Modelling floating riverine litter in the south-eastern Bay of Biscay: a regional distribution from a seasonal perspective

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Abstract

Although rivers contribute to the flux of litter to the marine environment, estimates of riverine litter amounts and detailed studies on floating riverine litter behaviour once it has reached the sea are still scarce. This paper provides an analysis of the seasonal behaviour of floating marine litter released by rivers within the south-eastern Bay of Biscay based on riverine litter characterizations, drifters and high-frequency radars observations, and Lagrangian simulations. Virtual particles were released in the coastal area as a proxy of the floating fraction of riverine litter entering from rivers and reaching the open waters. Particles were parameterized with a wind drag coefficient (Cd) to represent their trajectories and fate according to the buoyancy of the litter items. They were forced with numerical winds and measured currents provided by high-frequency radars covering selected seasonal week-long periods between 2009 and 2021. To gain a better insight on the type and buoyancy of the items, samples collected from a barrier placed at Deba river (Spain) were characterized at the laboratory. Items were grouped into two categories: low buoyant items (objects not exposed to wind forcing e.g., plastic bags) and highly buoyant items (objects highly exposed to wind forcing, e.g., bottles). Overall, low buoyant items encompassed almost 90% by number and 68% by weight. Low buoyant items were parametrized with Cd=0%, and highly buoyant items with Cd=4%, this later one as a result of the joint analysis of modelled and observed trajectories of four satellite drifting buoys released at Adour (France), Deba (Spain) and Oria (Spain) river mouths. Particles parametrized with Cd=4% drifted faster towards the coast by the wind, notably during the first 24 hours. In summer, over the 97% of particles beached after one week of simulation. In autumn this value fell to 54%. In contrast, low buoyant items took longer to arrive to the shoreline, particularly during Spring with fewer than 25% of particles beached by the end of the simulations. The highest concentrations (>200 particles/km) were recorded during summer for Cd=4% in the French region of Pyrénées-Atlantiques. Results showed that the regions in the study area were highly affected by rivers within or nearby the region itself. These results couple observations and a river-by-river modelling approach and can assist decision makers on setting emergency responses to high fluxes of floating riverine litter and on defining future monitoring strategies for heavy polluted regions within the south-eastern Bay of Biscay.

1 Introduction

Rivers act as key vectors bringing improperly disposed and mismanaged litter from land into the marine environment. Riverine litter poses a large threat to freshwater systems by degrading aquatic life, impacting freshwater quality and increasing economic losses linked with human activities (van Emmerik and Schwarz, 2020; Al-Zawaidah et al., 2021). However, most of the litter research conducted to date has focused on marine environments (87%) when compared to freshwaters systems (13%) (Blettler et al., 2018). Indeed, riverine litter contributions to oceans are still uncertain, and results vary depending on the input data and the model applied (Lebreton et al., 2017; Schmidt et al., 2017; Mai et al., 2020). Recent findings derived from extensive modelling efforts suggest that about 1,600 rivers worldwide account for 80% of plastic inputs to the ocean with small urban rivers among the most polluting (Meijer et al., 2021). Models require comprehensive field data and consistent and harmonized protocols to validate the amounts, type and size of riverine inputs (González-Fernández and Hanke, 2017; Wendt-Potthoff et al., 2020; Margenat et al., 2021). Such comprehensive data was obtained in Europe thanks to the RIMMEL project (González-Fernández and Hanke, 2017). This research concluded that between 307 and 925 million floating riverine litter items are annually transferred into the ocean mainly through small rivers, streams and coastal run-off (González-Fernández et al., 2021).

Once it has reached the sea, floating riverine litter can accumulate close to the shoreline or it can be transported to open waters, reaching even remote areas far from the coast. Indeed, the distribution and fate of floating litter in the marine environment is affected by the metocean conditions (currents, turbulence, wind) but also by the buoyancy of the objects (Ryan, 2015; Lebreton et al., 2019; Maclean et al., 2021). Objects with low buoyancy are mainly driven by currents contrary to highly buoyant items, which are driven along the water surface partially by winds. This wind effect ("windage") on floating marine litter behaviour has been further investigated by Lagrangian modelling studies in the open ocean (Allshouse et al., 2017; Maximenko et al., 2018; Lebreton et al., 2019; Abascal et al., 2009) when compared to the coastal area (Critchell and Lambrechts, 2016; Utenhove, 2019; Tong et al., 2021). The lack of observational data is one of the key limitations for parametrizing the windage effect and accurately predict floating marine litter behaviour. However, observations derived from drifting buoys, such as those provided for decades by the Global Drifter program, have been used to fill this gap. They have allowed simulating more realistic floating marine litter pathways from origin to fate by integrating experimental windage parametrizations and the corresponding comparison between observed and modeled trajectories (Duhec et al., 2015; Pereiro et al., 2018; Rizal et al., 2021). Nowadays, more affordable and environmentally friendly solutions are gaining force among researchers, as drifters built using biopolymers (Novelli et al., 2017; D'Asaro et al., 2020) or compact and lightweight designs with a GPS-tracking component for an easy deployment (Meyerjürgens et al., 2019; van Sebille et al., 2021).

At coastal scale, windage parametrization combined with realistic knowledge on coastal circulation become crucial to reduce the uncertainties of modelled trajectories (Van Sebille et al., 2020). Land-based high frequency radar systems (hereafter HF radars (Rubio et al., 2017)) offer the opportunity to monitor surface currents in coastal areas, where the transport processes are significantly more complex than open ocean waters due to the effect of the coast, the bathymetry and other local forcings (e.g., river discharges or coastal upwellings). In the south-eastern Bay of Biscay (hereafter SE Bay of Biscay), a HF radar provides, as part of the operational oceanography system EuskOOS, near-real-time surface currents fields. The system has been already used to study surface coastal transport processes in the area in combination with multisource data (Manso-Narvarte et al., 2018, 2021; Rubio et al., 2011, 2013, 2018, 2020; Solabarrieta et al., 2014, 2015, 2016). The HF radar is also a good example of effective monitoring of surface currents with strong potential for floating marine litter management. Research conducted by Declerck et al., (2019) in the SE Bay of Biscay provided the first assessment of floating marine litter transport and distribution in the region, coupling surface currents observations from EuskOOS system, Lagrangian modelling and riverine inputs. Nowadays, these observations are used by local authorities both in real time and in hindcast in the framework of the operational service FML-TRACK to collect floating marine litter in the area. However, the accurate modelling of transport and fate of floating marine litter need to consider the variety of floating objects and sources and additional physical parametrization as windage.

This paper aims at estimating the seasonal behaviour of the floating marine litter fraction released by rivers within the SE Bay of Biscay reaching open waters.To do so, a Lagrangian model was forced by real observations from the EuskOOS HF radar and particles were parameterized to represent floating marine litter trajectories of two groups of items according to their buoyancy. Riverine litter collected from a local barrier was characterized at the laboratory to explore the fraction of highly and low buoyant items. Since most of the items were low buoyant, simulations considering only surface currents were performed as the reference. Complementary Lagrangian simulations for highly buoyant items (and less abundant in the area) were also performed. In this case, 4 low-cost buoys with similar buoyancy of certain highly buoyant items were built and released at 3 different rivers. Drifter data were used to parameterize the wind effect on this type of items and consequently achieve more accurate results.

2 Study area

The study was conducted in the SE Bay of Biscay, between north-eastern Spain (Basque Country) and south-western France (Landes). The study area extends from 43.27°N to 44.58°N and from 3.18°W to 1.27°W, falling within the coverage area of the HF radar station of the operational oceanography system EuskOOS (Fig 1). The study area comprises two Basque regions - Bizkaia (Spain) and Gipuzkoa (Spain) -, two French departments - Pyrénées-Atlantiques (France) and Landes (France) -, and eight rivers - Deba (Spain), Urola (Spain), Oria (Spain), Urumea (Spain), Oiartzun (Spain), Bidasoa (Spain), Nivelle (France) and Adour (France) -. The mean annual river discharge varies widely between rivers - 3.71 m^3/s (Oiartzun) to 350 m^3/s (Adour) (Sheppard, 2018) and the population density differs between the Spanish and French border – 44.8 inhabitants/km^2 (Landes) to 303.7 inhabitants/km^2 (Basque Country) -(Eurostat, 2019). The bathymetry in the SE Bay of Biscay is characterized by the presence of a narrow continental shelf ranging between 7 and 24 km wide in the Basque area, gradually increasing along the French coast up to about 70 km (Bourillet et al., 2006; Rodríguez et al., 2021). The continental shelf in the SE Bay of Biscay comprises two mainly areas, the Aquitaine shelf with a N-S orientation and Cantabrian shelf with an E-W orientation. The continental slope is very pronounced, with a slope of the order up to 10%-12% (Sheppard, 2018). Over the continental shelf, the ocean circulation is marked by a seasonal variability. At shorter temporal scales, circulation in the study area is mostly modulated by the bathymetry and the coastal orientation, the density-driven currents, and winds (Le Boyer et al., 2013; Solabarrieta et al., 2014). Tidal currents are quite weak constrained by the topography and the width of the continental shelf (Lavin et al., 2006; González et al., 2007; Karagiorgos et al., 2020). Along-shelf currents are more intense and persistent during winter and autumn (about 10–15 cm s^{-1}), contrary to the other seasons, especially in summer (about 2.5 cm s^{-1}) (Charria et al., 2013). In winter, the prevailing SW winds causes an E to N flow from the Spanish coasts towards the French coasts. The moderate to strong NW winds occurring in spring and summer induce S and SW surface currents circulation accompanied by a greater variability (Solabarrieta et al., 2015). In winter, westerly winds in the Basque coast reinforce the slope current (named "*Iberian Poleward Current*" (IPC)), a warm and saline intrusion trapped within the 50 km of the shelf edge, reaching its greatest velocities (up to 70 cm s-1) during this season. The IPC favours the along slope transport of water masses (Solabarrieta et al., 2014; Porter et al., 2016). The exchange between shelf and deep sea waters in winter is associated to the generation of eddies, from the interaction of currents with the topography (Lavin et al., 2006; Rubio et al., 2018; Teles-Machado et al., 2016). Maximum run-offs combined with SW winds also allow river plumes spread northwards and along the French shore during winter. However, this path changes in spring, when river discharges are reduced and winds blow from NW (Lavin et al., 2006; Puillat et al., 2006).

First global modelling studies coupling ocean circulation and Lagrangian particle tracking models reported that the SE Bay of Biscay is a hotspot for floating marine litter (Lebreton et al., 2012; van Sebille et al., 2012). Recent Lagrangian modelling studies combining measured and predicted surface currents by the HF radar and the IBI Copernicus model revealed that floating marine litter circulation in the SE Bay of Biscay is marked by a high seasonal variability. Results showed a higher retention during spring and summer and a northward dispersion along the French coast during autumn and winter (Declerck et al., 2019; Rubio et al., 2020). Surface currents derived from Regional Ocean Modelling System (ROMS) and a particle-tracking model were combined by Pereiro et al., 2019 to track the numerical drifters representing floating marine litter in the Bay of Biscay. In this study, longer residence times and higher concentrations were observed in the SE Bay of Biscay when compared north-western Iberian coastal waters, particularly in winter. Rodríguez-Díaz et al., 2020 showed from numerical simulations run using HYCOM model that floating marine litter items with high windage (Cd=3%-5%) tend to accumulate in nearshore areas of the Bay of Biscay or end up beached. These trend is consistent with recent numerical simulations combining surface currents from the operational Iberian Biscay Irish System (IBI) and the numerical model TESEO that also revealed the highly buoyant items (Cd=4%) rapidly beach in the SE Bay of Biscay, mainly in spring and summer (Ruiz et al., 2022a). Since June 2020, innovative detection and tracking solutions combining ocean modelling and remote observation systems are operating in the SE Bay of Biscay for supporting floating marine litter reduction strategies both downstream (interception at sea with collect vessels and on beaches with cleaning facilities) and upstream (source identification and reduction) (Delpey et al., 2021).

However, research on floating marine litter behaviour in the SE Bay of Biscay is still in its early stage. Further experiments are needed to fully understand the role of windage, waves and tides in the complex 3D circulation patterns governing coastal accumulation

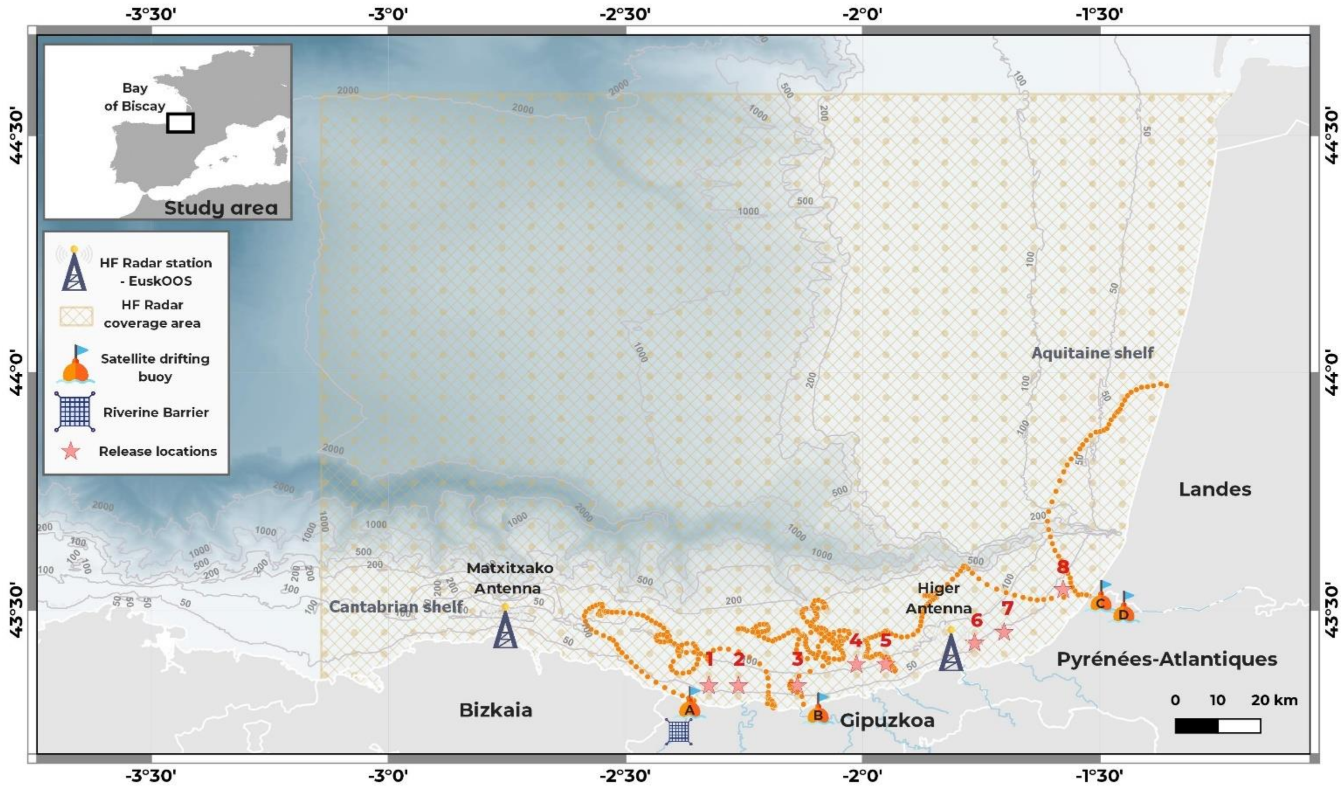


Fig 1. Study area with the release locations of the satellite drifting buoys and the riverine barrier. Dots in light yellow represent the nodes of the HF radar grid. Dots in orange represent the trajectories of the buoys. Numbers with stars in pink correspond to the particle releasing location for floating marine litter simulations: (1) Deba; (2) Urola; (3) Oria; (4) Urumea; (5) Oiartzun; (6) Bidasoa; (7) Nivelle; and (8) Adour River.

3 Methods and data

3.1 Riverine litter sampling

In Spring 2018, a riverine barrier was placed in Deba river (Gipuzkoa) to retain and collect floating riverine litter during low to moderate flows. This barrier enabled a passive sampling for characterize litter items at lab. The barrier, which consisted of a nylon artisanal net supported by hard floats (buoys), was 40 m long and 0.6 m high with a 60 mm mesh size (see photos in Appendix A). The sampling was conducted weekly from April 2018 to June 2018. In total eight riverine litter samples were collected. Litter items were quantified, weighted, and categorized at lab according to the Master list included in the "Guidance on Monitoring of Marine Litter in European Seas" (Galgani et al., 2013). Items were grouped into 7 types of material (artificial polymer materials, rubber, cloth/textile, processed/worked wood, paper/cardboard, metal, and glass/ceramics) and further classified into 44 categories (see the classification in Appendix B). Riverine litter items were also categorized into two groups (low and highly buoyant items) considering their exposure to wind based on (Ruiz et al., 2022a).

3.2 Drifters observations

Four satellite drifting buoys (herein after ‘low-cost buoys’) were built by the authors and deployed one-by-one in the river mouths of Deba (Buoy A), Oria (Buoy B), and Adour (Buoy C and D) between April 2018 and November 2018 (Fig 1, Table 1). The ‘low-cost buoys’ provided positioning every 5 minutes using satellite technology. ‘Low-cost buoys’ were 9 cm in height, 9.5 cm in float diameter and weighed approximately 200 g (Fig 2). A GPS (SPOT Trace device) powered by 4 AAA cells was placed in the bottom of a high-density polyethylene (HDPE) plastic container sealed to guarantee water tightness. They were chosen because of their capability to ensure a reasonable balance between an accurate signal emission and their purchase and communication fees. SPOT Trace devices have been used over the past few years in coastal and open ocean applications in a wide range of studies. Studies range for calibrating HF Radars (Martínez Fernández et al., 2021), tracking drifting objects as icebergs (Carlson et al., 2020), pelagic *Sargassum* (Putman et al., 2020; van Sebille et al., 2021) or fishing vessels (Widyatmoko et al., 2021; Hoenner et al., 2022) to search and rescue training (Russell, 2017) and oil spill and litter monitoring (Novelli et al., 2018; Meyerjürgens et al., 2019). Almost 2/3 of the buoy floated above the water surface thus preventing any satellite signal losses. Buoys A and D and transmitted their positions on an ongoing basis until their landing. Buoys B and C stopped emitting while they were drifting. In all cases, battery lifetime was enough for an adequate performance of the buoys. Once on land, citizens collected the buoys and reported their corresponding location.

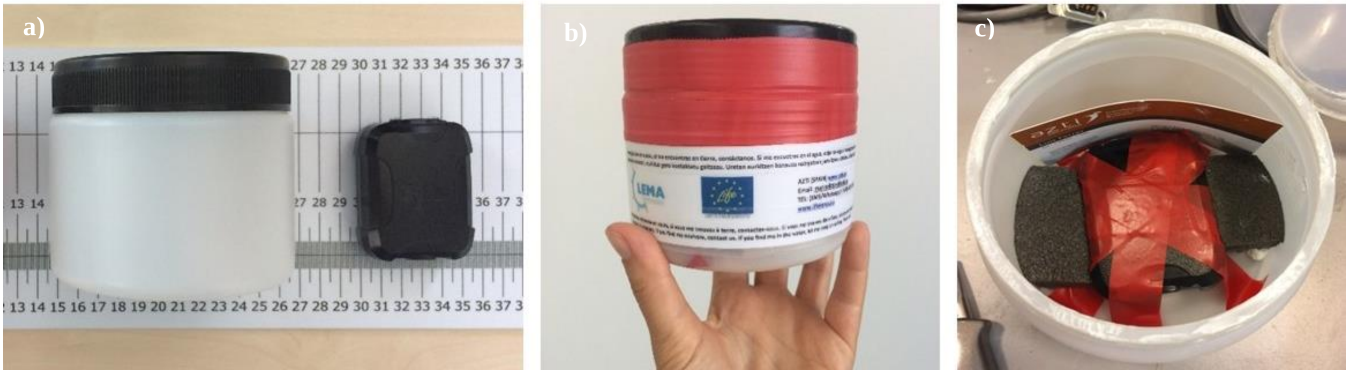


Fig 2. Main components of the “Low-cost buoy”. The structure: (a) HDPE container and SPOT Trace device powered by 4 AAA cells. Assembly process: (b) final appearance once the buoy is sealed. The buoy is labelled with contact information both within and outside; (c) the SPOT Trace was fixed at the base of the container with adhesive tape to avoid twists and turns of the buoy.

Table 1. Locations, periods, and distances covered by the drifting buoys

Buoy ID	River	Initial date	Final date	Distance covered (km)
A	Deba	16-Sept-2018 8:00	4-Oct-018 7:00	116.1
B	Oria	12- Apr-2018 16:00	18-Apr-2018 12:00	118.72
C	Adour	29-Jul-2018 20:00	2-Aug-2018 20:00	71.21
D	Adour	28-Nov-2018 9:00	30-Nov-2018 11:00	64.41

3.3 HF radar current observations and wind data

Surface velocity current fields were obtained from the EuskOOS HF radar station composed by two antennas located at Matxitxako and Higer Capes and covering the SE Bay of Biscay since 2009 a range up to 150 km from the coast. The EuskOOS HF radar is part of JERICO-RI and it is operated following JERICO-S3 project best practices, standards, and recommendations (see (Solabarrieta et al., 2016; Rubio et al., 2018) for details). Data consist of hourly current fields with a 5 km spatial resolution obtained from using the gap-filling OMA methodology (Kaplan and Lekien, 2007; Solabarrieta et al., 2021). 85 OMA modes, built setting a minimum spatial scale of 20 km and applied to periods with data from the two antennas, were used to provide the maximum spatiotemporal continuity in the HFR current fields, which is a prerequisite to performing accurate Lagrangian simulations. The application of OMA methodology has been validated for the Lagrangian assessment of coastal ocean dynamics in the study area by Hernández-Carrasco et al., 2018. HF radar velocities were quality controlled using procedures based on velocity and variance thresholds, signal-to-noise ratios, and radial and total coverage, following standard recommendations (Mantovani et al., 2020). Data subsets were built for the Lagrangian simulations avoiding periods with temporal gaps (still present in case of failure of one or the two antennas) of more than a few hours. Hourly ERA5-U10-wind fields were obtained from the atmospheric reanalysis computed using the IFS model of the European Center for Medium-Range Weather Forecast (ECMWF) (see (C3S, 2019) for details). ERA5 atmospheric database covers the Earth on a 30 km horizontal grid using 137 vertical levels from the surface up to a height of 80 km and provides estimates of a large number of atmospheric, land and oceanic climate variables, currently from 1979 to within 3 months of real time. Both HF radar current observations and wind data cover the drifter's emission periods and the selected week-long periods between 2009 and 2021 for riverine litter simulations (see Appendix C for the selected periods).

3.5 Particle transport model

The application of the transport module of the TESEO particle-tracking model (Abascal et al., 2007, 2017a, b; Chiri et al., 2020) was twofold: (1) simulate the transport and fate of floating marine litter entering from rivers and reaching the open waters of the SE Bay of Biscay and (2) estimate a windage coefficient by calibrating the model according to the 'low-cost buoys' trajectories. This module allows for simulating passive particles driven by surface currents, wind and turbulent diffusion. Particle trajectories were calculated using the following equation:

$$\frac{d\vec{x}i}{dt} = \overrightarrow{u_a}(\overrightarrow{x_i},t) + \overrightarrow{u_d}(\overrightarrow{x_i},t) \qquad (1)$$

where $\overrightarrow{u_a}$ and $\overrightarrow{u_d}$ are the advective velocity and diffusive velocity, respectively, for the $\overrightarrow{x_i}$ point and t time. The advective velocity is calculated as the lineal combination of the wind and currents according to:

$$\overrightarrow{u_a} = \overrightarrow{u_c} + C_d\overrightarrow{u_w} \qquad (2)$$

where $\overrightarrow{u_c}$ is the surface current velocity, $\overrightarrow{u_w}$ is the wind velocity at 10m over the sea surface and Cd is the wind drag coefficient. The turbulent diffusive velocity is obtained using Monte Carlo sampling in the range of velocities $[-\overrightarrow{u_{d,}}\ \overrightarrow{u_d}\ ]$ which are assumed to be proportional to the diffusion coefficients (Hunter et al., 1993; Maier-Reimer and Sündermann, 1982). For each timestep Δt, the velocity fluctuation is defined as:

$$|\overrightarrow{u_d}| = \sqrt{\frac{6D}{\Delta t}} \qquad (3)$$

where D is the diffusion coefficient, whose value is 1 m^2/s in accordance to previously modelling work for floating marine litter (Pereiro et al., 2019; Ruiz et al., 2022). Simulations were forced by HF radar surface current velocity and wind data and interpolated at the particle's position for integrating the trajectories. Beaching along the coast was implemented by a simple approach: if the particle reaches the shoreline, it is identified as beached, and it is removed from the computational process. TESEO has been calibrated and validated by comparing virtual particle trajectories to observed surface drifter trajectories at regional and local scale (Abascal et al., 2009, 2017a, b; Chiri et al., 2019). TESEO is a 3D numerical model conceived to simulate the transport and degradation of hydrocarbons but it has also been successfully applied to study of transport and accumulation of marine litter in estuaries (Mazarrasa et al., 2019; Núñez et al., 2019) and in open waters (Ruiz et al., 2022a).

3.5.1 Wind drag estimation

Two simulation strategies were combined for (1) estimating the wind drag coefficient and (2) study the seasonal behaviour of floating items in the area (section 3.5.2) The wind drag coefficient (Cd) was determined by comparing the observed trajectories provided by the 'low-cost buoys' and the modelled trajectories performed with TESEO. The test was done through different parametrizations of the wind drag coefficient ranging from 0% to 7% (Table 2). This range was chosen based on previously floating marine litter studies coupling Lagrangian modelling and observations from satellite drifting buoys (Carson et al., 2013; Stanev et al., 2019; Van Der Mheen et al., 2019). The coefficient providing the lowest error was considered the best coefficient to simulate highly buoyant litter. Due to the grid limitations of the surface currents and wind data in the coastal area, the comparison was not initialised at the launching position of the 'low-cost buoys' (river mouths) but instead it was initialised at the closest grid element that contained valid currents and wind data (Table 1). Observed positions were interpolated into a uniform one-hour time, fitting the met-ocean temporal resolution. A release of 1,000 virtual particles was performed every 4 hours at the corresponding observed position (Table 2). Particles were tracked over a 24-hour period and the trajectory of the center of mass of all the particles was computed at every time step to represent the track of the particle cloud. Observations were compared to modeled trajectories using the simple separation distance, which is the difference between the observed and the computed position of the center of mass at a time step t. Mean separation distance $\overline{\mathrm{D}(t^{mod})}$ was calculated for every modelled position based on the simple separation distance following Eq. (4):

$$\overline{\mathrm{D}(t^{mod})} = \frac{1}{N}\sum_{i=1}^{N} \left|\vec{X}^{mod}\,(t^{mod}) - \vec{X}^{obs}(t^{obs})\right| \qquad (4)$$

where $e\ \vec{X}^{mod}\ (t^{mod})$e and $\vec{X}^{obs}(t^{obs})$ are the modeled and observed trajectories for the simulation period i of a total of N periods. A mean separation distance curve was computed for every wind drag coefficient derived from the mean separation distance curves of the four buoys. The area beneath the mean separation distance curve was calculated to select the more suitable wind drag coefficient. The area $\widetilde{D}$ was calculated as a numerical integration over the forecast period via the trapezoidal method following Eq. (5). This method approximates the integration over an interval by breaking the area down into trapezoids with more easily computable areas:

$$\widetilde{D} \approx \int_{t^{mod}=1}^{t^{mod=24}} \overline{\mathrm{D}(t^{mod})}dt \quad (5)$$

3.5.2 Lagrangian seasonal simulation of riverine litter items

Seasonal simulations were run for low and highly buoyant items to assess the seasonal differences on the transport and fate of floating riverine litter once it has reached the open waters of the SE Bay of Biscay. Particles were released around 2.5 nautical miles off the shoreline due to the complexity in resolving small-scale processes of floating riverine and marine litter behaviour in and close to the river mouths. As parametrizations concerning wind effect linked to the object characteristics are scarce, the optimal wind drag coefficient estimated for the buoys (see section 3.5.1) was accounted for simulated the behaviour of the objects highly exposed to wind. No wind drag parametrization (Cd=0%) was applied for low buoyant objects not subjected to wind effect. A total of ten periods per season uniformly distributed within the study period (2009-2021) were considered for running the simulations based on the availability of HF radar surface current datasets (Appendix C). In total, 80 simulations (40 for Cd=0% and 40 for Cd=4%) were run for 7 days. For each simulation, 4,000 particles were released in 8 rivers (500 per river) assuming that river discharges are equal despite the seasonal variations and the morphological differences between rivers (Table 2). The total number of particles modeled for Cd=0% was the same as Cd=4%. A post-processing was carried out to compute by river: (1) the particles' evolution over the time from their release until their arrival to the shoreline; and (2) the particles' distribution on the shoreline, counting the number of beached particles per km of shoreline and indicating the spatial concentration per region.

Table 2. Simulation, release, and physical parameter values for wind drag estimation and floating riverine litter simulations.

	Simulation parameters			**Release parameters**		**Physical parameters**	
	Number of particles	Integration time	Time step	Release locations	Release time	Turbulent diffusion coefficient	Wind drag coefficient (Cd)
Simulations for wind drag estimation	1,000 per location	24 h	60 s	At the observed locations of the buoy	Over the emitting period of the buoy at spaced intervals of 4 hours	1 m^2/s	0 %, 2%, 3%, 4%, 5%, 6% , 7%
Seasonal riverine litter simulations	500 per river	1 week	60 s	At a distance of 2.5 nautical miles from the river mouth	At the beginning of the selected time period (10 periods per season)	1 m^2/s	0 %, 4%

4 Results

4.1 Riverine litter characterization

In total 1,576 items and 11.597 kg of floating riverine litter were sampled and characterised (Fig 3). *Plastic* was the most common type of riverine litter in terms of number of items (95.1%) and in weight (67.9%); they were also frequent *Glass/ceramics* (16.1%) and *Cloth/textile* items (6.9%) when counted by weight. The top ten litter items accounted for 93.3% by number and 72.6% by weight of the total riverine litter (Table 3). *Plastic/polystyrene pieces between 2.5 cm and 50 cm* and *Other Plastic/polystyrene identifiable items* (e.g., food labelling) were the most abundant in terms of number (71.2%) and weight (16.9%). *Low buoyant items* encompassed almost 91% by number and 68% by weight of litter items (Fig 4).

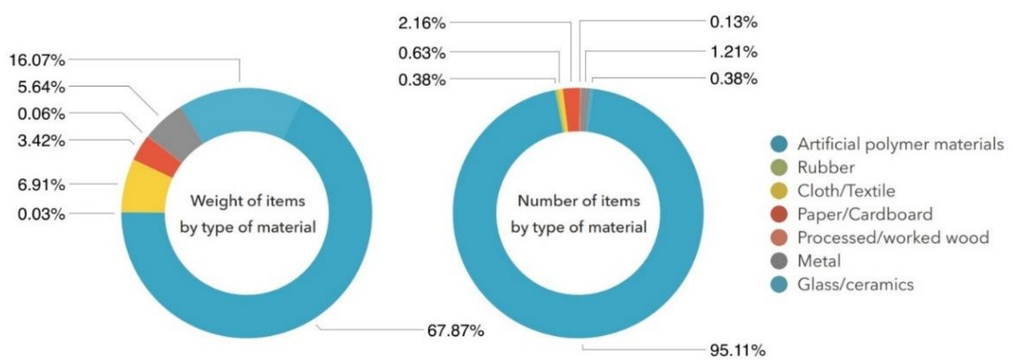


Fig 3. Composition of riverine litter by type of material in terms of number of items and weight. Items were collected by the barrier placed in Deba river (Gipuzkoa) between April and June 2018.

Table 3. Top ten (X) riverine litter items collected from the barrier located in Deba river (Gipuzkoa) between April and June 2018. Items have been ranked by abundance (left) and weight (right) according to the MSFD Master List Categories of Beach Litter Item and classified based on their exposure to wind effect.

Top X by number of items

Ranking	TSG_ML General code	General name	Number of items (%)	Type of item
1	G76	Plastic/polystyrene pieces 2.5 cm >< 50 cm	71.19%	Low buoyant
2	G10	Food containers incl. Fast food containers	6.21%	Highly buoyant
3	G124	Other plastic/polystyrene items (identifiables)	3.68%	Low buoyant
4	G30	Crips packets/sweet wrappers	3.55%	Low buoyant
5	G20-G24	Plastic caps and lids/Plastic rings	2.41%	Low buoyant
6	G96	Sanitary towels/panty liners/ backing strips	2.22%	Low buoyant
7	G158	Other paper items	1.33%	Low buoyant
8	G5	What remains of rip-off plastic bags	1.33%	Low buoyant
9	G77	Plastic/polystyrene pieces >50 cm	0.82%	Low buoyant
10	G3	Shopping bags incl.pieces	0.51%	Low buoyant
		TOTAL	93.25%	

Top X by weight of items

Ranking	TSG_ML General code	General name	Weight (%)	Type of item
1	G124	Other plastic/polystyrene items (identifiables)	16.88%	Low buoyant
2	G200	Bottles incl. Pieces	15.80%	Highly buoyant
3	G76	Plastic/polystyrene pieces 2.5 cm >< 50 cm	9.48%	Low buoyant
4	G96	Sanitary towels/panty liners/backing strips	9.48%	Low buoyant
5	G10	Food containers incl. Fast food containers	6.04%	Highly buoyant
6	G135	Clothing (clothes, shoes)	4.16%	Low buoyant
7	G77	Plastic/polystyrene pieces > 50 cm	2.91%	Low buoyant
8	G145	Other textiles (incl.rags)	2.77%	Low buoyant
9	G175-G176	Cans (beverage/food)	2.60%	Highly buoyant
10	G3	Shopping bags incl.pieces	2.52%	Low buoyant
		TOTAL	72.64%	

FLOATING RIVERINE LITTER CLASSIFICATION BY WIND EXPOSURE

	Highly buoyant items	Low buoyant items
Number of items	1,436	140
Weight of items (kg)	7.880	3.717

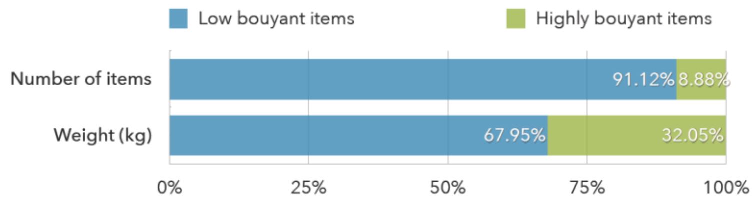


Fig 4. Riverine litter classification based on the exposure to wind effect. Items were collected from the barrier located in Deba river (Gipuzkoa) between April and June 2018.

4.2 Wind drag coefficient for drifting buoys

Total distances covered by drifting buoys ranged from 62 km to 118 km (Table 1) and they all scattered over the HF radar coverage area. Buoys provided their position data over 385 h before beached on Landes and Gipuzkoa shorelines. When compared with numerical trajectories obtained using different Cd parameterizations, the mean separation distance ($\overline{\mathrm{D}(t^{mod}}$)increased nearly linearly with time for all the parametrizations, achieving a maximum separation of almost 14 km at 24 hours for Cd=0% (Fig 5). Overall, using no windage parametrization provided the largest $\bar{\bar{D}}$. Simulations parametrized with Cd=4% provided the best results with an average ± standard deviation (SD) of 3.2 ± 1.25 km and a maximum value of 4.85 km at 24 h. When assessing the mean separation distance for all the modeled positions at every observed position of the buoys, the most common range separation distance for Cd=4% was 2- 4 km (Fig 6). Hence, a wind drag coefficient of 4% was applied in the remaining analysis to estimate the behaviour of highly buoyant items.

4.3 Seasonal trends on floating riverine litter transport and fate

Particle concentration in the shoreline varied between 0 and 258.46 particles/km (Fig 7). Particles parametrized with Cd=4% drifted faster towards the coast, notably during the first 24 hours. The highest concentrations (>200 particles/km) were recorded during summer in Pyrénées-Atlantiques for Cd=4%, probably due to the seasonal retention patterns within the study area

(Appendix D). Although less intensely, Cd=4% also lead to a high particle concentration in Pyrénées-Atlantiques (106.86 particles/km) and Gipuzkoa (166.1 particles/km) during winter. The lowest concentrations (0-20 particles/km) were recorded for Cd=0% after the first 24 hours of simulation, particularly during autumn. Overall, Bizkaia was the less impacted region for both windage coefficients (<40 particles/km). During summer, over the 97% of particles parametrized with Cd=4% beached after one week of simulation (Fig 8). In autumn this value fell to 54%. In contrast, beached particles parametrized with Cd=0% were less abundant by the end of the simulations, particularly during spring with less than 25% of particles trapped in the shoreline.

Overall, the average of particles parametrized with Cd=0% was higher when comparing to Cd=4% (Fig 9). Particles released in French rivers and parametrized with Cd=0% were less abundant during summer, though this trend was reversed in autumn. For Cd=0%, the number of particles released in Bidasoa river during summer were the least abundant after one week of simulation (<200 particles on average). The vast majority of particles released in Urumea river during winter were floating in the study area by the end of the simulations (479 particles on average). Particles parametrized with Cd=4% beached faster during the first 48 hours, mainly in summer and for those particles released in the French rivers. During this season, the average number of particles floating in the study area by the end of the simulation ranged between 0 and 250. Similar trends were observed within the same season between rivers, probably influenced by the vicinity of rivers and the spatiotemporal resolution of forcings. Over 40% of the total particles parametrized with Cd=4% and almost 12% of parametrized with Cd=0% beached in Gipuzkoa (Fig 10). During spring, almost 60% of beached particles parametrized with Cd=0% were located Bizkaia. For Cd=0%, particles released during summer in the rivers located in the western area of Gipuzkoa drifted longer distances and reached Landes shoreline. This trend changed during winter, when the vast majority of particles released in Gipuzkoa rivers beached mainly in Gipuzkoa and Bizkaia. Beached particles parametrized with Cd=0% experienced more seasonal variations derived from the surface current circulation patterns within the SE Bay of Biscay. For Cd=4%, particles beached in Gipuzkoa ranged between 51% in spring and 38% in winter and Bizkaia was the less affected region despite the season. Overall, all regions were highly affected by rivers within or nearby the region itself .

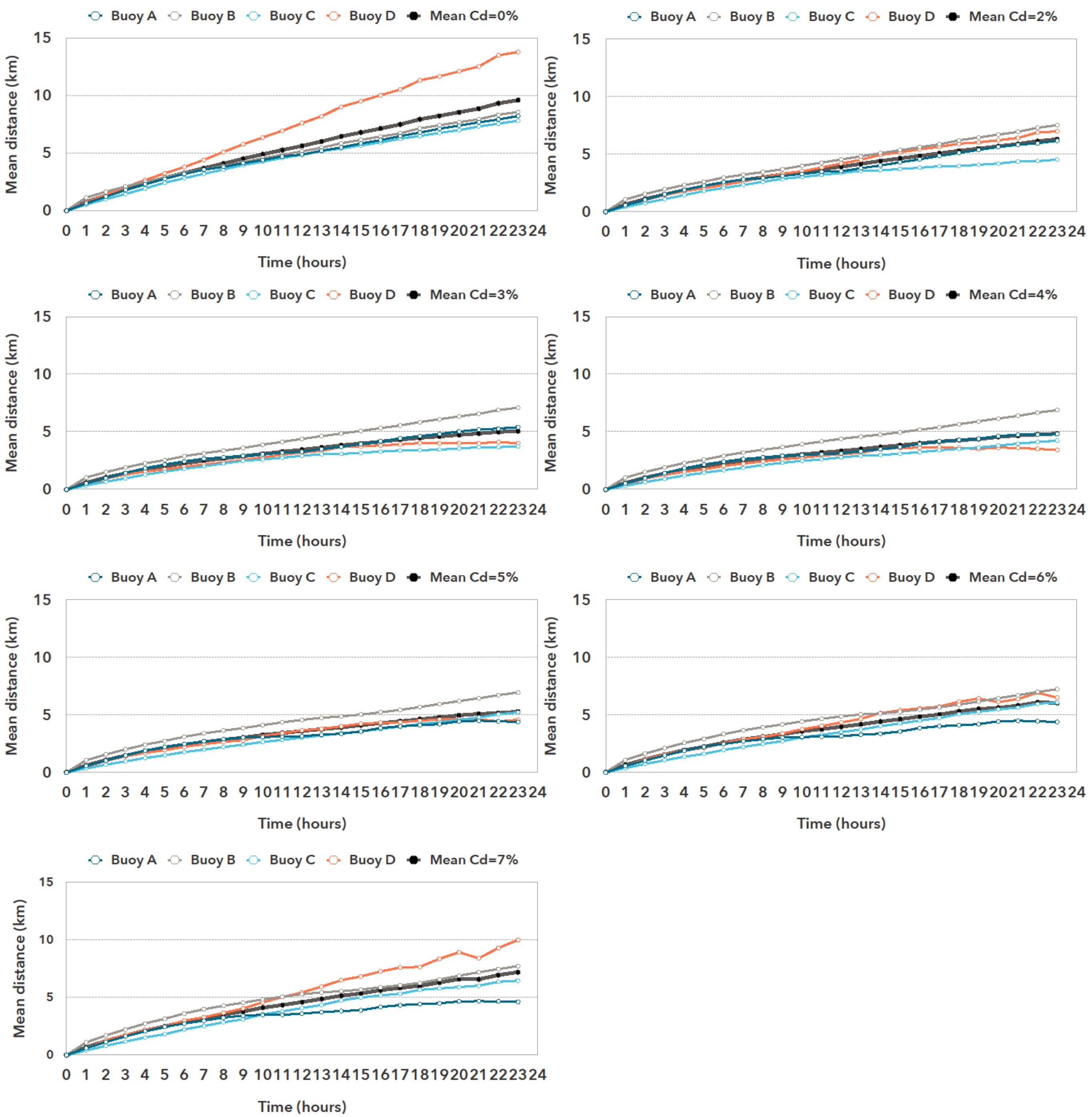


Figure 5. Mean separation distance between modelled and observed trajectories for each wind drag coefficient. The dark line is the mean curve used for the trapezoidal integration.

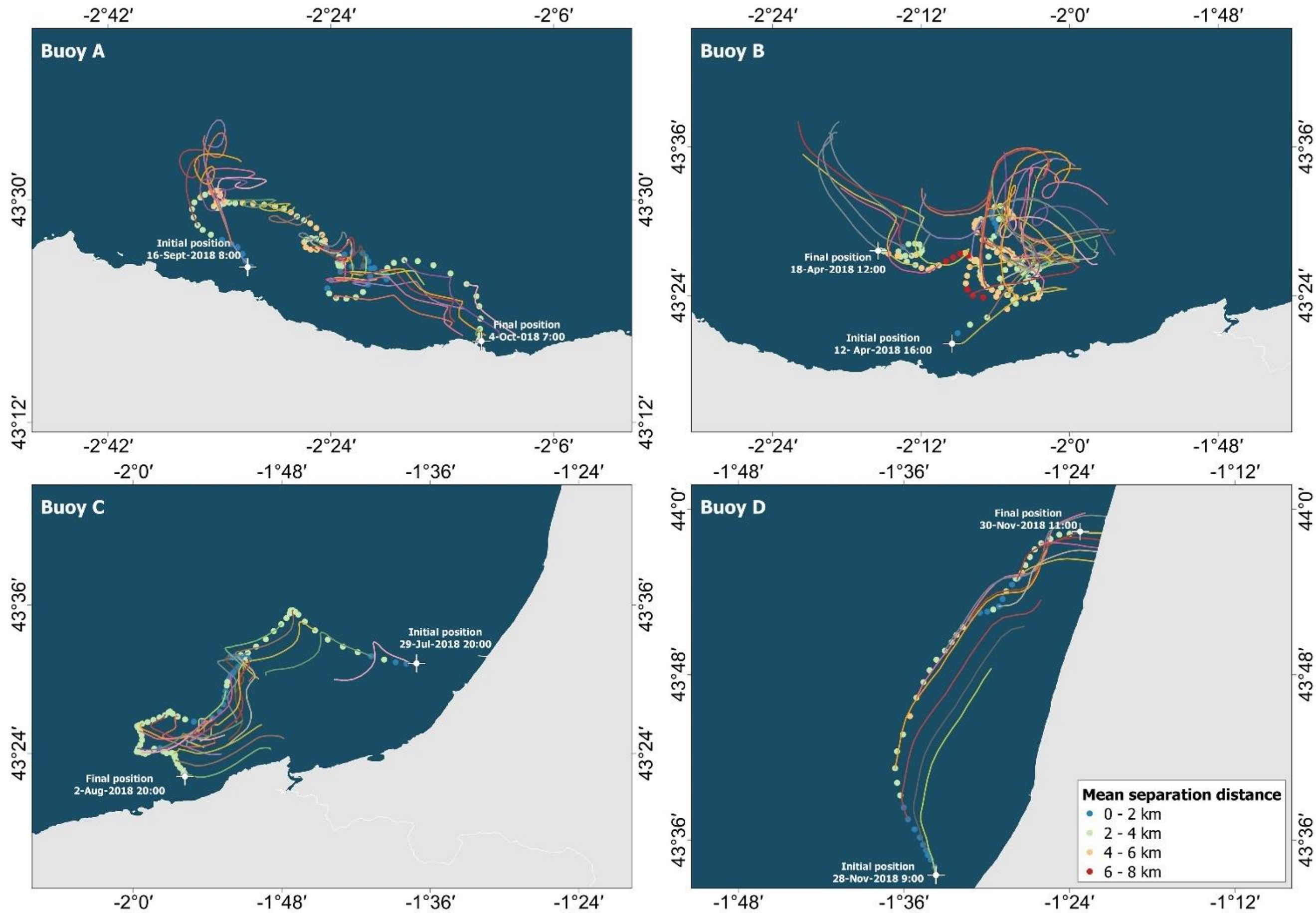


Figure 6. Spatial mean distance between modeled and observed trajectories of buoy A, B, C and D with a drag coefficient Cd=4%. Particle trajectories were simulated during 24 h, with a re-initialization period every 4 hours. The modeled trajectories are shown in solid lines. Circles represents at the observed position the mean separation distance for all the modeled position

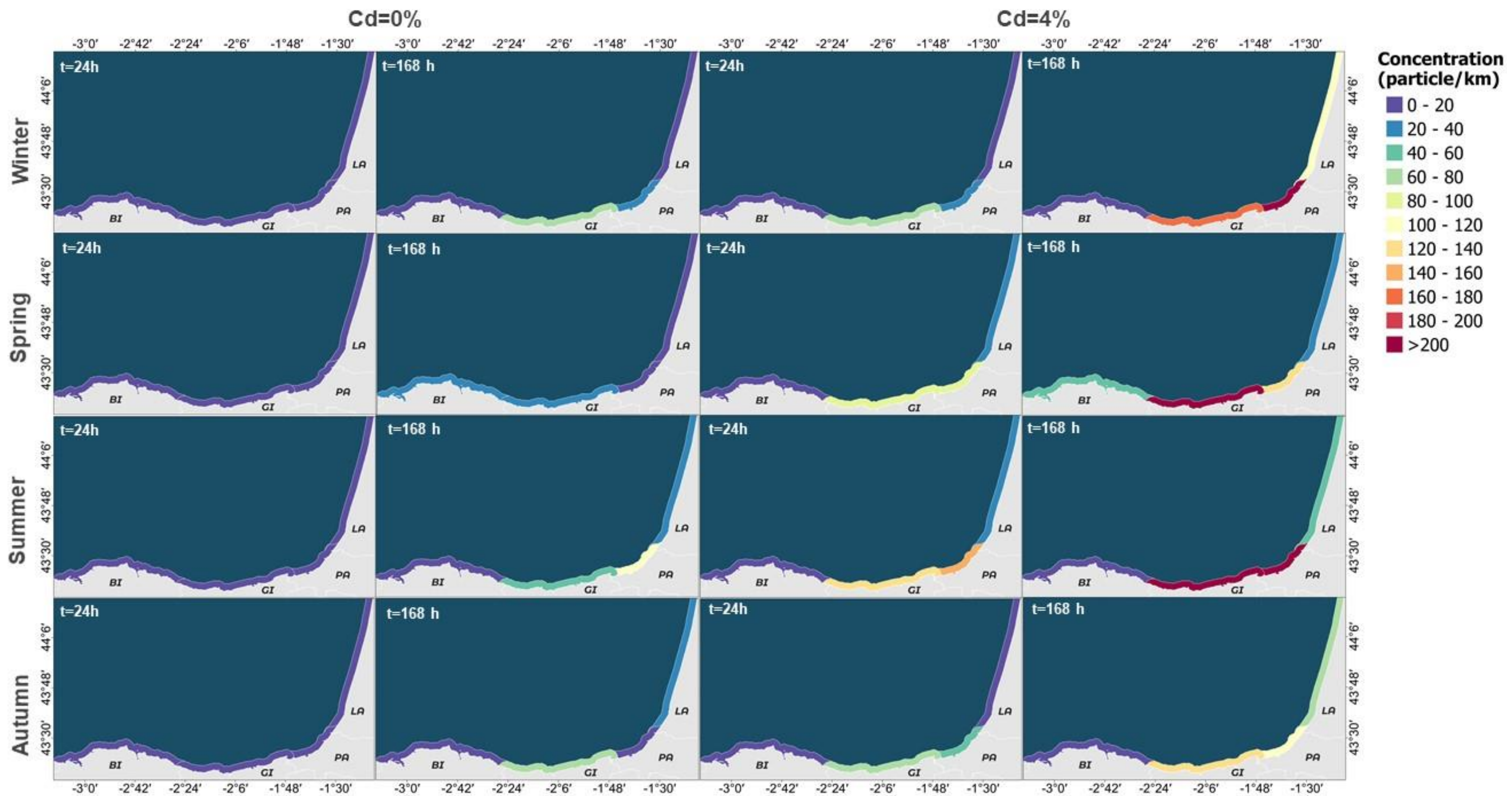


Figure 7. Particle concentration in Bizkaia, Gipuzkoa, Pyrénées-Atlantiques and Landes shoreline. The seasonal distribution is shown for Cd=0% and Cd=4% after 24 hours and 168 hours of simulation.

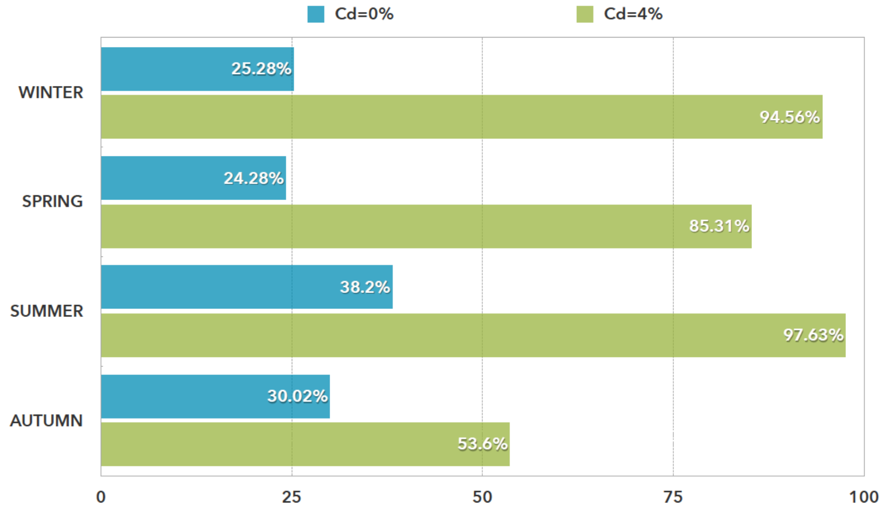


Figure 8. Seasonal amounts of beached particles parametrized with Cd=0% and Cd=4% after 168 hours of simulation.

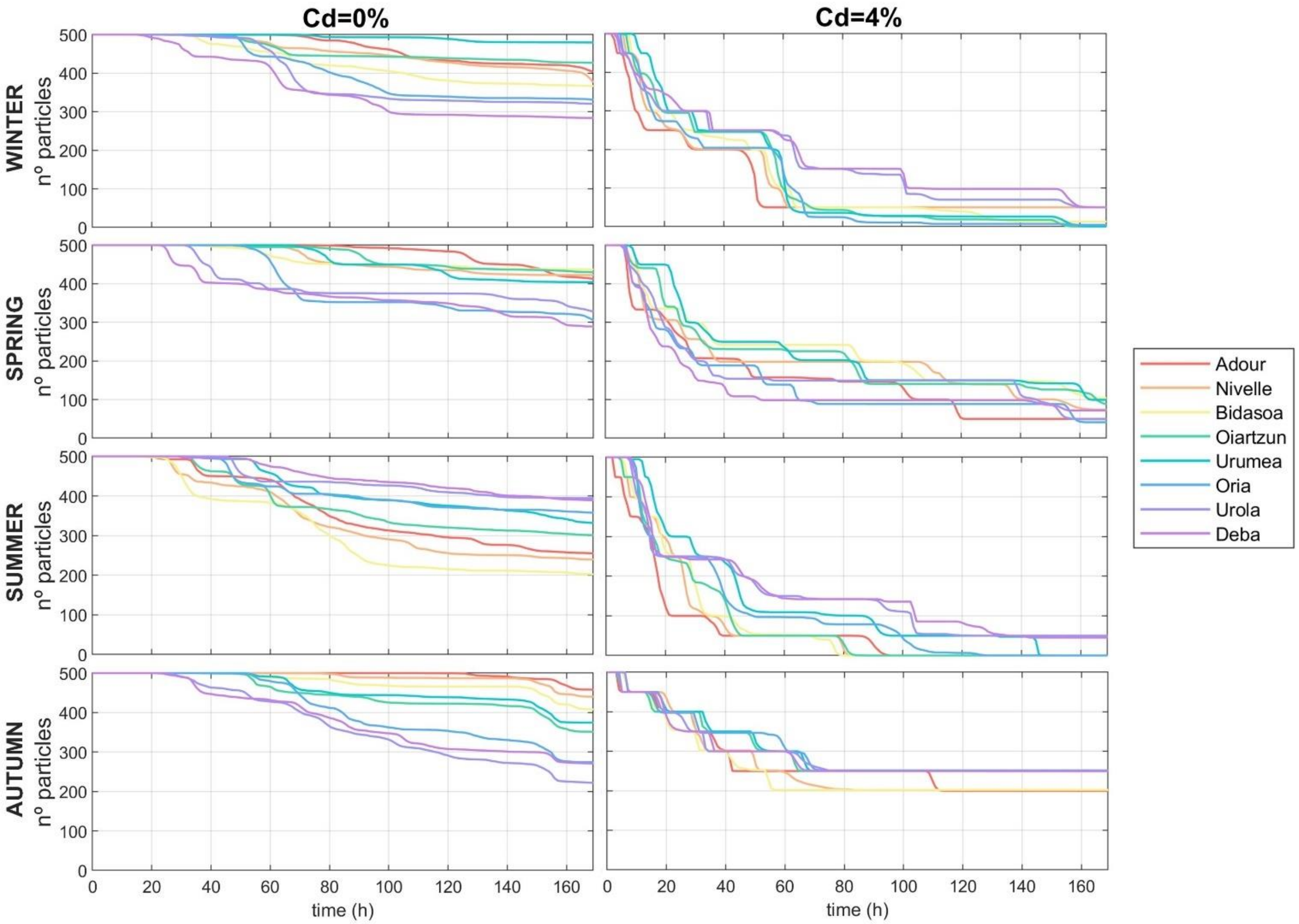


Figure 9. Temporal evolution of the particles parametrized with Cd=0% and Cd=4% throughout the different seasons. The curves represent the average number of particles floating in the water surface by river and for every time step.

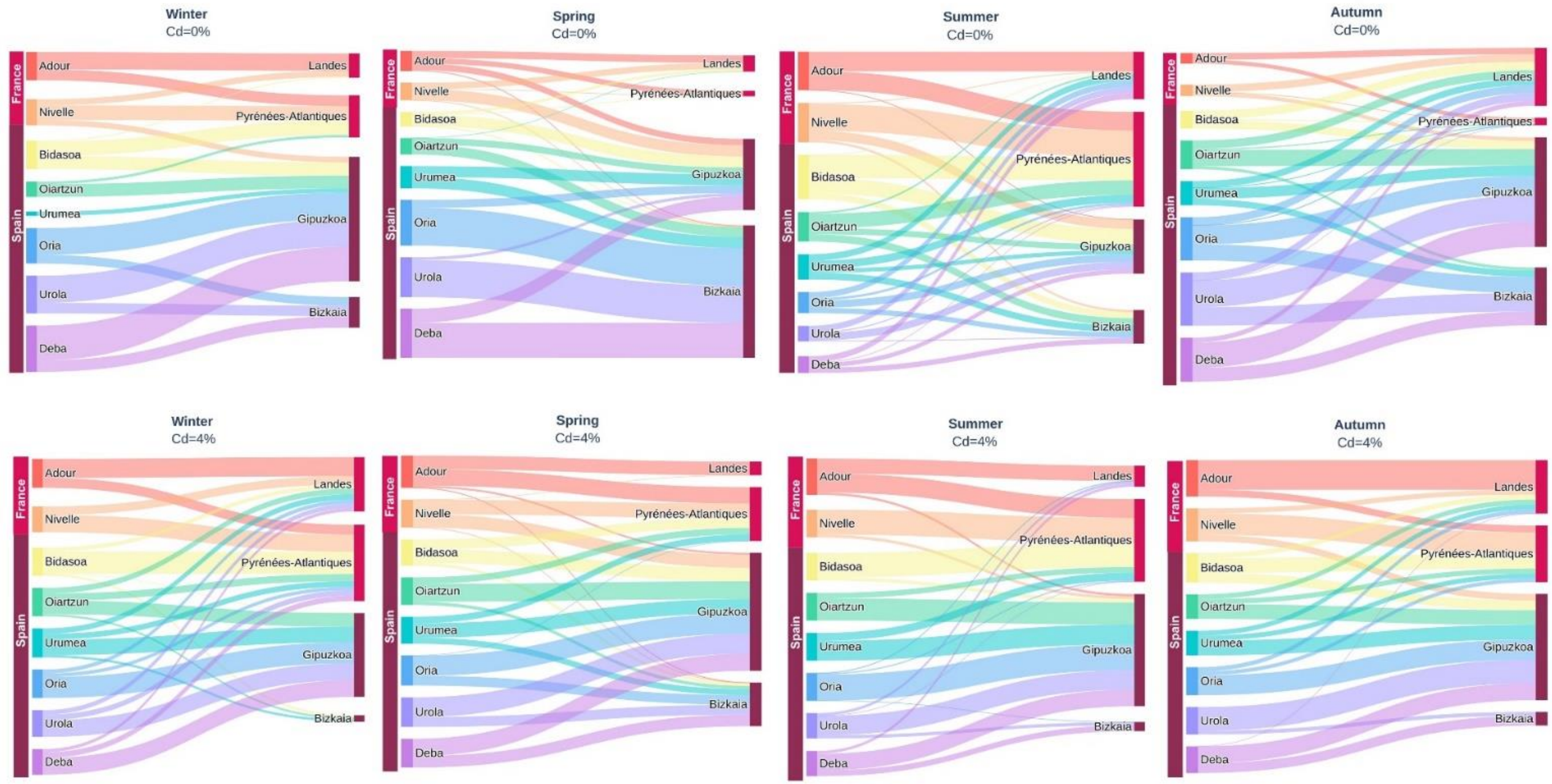


Figure 10. Seasonal analysis of the beached particles parametrized with Cd=0% and Cd=4% per region and river by the end of the simulation period. The nodes of the region correspond to the number of beached particles. The country to which each river belongs – France (Pyrénées-Atlantiques) and Spain (Gipuzkoa) – is shown on the left side of each figure. The width of the node depicts the sum of the beached particles, and the links represent the number of particles beached per river.

5 Discussion

5.1 Riverine litter composition

An artisanal net placed at the mouth of Deba river enabled sampling riverine litter in the study area during Spring 2018. Short and narrow rivers prevail in the SE Bay of Biscay, affected by a strong tidal regime, and very intense, stationary and persistent storms (Ocio et al., 2015). Studies aiming at reporting the abundance and composition of floating riverine litter in European rivers date back less than 10 years and they were performed in larger and more abundant rivers than Deba river. Despite the morphology and hydrological differences, plastic was the predominant material in Deba river, as in Siene (Gasperi et al., 2014), Danube (Lechner et al., 2014) or Rhine River (van der Wal et al., 2015). Similarities were also found when comparing the Top ten list of riverine litter items to rivers located in the North-East Atlantic region. *Plastic/polystyrene pieces between 2.5 cm and 50 cm* (71.2%) top the list in terms of number of items and their abundance was slightly higher when compared to North-East Atlantic rivers (54.53%) (Bruge et al., 2018; Gonzalez-Fernandez et al., 2018). Lower abundances were observed in the Mediterranean (25.01%) and the Black Sea (13.74%). Riverine litter items trapped on vegetation or deposited on the riverbank can be degraded by weather conditions (rain, wind, etc.) favouring the fragmentation in plastic pieces before their arrival to the coastal and marine environment (Chamas et al., 2020). The fragmentation can be also influenced by the material and the shape of the litter items (Woods et al., 2021). Differences on *Plastic/polystyrene pieces between 2.5 cm and 50 cm* abundances can be attributed to a faster fragmentation due to the variations on weather conditions between river basins. However, more detailed analyses on the physical characteristics of litter items (i.e., polymer type) are necessary to fully assess their impact on the occurrence of fragmented plastic pieces. Results are also in line with the ranking list of the Top ten beach litter items across the North-East Atlantic region revealing that Single Use Plastics (i.e. food containers, bottles and other packaging) are among the most abundant riverine litter items together with plastic fragments (Addamo et al., 2017). These results differed from the analysis performed in sea small-scale convergence areas of floating marine litter ("*litter windrows*") on the coastal waters of the SE Bay of Biscay, where fishing-related items were the second most abundant sub-category in terms of number after *Plastic/polystyrene pieces between 2.5 cm and 50 cm* (Ruiz et al., 2020). Substantial differences also exist between riverine litter sampled in Deba river and floating marine litter assessed by visual observation from research vessels in open waters of the Bay of Biscay (Ruiz et al., 2022a). Differences might be related to the monitoring method and, also, to the size of the items, since small items, as plastic pieces, can be overlooked by the observer when visual counting method is applied, contrary to riverine litter samplings for later analysis at lab. Overall, riverine litter data acquisition is mainly focused on the floating fraction and the litter loads under the surface water are often ignore. Increasing the quantity of rivers sampled, the frequency and the riverine water compartments is necessary to establish the composition and trends of riverine litter in the SE Bay of Biscay.

5.2 Wind drag estimation

One of the largest uncertainties for predicting floating riverine and marine litter behaviour is the proper quantification of a wind drag coefficient. Wind drag estimations conducted so far for floating marine litter items range between 0% and 6% (Ko et al., 2020; Critchell and Lambrechts, 2016; Neumann et al., 2014) with an upper limit of 10% (Yoon et al., 2010). However, only a few of them have been validated using observational data (Maximenko et al., 2018; Callies et al., 2017). In this study, data provided by "Low-cost buoys" combined with surface current measurements by HF radar were used as a proxy for modelling the drift of floating litter objects with similar buoy characteristics (density, size, and shape). Results demonstrated that Cd=4% was the optimal wind drag coefficient for accurately represent the pathways of the "Low-cost buoys" in the study area. This value can be consistent with the estimations of the partially emerged *Physalia physalis* for the Bay of Biscay (Ferrer and Pastor, 2017) but it is almost three times higher than the maximum wind drag coefficient reported in the area by Pereiro et al., 2018 . This can be explained by the fact that buoys used in the experiment remained submerged beneath the sea surface and were less exposed to wind effect. The estimated wind drag coefficient was also greater than the Cd=3% observed for the

Prestige oil spill accident (Abascal et al., 2009; Marta-Almeida et al., 2013). Indeed, oil spill studies refer to a range of wind drag coefficient between 2.5 to 4.4% of the wind speed, with a mean value of 3 - 3.5% (e.g., ASCE, 1996; Reed et al., 1994). Object characteristics may change over the time due to the exposure to wind, waves, UV radiation, seawater and the attachment of organic material (Kooi et al., 2017; Min et al., 2020). Objects become breakable, and biofouling increases their density, overcoming the positive buoyancy and impacting on their trajectory. Investigations so far pinpointed longer time scales (weeks to months, and lager) than considered in this study (days) for a significant change on the behaviour of floating objects (Ryan, 2015; Fazey and Ryan, 2016). Consequently, physical variations on the buoy properties were not accounted for the wind drag estimation. The separation distance between observed and modeled trajectories has been commonly used to evaluate the skill of particle-tracking models (Callies et al., 2017; Haza et al., 2019; Aksamit et al., 2020; Abascal et al., 2012). In this study, the purpose was no to evaluate the model accuracy but estimated the wind drag coefficient for the “Low-cost buoys”. However, the novel approach proposed by (Révelard et al., 2021) may be of particular interest for future experiments oriented to assess the wind drag coefficient of highly buoyant items drifting during short time periods in the coastal area.

5.3 Seasonal riverine litter distribution by region

It is broadly accepted that the SE Bay of Biscay is polluted with floating marine litter discarded or lost at the marine and coastal area but also with litter originated inland and transported via rivers and runoff. However, detailed studies on riverine litter contribution are still scarce and modelling efforts combining observations and physical parametrizations of floating litter properties are non-existent. This study shows that the exposure to wind effect largely control the transport and coastal accumulation of floating marine litter in the SE Bay of Biscay, with concentrations varying between regions and over the time. Concentrations in Pyrénées-Atlantiques and Gipuzkoa differed widely from the other studied regions. Indeed, the highest concentrations occurred in both regions during summer for low (100-120 particle/km) and highly buoyant items (>200 particles/km). A higher amount of particles beached in Gipuzkoa during summer when compared to Pyrénées-Atlantiques, but concentrations were lower since the Basque shoreline is longer. The pathways and fate of low buoyant items reflect the seasonal surface water circulation patterns in the SE Bay of Biscay. Results are in line with findings provided by Declerck et al., 2019 who pinpointed a higher coastal retention in the area during spring and summer. Low buoyant objects remained floating at the coastal waters and highly buoyant objects tended to beach remarkably faster as reported in literature by Rodríguez-Díaz et al., 2020). However, long-term data collected by in-situ observations of beached litter across the different regions are necessary to validate the large seasonal variations and to assess the reliability of concentration levels for addressing riverine litter issue in priority regions with heavily polluted coastlines.

5.4 Rivers as key vectors of riverine litter

The interpretation of the spatial and temporal riverine litter distribution by river can be challenging since riverine litter fluxes in the study area are highly uncertain. In the study area, two major assumptions were made regarding the river systems: (1) same river discharge for all rivers and (2) same river discharge for all seasons. This means that same amounts of riverine litter were allocated for every river regardless the differences on the width and depth and the seasonal flow variations. Since each river basin has its own particularities, future modelling approaches should be adapted to the the morphology and hydrological conditions of the catchment area. Other drivers as the land use or population density can be a determining factor on the amount of mismanaged litter that could contribute to riverine litter fluxes (Schmidt et al., 2017; Schuyler et al., 2021). It is also necessary to further investigate if higher river flows in the area are directly related to an increased discharge of riverine litter since analysis already performed in different river basins show contradicting relations between the occurrence of riverine litter and river fluxes (van Emmerik and Schwarz, 2020). Along with the complex nature of qualifying riverine litter fluxes, litter behaviour in the coastal area of the SE Bay of Biscay is still in its early stage, and much has yet to be revealed. Particular attention should be paid to Pyrénées-Atlantiques and Gipuzkoa, as main impacted regions in the studied area. Rivers in the study area are mainly located in Gipuzkoa which favours the accumulation of floating litter in this region regardless the season. Regional coordination should be reinforced due to the transboundary movement of floating riverine litter in the study area and reasonable efforts oriented to retain or remove riverine litter as clean-up measures in the riverbanks should be investigated to avoid litter being transported to the coastal and marine environment.

5.5 Model limitations

The interaction between floating litter and the shoreline is highly complex and relies in many processes including waves and tides. Indeed, waves and tides can constrain coastal accumulation since they can resuspend and transport litter back into the ocean (Brennan et al., 2018; Compa et al., 2022). The geomorphology can also affect the retention of litter washing ashore. Sandy beaches tend to be more efficient at trapping and accumulating litter than rocky areas, which favours litter fragmentation (Robbe et al., 2021; Weideman et al., 2020). How these processes contribute to the actual beaching is unknown and they cannot be resolved yet at a suitable resolution (Melvin et al., 2021). In this study, particles were released in open waters and once they reached the shoreline, they were classified as beached. The tidal effect and the wave-induced Stokes drift were not accounted to avoid introducing more uncertainties. However, further field and laboratory experiments to better understand on how these processes influence floating litter behaviour in the coastline is recommend. It is also important to consider for future research exploring the effect of the type of shoreline on coastal accumulation. In this study, a constant diffusion coefficient of 1 m^2/s was considered as a pragmatic choice based on previously modelling work for floating marine litter. However, more field measurements are necessary to accurately assess the influence of the diffusion process on the transport of floating marine litter.

6 Conclusions

The SE Bay of Biscay has been described by global and regional models as an accumulation zone for floating marine litter. However, detailed studies on floating riverine litter behaviour once items arrive to open waters are still scarce. Based on HF radar current observations and wind dataset, this contribution tries to fill this gap by providing insights on how low and highly buoyant litter released by several rivers of the SE Bay of Biscay may affect the nearby regions seasonally in terms of concentration and beaching. Analysis of riverine litter samples collected by a barrier placed in the study area showed that low buoyant objects were predominant although highly buoyant objects were also relevant in terms of weight. Simulations for assessing the seasonal trends of floating riverine litter transport and fate were performed with the Lagrangian model TESEO. To properly integrate the differences in litter buoyancy, simulations were parametrized with a wind drag coefficient for low and highly buoyant items. The wind drag for highly buoyant item was estimated by comparing the observed and the modelled positions of four drifters. The developed “Low-cost buoys” proved to be suitable to provide real time trajectories of highly buoyant objects exposed to wind. However, drifters with different characteristics should be used in future studies for accounting the windage effect on different type of items. The transport and fate of both highly and low buoyant items released by rivers was calculated by season. Highly buoyant items rapidly beached (in less than 48 hours), particularly in summer and winter; in contrast, despite the season over two thirds of low buoyant items remained floating after one week of being released. This highlights the discrepancy between behaviour for low and highly buoyant objects and the importance of parametrizing the windage effect in order to accurately predict riverine litter accumulation in the coastal area of the SE Bay of Biscay. Beached particles were mainly found in Gipuzkoa regardless the season and the wind drag coefficient. Overall, the less affected region was Bizkaia with the exception of Spring period for low buoyant items. Despite of the season, most of the riverine litter remained in the study area and rivers polluted the regions within the river basin or surrounding. Investigating what beaches are most likely to accumulate large quantities and the contribution per river can provide relevant input to response operations after storm events in the short to medium term and can also support the identification of priority rivers for monitoring program, assisting in the future for an adapted intervention of riverine pollution regionally.

Appendix A. Floating barrier for riverine litter collection

Figure A1. Floating barrier (a) and installation in Deba river (Gipuzkoa) (b)

Appendix B. Riverine litter classification based on the exposure to wind effect

Table B1. Data were gathered from surveys carried out during Spring 2018 in Deba river (Gipuzkoa)

TSG_ML General code	General name	Number of items	Weight (kg)
Low buoyant items transported by currents			
G1	4/6-pack yokes, six-pack rings	1	3.3
G2	Bags	7	170.7
G3	Shopping bags incl. pieces	8	292.44
G4	Small plastic bags, e.g freezer bags	4	50.9
G5	What remains form rip-off plastic bags	21	186.31
G20-G24	Plastic caps and lids/Plastic rings	38	216.39
G26	Cigarrette lighters	1	9.7
G27	Cigarrette butts and filters	1	0.1
G30	Crisps packets/sweet wrappers	56	250.2
G31	Lolly sticks	1	2.4
G32	Toys and party poppers	2	97.5
G36	Fertilisers/animal feed bags	1	11.5
G48	Synthetic rope	2	6.7
G76	Plastic/polystyrene pieces 2.5 cm> < 50 cm	1122	1788.32
G77	Plastic/polystyrene > 50 cm	13	337.34
G96	Sanitary towels/panty liners/backing strips	35	1099.8
G100	Medical/Pharmaceutical containers/tubes	7	69.4
G101	Dog faeces bag	2	106

G124	Other plastic/polystyrene items (identifiable)	58	1958.5
G125	Ballons and ballon sticks	5	1.1
G134	Other rubber pieces	1	1.6
G135	Clothing (clothes, shoes)	3	481.7
G145	Other textiles (incl. rags)	7	320.5
G148	Carboard (boxes & fragments)	3	85.7
G156-157	Paper & Paper fragments	2	121.2
G158	Other paper items	4	69.1
G159	Corks	4	21.2
G173	Other (specify)	21	99.3
G177	Foil wrappers, aluminium foil	1	7
G179	Bottle caps, lids & pull tabs	1	0
	Total	**91.12%**	**67.95%**
Highly buoyant items transported by wind and currents			
G7	Drink bottles <= 0.5 l	5	142.6
G8	Drink bottles > 0.5 l	3	91.1
G9	Cleaner bottles & containers	2	105.7
G10	Food containers incl. Fast food containers	98	723.9
G11-12	Cosmetics bottles & other containers (shampoo, shower gel, deodorant)	4	100.3
G17	Injection gun containers	1	18.3
G33	Cups and cup lids	6	32.6
G150-151	Cartons/Tetrapack	2	121.2
G153	Cups, food trays, food wrappers, drink containers	4	69.1
G174	Aerosol/Spray cans industry	2	143.2
G175-176	Bottle caps, lids & pull tabs	2	5
G177	Bottles incl.Pieces	5	1832.3
G178	Light bulbs	1	31.7
	Total	**8.88%**	**32.05 %**

Appendix C. Selected seasonal week-long periods from the HF radar (2009-2021)

Table C1. Periods selected between 2009 and 2021 based on the availability surface current datasets provided by the HF radar

Winter										
	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 6**	**Period 7**	**Period 8**	**Period 9**	**Period 10**
Initial date	07-Feb-2013 08:00:00	09-Mar-2021 22:00:00	23-Jan-2009 01:00:00	02-Jan-2013 11:00:00	18-Jan-2016 17:00:00	02-Jan-2014 15:00:00	17-Feb-2017 06:00:00	17-Jan-2012 09:00:00	22-Jan-2017 17:00:00	12-Jan-2021 23:00:00
Final date	14-Feb-2013 07:00:00	16-Mar-2021 21:00:00	30-Jan-2009 00:00:00	09-Jan-2013 10:00:00	25-Jan-2016 16:00:00	09-Jan-2014 14:00:00	24-Feb-2017 05:00:00	24-Jan-2012 08:00:00	29-Jan-2017 16:00:00	19-Jan-2021 22:00:00

Spring										
	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 6**	**Period 7**	**Period 8**	**Period 9**	**Period 10**
Initial date	14-Apr-2015 23:00:00	16-May-2012 00:00:00	16-Apr-2017 14:00:00	21-Apr-2012 08:00:00	05-Jun-2014 06:00:00	11-Apr-2021 20:00:00	06-May-2012 06:00:00	10-Apr-2015 08:00:00	08-May-2018 22:00:00	22-Apr-2016 11:00:00
Final date	21-Apr-2015 22:00:00	22-May-2012 23:00:00	23-Apr-2017 13:00:00	28-Apr-2012 07:00:00	12-Jun-2014 05:00:00	18-Apr-2021 19:00:00	13-May-2012 05:00:00	17-Apr-2015 07:00:00	15-May-2018 21:00:00	29-Apr-2016 10:00:00

Summer										
	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 6**	**Period 7**	**Period 8**	**Period 9**	**Period 10**
Initial date	19-Aug-2017 01:00:00	04-Jul-2015 16:00	15-Aug-2016 18:00:00	08-Aug-2012 11:00:00	14-Aug-2015 00:00:00	08-Sep-2013 23:00:00	11-Sep-2017 11:00:00	13-Sep-2015 02:00:00	08-Jul-2019 4:00	05-Aug-2014 20:00:00
Final date	26-Aug-2017 00:00:00	11-Jul-2015 15:00	22-Aug-2016 17:00:00	15-Aug-2012 10:00:00	20-Aug-2015 23:00:00	15-Sep-2013 22:00:00	18-Sep-2017 10:00:00	20-Sep-2015 01:00:00	15/-Jul-2019 3:00	12-Aug-2014 19:00:00

Autumn										
	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 6**	**Period 7**	**Period 8**	**Period 9**	**Period 10**
Initial date	16-Oct-2014 22:00	17-Oct-2011 8:00	24-Oct-2015 11:00	08-Nov-2011 17:00:00	10-Dec-2020 10:00:00	06/11/2015 1:00	23-Nov-2015 21:00:00	04-Oct-2017 23:00:00	04-Oct-2015 20:00:00	23-Nov-2020 04:00:00
Final date	23-Oct-2014 21:00	24-Oct-2011 7:00	31-Oct-2015 10:00	15-Nov-2011 16:00:00	17-Dec-2020 09:00:00	13/11/2015 0:00	30-Nov-2015 20:00:00	11-Oct-2017 22:00:00	11-Oct-2015 19:00:00	30-Nov-2020 03:00:00

Appendix D. Seasonal mean current and wind fields (2009-2021)

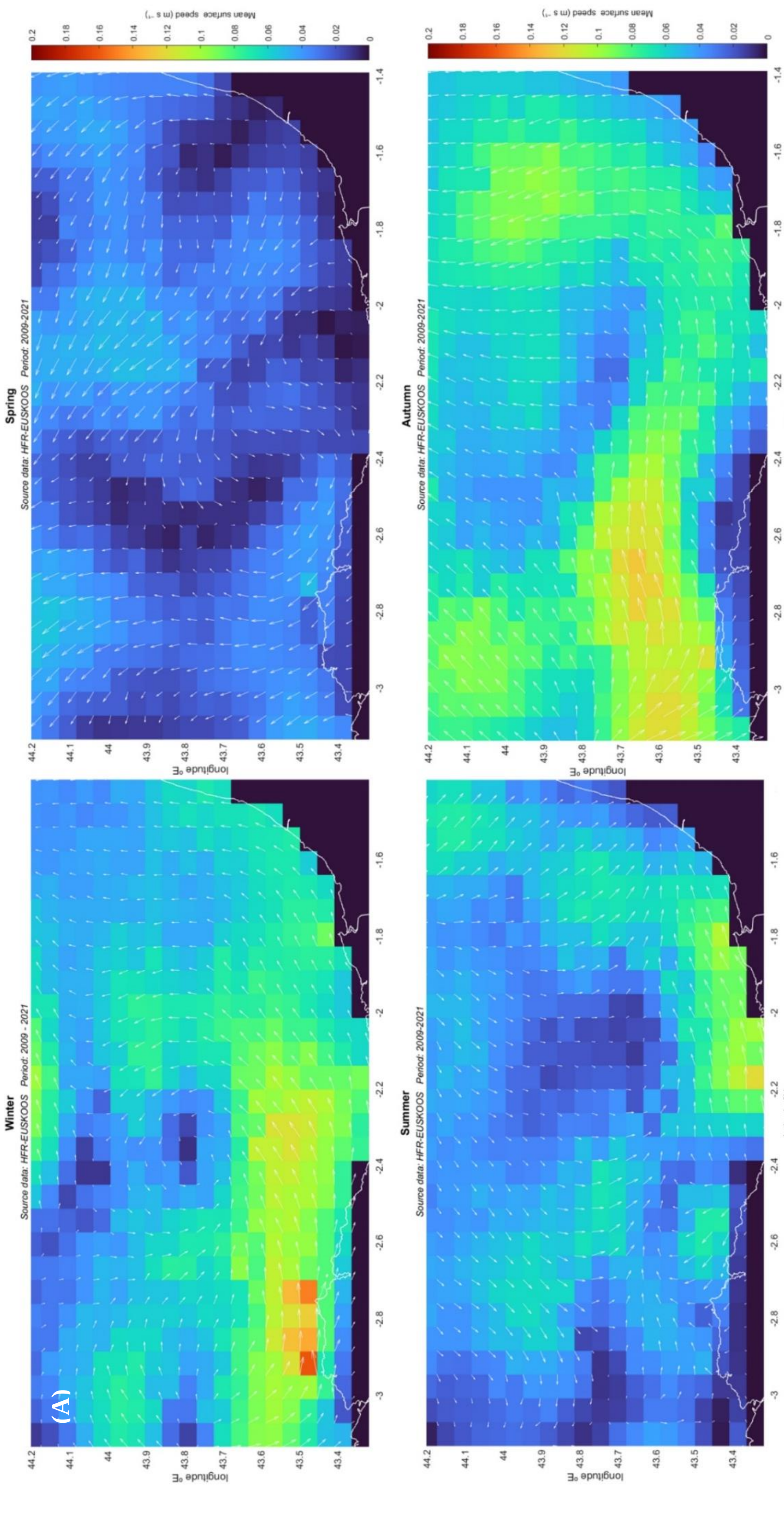
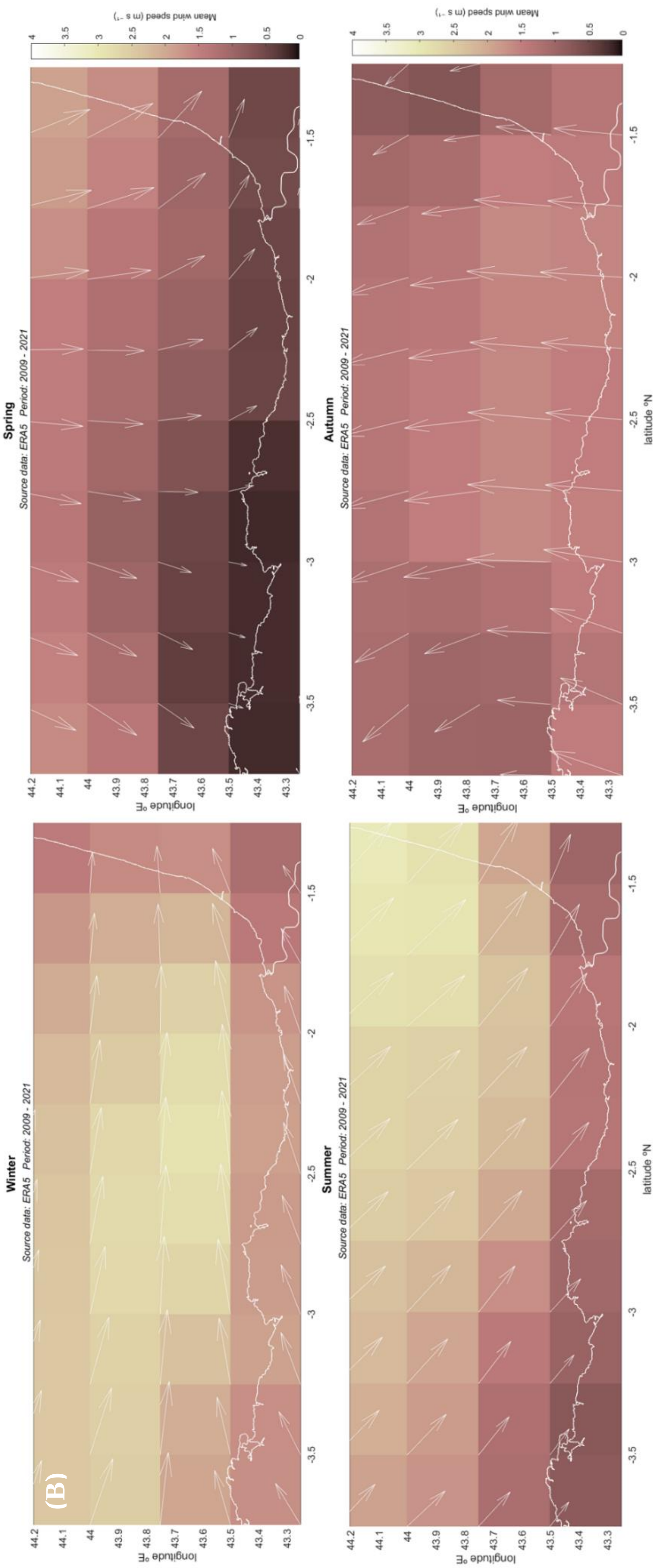


Figure D1. Mean current (A) and wind fields (B) in the study area during each season for the selected periods between 2009 and 2021. The colour-bars represent the magnitude of current and wind speed. The arrows indicate the current and wind mean direction and are scaled with currents and wind speed (Data source: HFR – EuskOOS https://www.euskoos.eus/en/data/basque-ocean-meteorological-network/high-frequency-coastal-radars/ and ERA5 https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5)


(B)
Winter
Source data: ERA5 Period: 2009 - 2021
Spring
Source data: ERA5 Period: 2009 - 2021
Summer
Source data: ERA5 Period: 2009 - 2021
Autumn
Source data: ERA5 Period: 2009 - 2021
Mean wind speed (m s⁻¹)
longitude ºE
latitude ºN

Video supplement

Animations of the surface currents, winds and Lagrangian simulations area available for the study period 2009-2021.

Author contributions

IR: Investigation, formal analysis, visualization and writing – original draft preparation. AJ: Conceptualization, methodology, software, writing – review & editing. OCB: Conceptualization, supervision, resources, review and editing. AR: Conceptualization, methodology, supervision, resources, review and editing. All authors contributed to refining the manuscript for submission. This paper is part of the PhD research of IR supervised by OCB and AR.

Competing interests

The authors declare that they have no conflict of interest.

Financial support

This research has been partially funded through the EU's LIFE Program (LIFE LEMA project, grant agreement no. LIFE15 ENV/ES/000252) and by EU's H2020 Program (JERICO-S3 project, grant agreement No. 871153).

Acknowledgements

We are grateful to the Emergencies and Meteorology Directorate – Security department – Basque Government for public data provision from the Basque Operational Oceanography System EuskOOS. Authors also acknowledge support from the JERICO-S3 project, funded by the European Union's Horizon 2020 Research and Innovation Program under grant agreement no. 871153. This study has been conducted using EU Copernicus Marine Service information. We thank Luis Ferrer for sharing his valuable knowledge on custom-built the drifters. We thank Cristina Barreau, Antoine Bruge, Igor Granado, Théo Destang, Alix McDaid and Jon Andonegi for their support with drifters' releasing. We thank the citizens who collected and reported drifters' arrival to Basque and French coasts. This is contribution number XXX of AZTI - Marine Research (BRTA).

Review statement

This paper was edited by XXX and reviewed by XXX anonymous referees.

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