific, North Indian and North Atlantic shorelines, mainly because these are the main sources of particles (Fig. 6). In the population scenario, most of the particles released from the Mediterranean shores actually beached. Depending on the region, the balance of *open-ocean-fate* (*case a*) and *coastal-fate* (*case b* and *c*) is variable (Fig. S5). The following regions contribute more than 50% of the total coastal pollution, as diagnosed in *cases b* and *c*: North Indian (56%), NW and SE Pacific (70% and 96%), North Atlantic (93%) and Mediterranean (97%) with the river scenario; and NW Pacific (57%), North Atlantic (65%) and Mediterranean (96%) with the population scenario (Fig. S5).

The origin of the particles that accumulate along the coast is mostly local (Figs. 7, 8, S6 and S7), i.e., the initial and final positions are in the same region (this is also true for the particles that stay on the coast in *case c*, Fig. S8). In both scenarios, we estimate that 85% (~2000,000 particles) of the beached particles have a local origin (this number is computed as the sum of the diagonal terms of the connectivity matrix, Fig. 8) likely due to coastal retention and coastal recirculation. That is especially true for the NW Pacific, North Indian and North Atlantic in both scenarios, and additionally for the Mediterranean in the population scenario. It is not surprising that in the river scenario, the positioning of local beaching pollution corresponds to the river areas, i.e., the Niger, the Amazon, the Ganges and rivers of the NW Pacific region (Mekong, Yangtze, etc.) (Figs. 7 and S6). Rivers also appear to be hotspots for particle retention on coasts (with 34% of particles in *case c*, Fig. 6 and S8). With regard to the population scenario, where sources are more widely distributed, beaching locations appear to be widespread along the shores and, to a lesser extent, even in divergent regions such as coastal upwelling areas like California, Peru or NW Africa (Fig. 7).

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

To summarize, the impact of local pollution on beaching is even greater with population inputs rather than with river inputs. This result deserves more attention and, because of uncertainties and gaps in the observations of plastic waste, it remains challenging to predict the sources and fate of plastics in coastal systems, as reported recently by

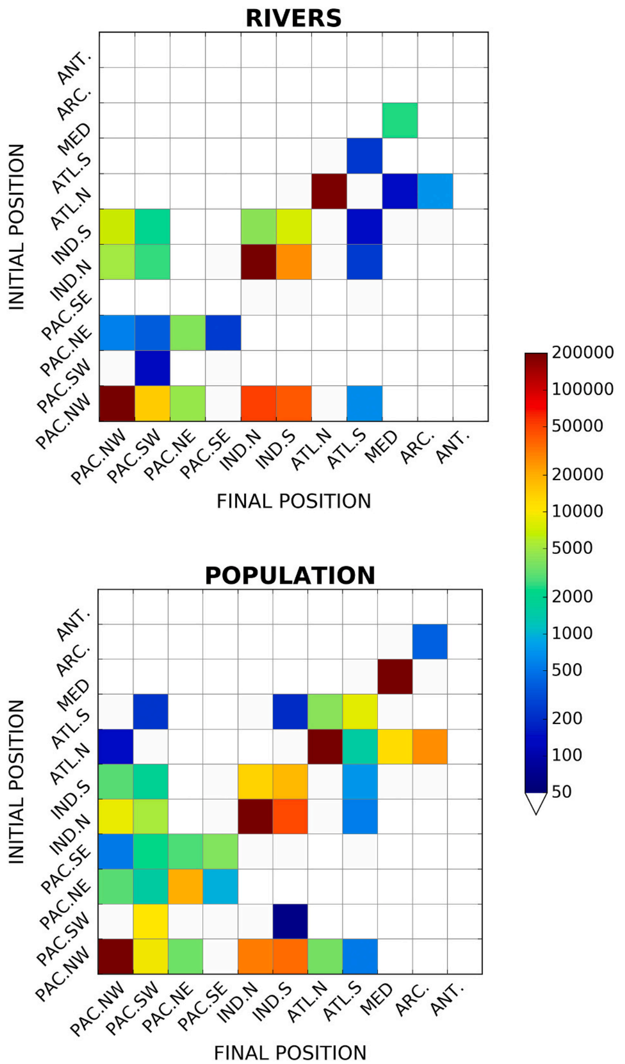

Fig. 8. Connectivity matrix for beached particles (case b) in the river scenario (top) and population scenario (i.e., mismanaged waste from the coastal population) (bottom). The cells are colored according to the number of particles originating from the region indicated on the y-axis and ending up in the region indicated on the x-axis. White cells indicate low connectivity (fewer than 50 particles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

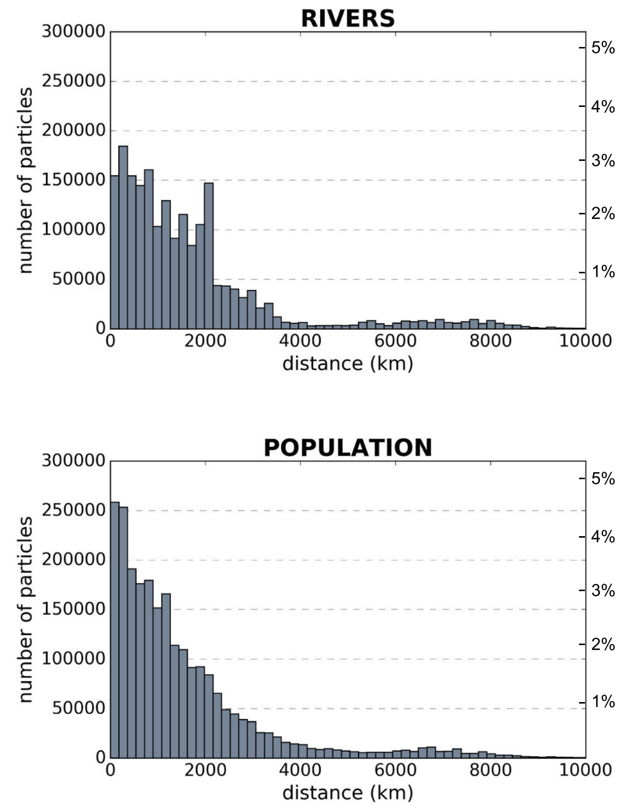

Fig. 9. Histogram of the distances traveled by beached particles (case b) in the river scenario (top, 2,400,151 beached particles in case b) and population scenarios (i.e., mismanaged waste from the coastal population) (bottom, 2,003,808 beached particles in case b). Distances are computed between the initial position and the beached position (see details in Section 4). Percentages on the right are given relatively to the total particles released.

Galgani et al. (2021). As for the particles at sea in the CVZs, the differences between the two scenarios appear mainly in the North Atlantic and SE Pacific, where the sources are very different (Fig. S1). In the North Atlantic, river inputs tend to stay locally on the coast (mostly from the Amazon and Niger), whereas population inputs represent a high source of beached and offshore pollution (from Europe and North America). In the SE Pacific, this local pollution is represented by a significant proportion of offshore pollution with population inputs. The Mediterranean and NE Atlantic are largely affected by beaching and coastal retention (Figs. 6 and S8) with population inputs. Interestingly, these results highlight the disparity between regions in terms of plastic pollution: some regions are strongly affected by coastal pollution (e.g., the North Pacific), due to coastal retention and coastal recirculation, while others have a significant proportion of particles staying offshore (e.g., North Indian and NW Pacific). In contrast to local pollution, there are a significant number of beached particles that have traveled long distances in both scenarios and this study highlights the main pathways of plastic debris between coastal regions and their ability to travel long distances before ending up at the coast. Note that the geographic differences found in the final positions of the particles between the two scenarios are directly related to the location of the input sources and differences in concentration. Given these differences between the input scenarios, the particles may encounter different oceanographic features and dynamics that are likely to influence their final positions. However, the statistical robustness of our approach relies on the use of several million particles to diagnose the main pathways from initial positions to final positions, overcoming the effect of small scales. Moreover, in our simulations, the particles do not sink, whereas in reality, such old particles would most likely fall down the water column (Egger et al., 2020; Pabortsava and Lampitt, 2020) under the action of biology (biofouling, ingestion, or aggregation) (e.g., Kooi et al., 2017; van Sebille et al., 2020).

A qualitative comparison with global beaching patterns, as compiled for instance in the LITTERBASE database (https://litterbase.awi.de/litter, Tekman et al., 2018), generally shows relatively good agreement, except for some regions. For instance, the database reports no beachings along the east coast of Africa from Somalia to Mozambique, and along the coasts of Oman and Yemen, probably due to a lack of observations. A striking difference between the 2 scenarios is the complete absence of beachings along the Pacific coast of South America. Coastal plastic and other debris reported along the Chilean coast suggest that the river input scenario is not sufficient to supply plastic particles to the South Pacific, and in this respect the population scenario is more satisfactory (as reported in LITTERBASE from Thiel et al., 2003; Hinojosa and Thiel, 2009; Hinojosa et al., 2011; Thiel et al., 2013; Miranda-Urbina et al., 2015, Hidalgo-Ruz et al., 2018). Similarly, the 2 scenarios differ greatly along the east coast of America, where the river scenario leads to almost no beaching north of Florida. This is not the case in LITTERBASE, confirming once again the need for population inputs. Beaching patterns around the Indian basin and along the West Pacific coasts are not significantly different between the 2 scenarios, and are in good agreement with previously published results (van der Mheen et al., 2020). Beaching patterns around Australia (PAC. SW in Fig. 8) differ from the 2 scenarios and the population scenario is in better agreement with recent studies (Galaiduk et al., 2020) with significant input from local and northwest Pacific shores.

5. Conclusions

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

A large fraction of the total particles released ends up along the coast, between 54% in the population scenario and 70% in the river scenario. The number of particles that beach in certain areas also depends particularly on the input scenario, such as the European West Coast, the Mediterranean Sea, and African East Coast with the population input. Rivers represent a large source of local coastal pollution, probably due to the retention and recirculation of coastal waters. Regardless the input scenario, some regions are more subject to offshore pollution such as the South Atlantic and the NE Pacific, while others are more largely affected by coastal pollution (beaching) such as the NW Pacific, North Atlantic and Mediterranean shores. We have found that particles can travel up to several thousand kilometers, allowing remote connectivity between coastal regions. This property is of interest for the application to other types of floating pollution or any conservative biogeochemical properties, or viruses and pathogens.

Our study remains an idealized case from several aspects, and from our point of view, the main approximations are the “oversimplified” beaching process and the related dynamical processes. Indeed, beaching of plastics is a complex process that is strongly influenced by small-scale coastal ocean dynamics (Isobe et al., 2014), and by the local morphology of the coastline (Zhang, 2017). Including Stokes-drift, waves or tides can also influence the number of particles stuck to the coast, and increase it by more than three times (Dobler et al., 2019). Another key point is the definition that can be given to the term “beaching”. Using a $1/12^{\circ}$ eddy-resolving ocean model, our definition is purely probabilistic since we define as beached particles those that are at a certain distance from the coast (i.e., one grid point) (as similar studies, e.g., van der Mheen et al. (2020)).

Although this study is still based on available scenarios for plastic sources, it provides new insights on connectivity between regions, on offshore pollution with CVZ composition and on coastal pollution in terms of beaching. There are many ways to add complexity to these processes. Indeed, for the sake of simplicity, we have neglected many key factors such as the temporal/seasonal variability of coastal inputs that could change with rainfall (e.g., Lebreton et al., 2017; van der Mheen et al., 2020), and also the significant worldwide increase in plastic inputs to the sea in relation to population growth and the rapid increase in plastic production (Ostle et al., 2019). We have also ignored the contribution of pollution from maritime inputs along shipping route or fishery activities (e.g., Lebreton et al., 2012). With the $1/12^{\circ}$ eddy-resolving ocean model used, one might have expected to find particles crossing the Antarctic Polar Front and reaching the Southern Ocean (Fraser et al., 2018), but it is likely that the absence of extreme events and Stokes drift (driven by surface winds) does not allow such connectivity. Finally, we focus on floating debris that could experience vertical motion in response to physical or biological processes (van Sebille et al., 2020). It could be interesting to implement models that allow interaction with the marine ecosystem – e.g., processes such as ingestion by plankton and fish, sedimentation by biofouling (Kooi et al., 2017) which could represent an important sink for particles toward the deep ocean (van Sebille et al., 2020). Indeed, it has recently been documented by Egger et al. (2020) that we can find below the surface (5 m depth) to 2000 m about 56%–80% of what is seen at the surface.

Marine plastic pollution represents an increasing threat to the environment. Because of their serious detrimental effects on marine ecosystems (see examples in Napper and Thompson (2020)) and given the huge cost of removing this pollution from beaches (e.g., Burt et al., 2020; Cruz et al., 2020; Napper and Thompson, 2020), it is today fundamental to understand the fate and pathway of marine plastic debris. Such studies are needed to better inform and guide the stakeholders involved in the reduction of plastic pollution and waste management decision makers. However, a consensus is needed among researchers and a major step forward will be to improve the quality of information available on beached marine debris, which would require standardization of data sets (e.g., reporting metrics and sampling methods) (Serra-Gonçalves et al., 2019; Galgani et al., 2021).

CRediT authorship contribution statement

F. Chenillat: Conceptualization, Formal analysis, Investigation, Validation, Methodology, Writing – original draft, Visualization. **T. Huck:** Project administration, Conceptualization, Supervision, Methodology, Writing – review & editing. **C. Maes:** Conceptualization, Supervision, Methodology, Writing – review & editing. **N. Grima:** Resources, Methodology, Software, Data curation. **B. Blanke:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112116.

References

Arakawa, A., Lamb, V.R., 1977. Computational design of the basic dynamical process of the UCLA general circulation model. Methods Comput. Phys. 17, 173–265. https://doi.org/10.1016/B978-0-12-460817-7.50009-4.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. Lond. B Biol. Sci. 364, 1985–1998.

Bergmann, M., Lutz, B., Tekman, M.B., Gutow, L., 2017. Citizen scientists reveal: marine litter pollutes Arctic beaches and affects wild life. Mar. Pollut. Bull. 125 (1–2), 535–540. https://doi.org/10.1016/j.marpolbul.2017.09.055.

Black, J.E., Holmes, D.E., Carr, L.M., 2020. A geography of marine plastics. Ir. Geogr. 53 (1) https://doi.org/10.2014/igj.v53i1.1411.

Blanke, B., Raynaud, S., 1997. Kinematics of the Pacific equatorial undercurrent: an eulerian and lagrangian approach from GCM results. J. Phys. Oceanogr. 27, 1038–1053.

Burt, A.J., Raguain, J., Sanchez, C., et al., 2020. The costs of removing the unsanctioned import of marine plastic litter to small island states. Sci. Rep. 10, 14458. https://doi.org/10.1038/s41598-020-71444-6.

Collignon, A., Hecq, J., Galgani, F., Voisin, P., Collard, F., et al., 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Mar. Pollut. Bull. 64, 861–864.

Cózar, A., Echevarría, F., González-Gordillo, J.I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, Á.T., Navarro, S., García-de-Lomas, J., Ruiz, A., Fernández-de-Puelles, M.L., Duarte, C.M., 2014. Plastic debris in the open ocean. PNAS 111 (28), 10239–10244. https://doi.org/10.1073/pnas.1314705111.

Cruz, C.J., Muñoz-Perez, J.J., Carrasco-Braganza, M.I., Poullet, P., Lopez-Garcia, P., Contreras, A., Silva, R., 2020. Beach cleaning costs. Ocean Coast. Manag. 188, 105118. https://doi.org/10.1016/j.ocecoaman.2020.105118.

Dobler, D., Huck, T., Maes, C., Grima, N., Blanke, B., Martinez, E., Ardhuin, F., 2019. Large impact of Stokes drift on the fate of surface floating debris in the South Indian Basin. Mar. Pollut. Bull. 148 (148), 202–209. https://doi.org/10.1016/j.marpolbul.2019.07.057.

Egger, M., Sulu-Gambari, F., Lebreton, L., 2020. First evidence of plastic fallout from the North Pacific Garbage Patch. Sci. Rep. 10, 7495. https://doi.org/10.1038/s41598-020-64465-8.

Faris, J., Hart, K., 1994. Seas of Debris: A Summary of the Third International Conference on Marine Debris (N.C. Sea Grant College Program and NOAA).

Fraser, C.I., Morrison, A.K., Hogg, A.M., et al., 2018. Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. Nature Clim. Change 8, 704–708. https://doi.org/10.1038/s41558-018-0209-7.

Froyland, G., Stuart, R.M., van Sebille, E., 2014. How well connected is the surface of the global ocean? Chaos 24 (033), 126.

Galaiduk, R., Lebreton, L., Techera, E., Reisser, J., 2020. Transnational plastics: an Australian case for global action. Front. Environ. Sci. 8, 115. https://doi.org/10.3389/fenvs.2020.00115.

Galgani, F., Brien, A.S., Weis, J. et al., 2021. Are litter, plastic and microplastic quantities increasing in the ocean?. Micropl.&Nanopl. 1, 2. doi:https://doi.org/10.1186/s43591-020-00002-8.

Geyer, R., J.R. Lambeck, K. Lavender Law, 2017: Production, use, and fate of all plastics ever made. Science Advances, 3, 1–5, 19July2017.

Hardesty, B.D., Harari, J., Isobe, A., Lebreton, L.C.M., Maximenko, N.A., Potemra, J., van Sebille, E., Vethaak, A.D., Wilcox, C., 2017. Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. Front. Mar. Sci. 4, 30. https://doi.org/10.3389/fmars.2017.00030.

Hidalgo-Ruz, V., Honorato-Zimmer, D., Gatta-Rosemary, M., Nuñez, P., Hinojosa, I.A., Thiel, M., 2018. Spatio-temporal variation of anthropogenic marine debris on Chilean beaches. Mar. Pollut. Bull. 126, 516–524. https://doi.org/10.1016/j.marpolbul.2017.11.014.

Hinojosa, I., Thiel, M., 2009. Floating marine debris in fjords, gulfs and channels of southern Chile. Mar. Pollut. Bull. 58, 341–350.

Hinojosa, I.A., Rivadeneira, M.M., Thiel, M., 2011. Temporal and spatial distribution of floating objects in coastal waters of central–southern Chile and Patagonian fjords, Continental Shelf Research, 31. Issues 3–4, 172–186. https://doi.org/10.1016/j.csr.2010.04.013.

Horton, A.A., Dixon, S.J, 2018. Microplastics: An introduction to environmental transport processes. WIREs Water 5, e1268. https://doi.org/10.1002/wat2.1268.

Isobe, A., Kubo, K., Tamura, Y., Kako, S., Nakashima, E., Fujii, N., 2014. Selective transport of microplastics and mesoplastics by drifting in coastal waters. Mar. Pollut. Bull. 89, 324–330. https://doi.org/10.1016/j.marpolbul.2014.09.041.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771. https://doi.org/10.1126/science.1260352.

Kooi, M., van Nes, E.H., Scheffer, M., Koelmans, A.A., 2017. Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. Environ. Sci. Technol. 51, 7963–7971. https://doi.org/10.1021/acs.est.6b04702.

Kubota, M., 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. J. Phys. Oceanogr. 24, 1059–1064. https://doi.org/10.1175/1520-0485.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., et al., 2020. Evaluating scenarios toward zero plastic pollution. Science 369 (6510), 1455–1461. https://doi.org/10.1126/science.aba9475.

Law, K.L., Morét-Ferguson, S.E., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329, 1185–1188.

Law, K.L., Morét-Ferguson, S.E., Goodwin, D.S., Zettler, E.R., DeForce, E., Kukulka, T., Proskurowski, G., 2014. Distribution of surface plastic debris in the Eastern Pacific Ocean from an 11-year data set. Environ. Sci. Technol. 48, 4732–4738.

Lebreton, L.C.M., Greer, S., Borrero, J., 2012. Numerical modelling of floating debris in the world's ocean. Mar. Pollut. Bull. 64, 653–661.

Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611. https://doi.org/10.1038/ncomms15611.

Lebreton, L.C.M., Slat, B., Ferrari, F., Sainte-Rose, B., et al., 2018. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Nat. Sci. Rep. 8, 4666. https://doi.org/10.1038/s41598-018-22939-w.

Lebreton, L., Egger, M., Slat, B., 2019. A global mass budget for positively buoyant macroplastic debris in the ocean. Sci. Rep. 9, 12922. https://doi.org/10.1038/s41598-019-49413-5.

Lellouche, J.-M., Greiner, E., Le Galloudec, O., Garric, G., Regnier, C., Drevillon, M., Benkiran, M., Testut, C.-E., Bourdalle-Badie, R., Gasparin, F., et al., 2018. Recent updates to the Copernicus Marine Service global ocean monitoring and forecasting real-time 1/12 high-resolution system. Ocean Sci. 14, 1093–1126. https://doi.org/10.5194/os-14-1093-2018.

Maes, C., N. Grima, B. Blanke, E. Martinez, T. Paviet-Salomon, T. Huck, 2018: A surface "super-convergence" pathway connecting the South Indian Ocean to the subtropical South Pacific gyre. Geophysical Research Letters, 45, (4) 1915–1922, 2017GL076366, doi:https://doi.org/10.1002/2017GL076366.

Maes, T., Perry, J., Alliji, K., Clarke, C., Birchenough, S.N.R., 2019. Shades of grey: marine litter research developments in Europe. Mar. Pollut. Bull. 146, 274–281. https://doi.org/10.1016/j.marpolbul.2019.06.019.

Maximenko, N.A., Hafner, J., Niiler, P., 2012. Pathways of marine debris from trajectories of Lagrangian drifters. Mar. Pollut. Bull. 65 (1–3), 51–62. https://doi.org/10.1016/j.marpolbul.2011.04.016.

Maximenko, N., Corradi, P., Law, K.L., Van Sebill, E., Garaba Shungudzemwoyo, P., et al., 2019. Toward the integrated marine debris observing system. Frontiers in Marine Science 6, 447. https://doi.org/10.3389/fmars.2019.00447.

Miranda-Urbina, D., Thiel, M., Luna-Jorquera, G., 2015. Litter and seabirds found across a longitudinal gradient in the South Pacific Ocean, Marine Pollution Bulletin, Volume 96. Issues 1–2, 235–244. https://doi.org/10.1016/j.marpolbul.2015.05.021.

Napper, I.E., Thompson, R.C., 2020. Plastic debris in the marine environment: history and future challenges. Global Chall. 4, 1900081. https://doi.org/10.1002/gch2.201900081.

Ostle, C., Thompson, R.C., Broughton, D., et al., 2019. The rise in ocean plastics evidenced from a 60-year time series. Nat. Commun. 10, 1622. https://doi.org/10.1038/s41467-019-09506-1.

Pabortsava, K., Lampitt, R.S., 2020. High concentrations of plastic hidden beneath the surface of the Atlantic Ocean. Nat. Commun. 11, 4073. https://doi.org/10.1038/s41467-020-17932-9.

Reisser, J., Shaw, J., Wilcox, C., Hardesty, B., Proietti, M., 2013. Marine plastic pollution in the waters around Australia: characteristics, concentrations and pathways. PLoS One 8. https://doi.org/10.1371/journal.pone.0080466.

Ryan, P.G., 2013. A simple technique for counting marine debris at sea reveals steep litter gradients between the Straits of Malacca and the Bay of Bengal. Mar. Pollut. Bull. 69, 128–136. https://doi.org/10.1016/j.marpolbul.2013.01.016.

Serra-Gonçalves, C., Lavers, J.L., Bond, A.L., 2019. Global review of beach debris monitoring and future recommendations. Environ. Sci. Technol. 53 (21), 12158–12167. https://doi.org/10.1021/acs.est.9b01424.

Tekman, M.B., Gutow, L., Macario, A., Haas, A., Walter, A., Bergmann, M., 2018. LITTERBASE; Alfred Wegener Institute for Polar and Marine Research: Bremerhaven, Germany, 2018. http://litterbase.awi.de/interaction_detail.

Thiel, M., Hinojosa, I., Vásquez, N., Macaya, E., 2003. Floating marine debris in coastal waters of the SE-Pacific (Chile), Marine Pollution Bulletin, 46. Issue 2, 224–231. https://doi.org/10.1016/S0025-326X(02)00365-X.

Thiel, M., Hinojosa, I.A., Miranda, L., Pantoja, J.F., Rivadeneira, M.M., Vásquez, N., 2013. Anthropogenic marine debris in the coastal environment: a multi-year comparison between coastal waters and local shores, Marine Pollution Bulletin, 71. Issues 1–2, 307–316. https://doi.org/10.1016/j.marpolbul.2013.01.005.

van der Mheen, M., van Sebille, E., Pattiaratchi, C., 2020. Beaching patterns of plastic debris along the Indian Ocean rim. Ocean Science 16, 1317–1336. https://doi.org/10.5194/os-2020-5.

van Sebille, E., 2015. The oceans' accumulating plastic garbage. Phys. Today 68, 60–61.

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Van Franeker, J. A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. Environ. Res. Lett. 10, 124006, 12 pp. https://doi.org/10.1088/1748-9326/10/12/124006.

van Sebille, E., Griffies, S.M., Abernathey, R., Adams, T.P., Berloff, P., Biastoch, A., Blanke, B., Chassignet, E.P., Cheng, Y., Cotter, C.J., Deleersnijder, E., Döös, K., Drake, H.F., Drijfhout, S., Gary, S.F., Heemink, A.W., Kjellsson, J., Koszalka, I.M., Lange, M., Lique, C., MacGilchrist, G.A., Marsh, R., Mayorga Adame, C.G., McAdam, R., Nencioli, F., Paris, C.B., Piggott, M.D., Polton, J.A., Rühs, S., Shah, S.H., Thomas, M.D., Wang, J., Wolfram, P.J., Zanna, L., Zika, J.D., 2018. Lagrangian ocean analysis: fundamentals and practices. Ocean Model 121, 49–75. https://doi.org/10.1016/j.ocemod.2017.11.008.

van Sebille, E., et al., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett. 15, 023003 https://doi.org/10.1088/1748-9326/ab6d7d.

Viatte, C., Clerbaux, C., Maes, C., Daniel, P., Garello, R., Safieddine, S., Ardhuin, F., 2020. Air pollution and sea pollution seen from space. Surv. Geophys. https://doi.org/10.1007/s10712-020-09599-0.

Karina von Schuckmann, Pierre-Yves Le Traon, Enrique Alvarez-Fanjul, Lars Axell, et al., 2016: The Copernicus Marine Environment Monitoring Service Ocean State Report, Journal of Operational Oceanography, 9:sup2, s235–s320, DOI:https://doi.org/10.1080/1755876X.2016.1273446.

Williamson, P., Smythe-Wright, D., Burkill, P. (Eds.), 2016. Future of the Ocean and Its Seas: A Non-governmental Scientific Perspective on Seven Marine Research Issues of G7 Interest. ICSU-IAPSO-IUGG-SCOR, Paris.

Zhang, H., 2017. Transport of microplastics in coastal seas. Estuar. Coast. Shelf Sci. 199, 74–86. https://doi.org/10.1016/j.ecss.2017.09.032.