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Modelling the distribution of fishing-related floating marine litter within the Bay of Biscay and its marine protected areas☆

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A R T I C L E I N F O

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A B S T R A C T

Sea-based sources account for 32–50 % of total marine litter found at the European basins with the fisheries sector comprising almost 65 % of litter releases. In the south-east coastal waters of the Bay of Biscay this figure approaches the contribution of just the floating marine litter fraction. This study seeks to enhance knowledge on the distribution patterns of floating marine litter generated by the fisheries sector within the Bay of Biscay and in particular on target priority Marine Protected Areas (MPAs) to reinforce marine litter prevention and mitigation policies. This objective is reached by combining the data on geographical distribution and intensity of fishing activity, long-term historical met-ocean databases, Monte Carlo simulations and Lagrangian modelling with floating marine litter source and abundance estimates for the Bay of Biscay. Results represent trajectories for two groups of fishing-related items considering their exposure to wind; they also provide their concentration within 34 MPAs. Zero windage coefficient is applied for low buoyant items not subjected to wind effect. Highly buoyant items, strongly driven by winds, are forced by currents and winds, using a windage coefficient of 4 %. Results show a high temporal variability on the distribution for both groups consistent with the met-ocean conditions in the area. Fishing-related items driven by a high windage coefficient rapidly beach, mainly in summer, and are almost non-existent on the sea surface after 90 days from releasing. This underlines the importance of windage effect on the coastal accumulation for the Bay of Biscay. Only around 20 % of particles escaped through the boundaries for both groups which gives added strength to the notion that the Bay of Biscay acts as accumulation region for marine litter. MPAs located over the French continental shelf experienced the highest concentrations (>75 particles/km^2) suggesting their vulnerability and need for additional protection measures.

1. Introduction

Worldwide fast-growing levels of marine litter pose a complex and multi-dimensional concern requiring prompt and tailor-made measures and solutions to ensure a real protection for the marine environment. Efforts have been undertaken over the last years to gain a comprehensive understanding on the marine litter issue. They all have plugged significant knowledge gaps and boosted decision-making at national, regional, and international levels. However, despite the increasing research and the political actions achieved, long-term datasets to characterize the sources, define quantities, behaviour and impacts of marine litter are still scarce.

There is a scientific agreement regarding the categorization of sea- and land-based marine litter origins (Galgani et al., 2015; Kershaw et al., 2019; Thushari and Senevirathna, 2020) or the large proportion of marine litter made up of plastic (Cózar et al., 2014; Barboza et al., 2019; Morales-Caselles et al., 2021). Nonetheless, the research made to date reveals a wide disparity between the estimations of plastic litter generated on land entering the ocean (Jambeck et al., 2015; Boucher and Friot, 2017; Ryberg et al., 2018) and the amount of marine litter floating on the ocean surface (Eriksen et al., 2014; van Sebille et al., 2015). Besides, the vast majority of the studies have focused on land-based sources overshadowing marine litter contribution resulting from sea-based activities (Kershaw et al., 2020). It is broadly accepted that land-based sources account for 78 % of marine litter in the world's oceans, while at least the 22 % is originated from sea-based sources (UNEP, 2014; Li et al., 2016; Pawar et al., 2016). However, studies documenting the actual released quantities and the differences on litter

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origins between marine regions are still limited (Sherrington et al., 2016; UNEP, 2016; Morales-Caselles et al., 2021). At European level, sea-based sources account for over 40 % litter items in some regions causing 20–40 % of the total marine litter input by weight (Sherrington et al., 2016; Veiga et al., 2016). Sea-based sources can be dominated by the fisheries and shipping sectors in certain marine areas; overall 70 % by weight of floating marine litter (hereinafter FML) in the open ocean is fishing-related (Eriksen et al., 2014; UNEP, 2016). Surveys undertaken on European beaches accounted for 3–15 % of fishing-related items (Addamo et al., 2017) reaching 17 % in the North-East Atlantic region (OSPAR, 2020).

In the less explored Bay of Biscay (hereinafter BoB) region, fisheries and aquaculture sectors represents the source of the 14–38 % of the total items recorded for Spanish beaches, 50 % for French beaches (Gago, 2014; Rayon-Viña et al., 2018), and the 35 % (in number of items) or the 55 % (in weight) of the FML (Ruiz et al., 2020). However, these percentage values can vary depending on the geographical origin, the transport mechanisms, the pathways or the durability of the fishing items and can even increase in areas with intensive fishing activities (Veiga et al., 2016).

MPAs are globally recognised to safeguard marine ecosystems and biodiversity by balancing ecological constraints and economic activities (EEA, 2018). They are defined as geographical zones with management objectives oriented to regulate human activities (e.g: fishing, dredging) for a long-term protection and conservation of the marine environment (Day et al., 2012). However, MPAs are exposed to the same levels of marine pollution as non-protected areas since the spatial delimitation of MPAs does not represent an effective impediment to avoid marine litter presence (Nelms et al., 2020). Initiatives to assess the environmental and socio-economic impact of sea-based sources can be of particular interest for establishing policy priorities and effective regulations in MPAs (Fossi and Panti, 2020; Purba et al., 2020). Yet, research on the occurrence, sources and distribution of marine litter in MPAs is patchy and, in some cases, limited to remote locations (Barnes et al., 2018; Luna-Jorquera et al., 2019). However, it has been observed that in North-East Atlantic and Mediterranean based MPAs, fishing and shipping related marine litter represented over 55 %–88 % of the total litter abundance (La Beur et al., 2019; Liubartseva et al., 2019; Luna-Jorquera et al., 2019). Fishing litter and, in particular, derelict abandoned, lost and discarded fishing gear (ALDFG) impacts endangered species and benthic environment, and favours a long duration of ghost fishing efficiency (Macfadyen et al., 2009; Gilman et al., 2021). Recent studies estimate that 5.7 % of all fishing nets, 8.6 % of all traps and 29 % of all lines are lost to the world's ocean annually (Richardson et al., 2019) and the damage caused to marine invertebrates, such as gorgonians and coralligenous biocenosis, has been already documented for the Mediterranean MPAs (Consoli et al., 2019; Betti et al., 2020).

Despite the ocean surface is the best sampled oceanic compartment, the observations made so far are insufficient to predict accurately the transport and destination of FML. The relative immensity of the ocean and the spatio-temporal variability of the circulation and transport processes hinder the research of FML distribution (Hardesty et al., 2016; Maximenko et al., 2019). Thus, modelling approaches can be useful to gain a better understanding of FML behaviour when few observations are available. They provide insights into circulation patterns and support the identification of accumulation zones. A broad variety of FML modelling approaches has been undertaken up till now, from models oriented to simulate litter destination and origin at global scale (Lebreton et al., 2012; Chassignet et al., 2021; Onink et al., 2021) to regional models with higher spatiotemporal resolutions and more reduces coverage such those applied in the Mediterranean Sea (Liubartseva et al., 2018b; Macias et al., 2019; Politikos et al., 2020), the Black Sea (Stanev and Ricker, 2019; Miladinova et al., 2020), the North Sea (Neumann et al., 2014) or the Adriatic Sea (Liubartseva et al., 2016). Also the application of three-dimensional models simulating the dynamic behaviour of FML is also becoming increasingly widespread (Jalón-Rojas et al., 2019; van Gennip and et al., 2019; Soto-Navarro et al., 2020). In particular, Lagrangian particle tracking techniques have turned out to be an effective approach to solve for FML trajectories using statistical long term database of winds and currents (Hardesty et al., 2017; Van Sebille et al., 2018b). Besides, their capability to incorporate additional parametrizations makes them suited for addressing the direct effect of wind ("windage" as defined by Breivik et al. (2011)) on destination and travel time for different items (NOAA, 2016), as verified by the FML simulation results from the Great Japan Tsunami of 2011 (Maximenko et al., 2018). Object windage classification and parametrization also contributes to identify accurately the potential source regions of FML reaching the coastal areas (Duhec et al., 2015). Even then, the majority of the literature focuses on transport modelling of buoyant and fully submerged objects induced only by surface currents with a global (Lebreton et al., 2012; van Sebille et al., 2015) and regional application (Zambianchi et al., 2017; Miladinova et al., 2020; Politikos et al., 2020).

In the BoB, recent modelling studies have helped to shed some light on the regional circulation of FML. Results emphasize the hypothesis of the Bay being a FML accumulation zone and draw the attention on the high seasonal variability of FML transport (Pereiro et al., 2018; Declerck et al., 2019; Pereiro et al., 2019). Additional research accounting for windage effect highlight the importance of the size of the items on FML entrapment, particularly for the larger ones (>5 mm), more likely to stay in nearshore areas and beached (Rodríguez-Díaz et al., 2020).

However, many questions remain unanswered on FML transport and accumulation patterns based on the origin, windage parametrizations and the subsequent impacts on the marine environment and MPAs. Within this context and to better response to anthropogenic stressors for the coastal waters of the Bay of Biscay in the framework of JERICO-S3 project, the objective of this study is twofold: (1) to provide insights into distribution patterns of fishing-related items uninfluenced by winds and those strongly influenced by windage effect and (2) to assess their concentration in MPAs to put in place future-oriented and effective management and conservation strategies.

2. Study area

The study area is located within the OSPAR region IV *Bay of Biscay and Iberian Coast* and covers the large part of the FAO region *Bay of Biscay* (subarea 27.8 of FAO major area 27). It extends from 43°N to 48°N and from 11°W to the Spanish and French coastlines (Fig. 1) and comprises the Spanish and French marine waters defined by the Economic Exclusive Zone (EZZ) boundary.

Intense fishing activities occurred in the study area fostered by the primary production levels and the topographic characteristics of the shelf basin (Lavin et al., 2006). The most common fishing fleet are trawlers together with set longliners and purse seiners since they represent 60–75 % of the fishing hours in the BoB (Fernandes et al., 2019). Fishing activity has become a relatively important human pressure in the BoB and ALDFG has been identified as a hazard for marine mammal populations resulting in fishing mortalities due to their ability to continue to fish target and non-target species (ICES, 2016; Borja et al., 2019).

The circulation in the BoB enhances the seasonal dispersion patterns of FML with high wind drifts south-eastward in winter and north-westward in summer (Borja et al., 2019; Pereiro et al., 2019). The coastline influences the less variable circulation in the inner shelf of the BoB compared to the outer shelf, where variability associated with mesoscale activity govern FML behaviour (Solabarrieta et al., 2014; Pereiro et al., 2018). FML tends to accumulate in the southeast of the Bay during spring and summer with longer residence times comparing to the north-western Iberian coastal waters. During autumn and winter, the northward transport contributes to the dispersion along the French coast (Declerck et al., 2019; Rubio, 2020).

The study area encompasses 34 MPAs - 27 in France and 7 in Spain –

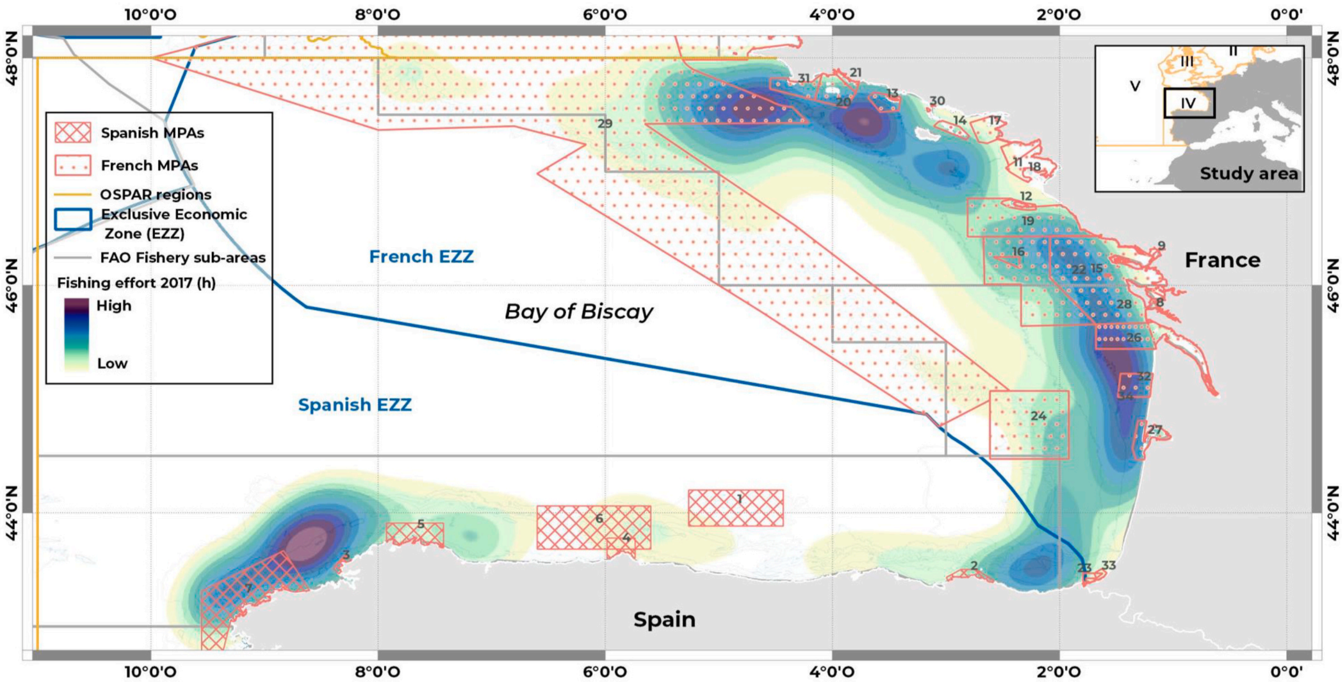

Fig. 1. Area of study with the location of the selected Marine Protected Areas (MPAs) - Spanish MPAs in polygons with crosses and French MPAs in polygons with dots-. Numbers correspond to the name of each MPA in Table 1.

aiming to protect mainly benthic habitats, marine mammals and seabirds. Their surface extension range between 26 and 8192 km^2 and the average size per MPA is 3442 km^2 (Table 1). The MPAs considered in this study are predominantly or entirely marine protected areas assigned by UNEP-WCMC (UNEP-WCMC, 2019) and established under the framework of the EU nature Directives, national designations and Regional Sea Conventions (RSCs) (Agnesi et al., 2020).

3. Data and modelling methodology

3.1. Modelling rationale

Fishing-related FML data obtained in sea surveys were combined with met-ocean datasets to model fishing-related FML trajectories (Fig. 2). Information derived from FML samples was used to categorize the items collected into two groups: low buoyant objects driven by currents and highly buoyant objects driven by wind and currents. Incorporating windage effect allowed the parameters of the model to be adjusted so the modelled outputs agree more closely with the real trajectories of the items. Measurements of fishing effort (hours spent by vessels catching fish) were used for setting the starting locations (sources) of particles carried by currents and wind. The number of particles released per group was proportional to the amount of low and highly buoyant fishing-related items collected in sea surveys. Particles were monthly distributed in the starting locations according to the fishing effort in the region. Particles were initialized randomly every month (from January to December) over a one-year period and their evolution was tracked for 90 days. The two sets of trajectories were post-processed considering the fate of the particles: escaped through the boundaries of the study area (northern, southern, or western boundary) or remained (floating or beached). Results provided the fishing FML distribution patterns and concentration in MPAs.

3.2. Fishing-related FML data

FML data were gathered from marine litter windrows - concept described in Cózar et al. (2021) - over Spring and Summer 2018 on the coastal waters of the BoB. Marine litter windrows were detected by visual observations, and, straight after, net tows were carried out along the litter windrow following the streak of higher FML concentration. The FML was stored in 1 m^3 big bags and a portion from the collected FML (≈0.2 m^3) was randomly retrieved as a sample for the characterization (for further information on the methodology see Ruiz et al. (2020)). In total 11 samples were gathered. Origins and characteristics of the items collected in the windrows showcased the fishing contribution to FML in the area. Over 115 kg and 1400 sea-based litter items were classified into two groups considering their exposure to wind (Table 2):

- Low buoyant items: items not exposed to wind and mainly transported by currents (e.g: nets or gloves). In total, 1384 items and 77.16 kg in weight.
- Highly buoyant items: items strongly exposed to wind and partially transported by winds and currents (e.g: buoys or fishing boxes). In total, 70 items and 37.94 kg.

The division was chosen based on existing FML windage classification approaches (Yoon et al., 2010; Neumann et al., 2014; Duhec et al., 2015; Maximenko et al., 2018; Pereiro et al., 2019; Van Sebille et al., 2018a). The classification was refined by adding new items not included in previously studies in order to simulate all fishing-related items collected in the surveys. Shipping related items were assigned to the fishing category due to their small contribution to FML in the samples. The classification in terms of weight was the basis for allocating the number of particles to the simulation sets. From the released particles, 67 % (241,200) were parameterized to simulate the trajectories with a zero windage coefficient (Set 1; Cd = 0); 33 % of the particles (118,800) were released and run with a high windage coefficient (Set 2; Cd = 04 %).

Input on location of fishing FML sources is crucial for modelling transport and accumulation; thus, the release locations were carefully selected, identifying as 'initial point of fishing-based litter sources' the reported monthly AIS fishing positions corresponding to fishing effort measured on a regular grid of 0.01° within the FAO region *Bay of Biscay* (subarea 27.8 of FAO major area 27) for 2017. These values exclude the

Table 1
Marine Protected Areas (MPAs) within the study area. ID indicates the MPA in Fig. 1.

ID	Name	Area (km^2)	Location	Designation
1	El Cachucho	2349.503	ESP	Marine Protected Area
2	Espacio marino de la Ria de Mundaka-Cabo de Ogoño	175	ESP	Marine Protected Area (OSPAR)
3	Espacio marino de la Costa de Ferrolterra - Valdoviño	68	ESP	Marine Protected Area (OSPAR)
4	Espacio marino de Cabo Peñas	320.6099	ESP	Special Protection Area (Birds Directive)
5	Espacio marino de Punta de Candelaria-Ría de Ortigueira-Estaca de Bares	771.5168	ESP	Special Protection Area (Birds Directive)
6	Sistema de cañones submarinos de Avilés	3390	ESP	Marine Protected Area (OSPAR)
7	Espacio marino de la Costa da Morte	3162.8305	ESP	National Nature Reserve
8	Moëze-Oléron	67.19382	FRA	National Nature Reserve
9	Baie De L'Aiguillon (Charente-Maritime)	26	FRA	Marine Nature Park
10	Iroise	3500	FRA	Site of Community Importance (Habitats Directive)
11	Estuaire de la Loire Nord	307.14	FRA	Site of Community Importance (Habitats Directive)
12	Plateau rocheux de l'île d'Yeu	119.98	FRA	Site of Community Importance (Habitats Directive)
13	Ile de Groix	283.3697	FRA	Site of Community Importance (Habitats Directive)
14	Iles Houat-Hoëdic	177.6983	FRA	Site of Community Importance (Habitats Directive)
15	Pertuis Charentais	4560.27	FRA	Site of Community Importance (Habitats Directive)
16	Plateau de Rochebonne	97.15	FRA	Special Protection Area (Birds Directive)
17	Mor Braz	402.76	FRA	Special Protection Area (Birds Directive)
18	Estuaire de la Loire - Baie de Bourgneuf	802.02	FRA	Special Protection Area (Birds Directive)
19	Secteur marin de l'île d'Yeu jusqu'au continent	2454.1	FRA	Special Protection Area (Birds Directive)
20	Archipel des Glénan	587.9	FRA	Special Protection Area (Birds Directive)
21	Dunes et côtes de Trévignon	98.74	FRA	Special Protection Area (Birds Directive)
22	Pertuis charentais - Rochebonne	8192.58	FRA	Special Protection Area (Birds Directive)
23	Estuaire de la Bidassoa et baie de Fontarabie	94.57	FRA	Special Protection Area (Birds Directive)
24	Tête de Canyon du Cap Ferret	3656.39	FRA	Marine Protected Area (OSPAR)
25	Marais de Moëze	67	FRA	Marine Protected Area (OSPAR)
26	Panache de la Gironde et plateau rocheux de Cordouan	952	FRA	Marine Nature Park
27	Bassin D'Arcachon	435	FRA	Marine Nature Park
28	Estuaire De La Gironde et mer des Pertuis	6500	FRA	Special Protection Area (Birds Directive)
29	Mers Celtiques - Talus du golfe de Gascogne	71860.94	FRA	Special Protection Area (Birds Directive)
30	Baie de Quiberon	9.05	FRA	Special Protection Area (Birds Directive)
31	Roches de Penmarc'h	457.28	FRA	Special Protection Area (Birds Directive)
32	Au droit de l'étang d'Hourtin-Carcans	507.16	FRA	Special Protection Area (Birds Directive)
33	Côte Basque rocheuse et extension au large	78	FRA	Marine Protected Area (OSPAR)
34	Portion du littoral sableux de la côte aquitaine	507	FRA	Marine Protected Area (OSPAR)

time spent searching for fish and transit periods (see Taconet et al. (2019) for details). Over one million fishing hours and their corresponding vessel positions were considered in the analysis.

3.3. Met-ocean data

Surface currents were obtained from the operational IBI (Iberian Biscay Irish) Ocean Analysis and Forecasting System, provided by the Copernicus Marine Environment Monitoring Service (CMEMS). The system is based on a NEMO model and forced with 3-hourly atmospheric fields from ECMWF (see (Sotillo et al., 2015) for details). The data is available at a 0.083° × 0.083° horizontal resolution using 50 vertical levels. Surface currents were extracted in the same horizontal grid at the nominal depth of 1 m.

For Set 2, simulations were driven by the one-hourly ERA5-U10-wind fields generated by the atmospheric IFS model of the European Center for Medium-Range Weather Forecast (ECMWF) (see (C3s, 2019) for details). ERA5 atmospheric reanalysis 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 on a 0.3° × 0.3° grid, currently from 1979 to within 3 months of real time. Both hourly simulated winds and surface currents were extracted from 1998 to 2017 and coupled to the model.

3.4. Methods

The modelling methodology was underpinned on realistic descriptions of fishing-related FML sources defined in Section 3.2. The availability of met-ocean long-term datasets allowed to apply the probabilistic Monte Carlo technique to consistently simulate particle trajectories throughout the year. A database of FML trajectories under different met-ocean conditions (scenarios) was achieved for each month. Monte Carlo is considered a useful approach to overcome the uncertainty of modelling complex situations where many random variables are involved; Monte Carlo technique can be applied for predicting potential pollution events (Abascal et al., 2010; Alves et al., 2014; Morell Villalonga et al., 2020), assessing beach litter presence (Martínez-Ribes et al., 2007; Schulz et al., 2019; Álvarez et al., 2020) or forecasting marine litter transport (Quan Luna et al., 2012; Liubartseva et al., 2018a). Abascal et al. (2010) revealed that 200 scenarios can be suitable to characterize the seasonally particle behaviour within the BoB. Following this recommendation, in this analysis, 200 scenarios per month and 2400 in total were randomly selected. The number of

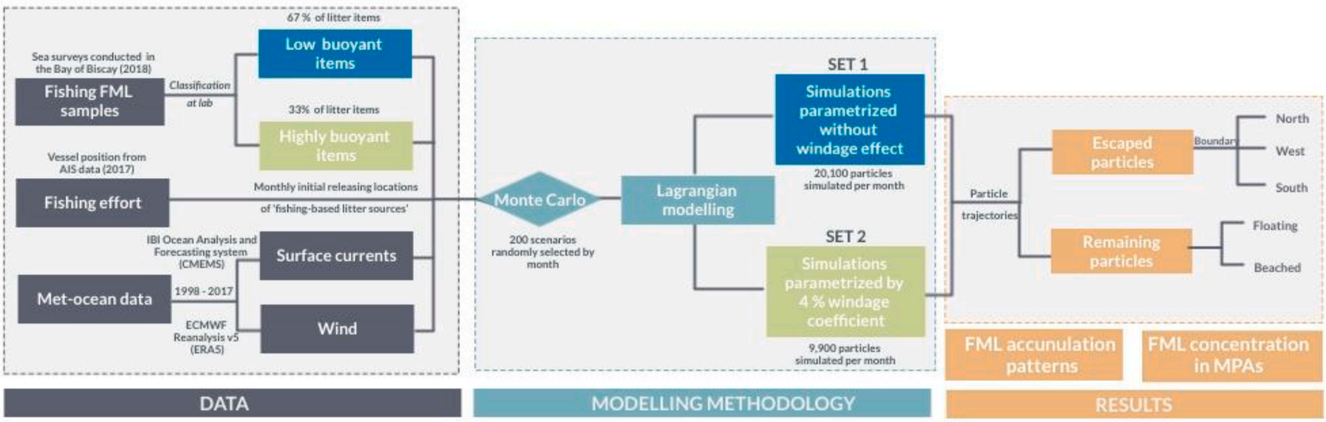

Fig. 2. Methodological framework for assess fishing-related floating marine litter distribution and concentration within the Bay of Biscay and Marine Protected Areas.

Table 2
Fishing – related items classification based on the exposure to wind effect. Data were gathered from surveys carried out during Spring and Summer 2018 in the south-east coastal waters of the Bay of Biscay.

TSG_ML General code	General name	Number of items	Weight (kg)
Low buoyant items transported by currents			
G39; G40; G41	Gloves	2	0.16
G42	Pots, including pieces	15	1.81
G43	Tags (fishing and industry)	11	0.26
G48; G49; G50	String and cords	1165	3.14
G51; G52; G53; G54	Nets and pieces of net	28	52.28
G56	Tangled nets and cords	98	17.31
G66	Strapping bands	61	0.2
G127	Rubber boots	2	2
G182	Fishing related (weights, sinkers, lures, hooks)	2	0.02
	Total	94.99 %	67.04 %
Highly buoyant items transported by wind and currents			
G57	Fish boxes - plastic	16	17.65
G58	Fish boxes – expanded polystyrene	5	0.9
G60; G62; G63	Light sticks/Floats for fishing nets/Buoys	23	18.5
G174	Sprays	1	0.28
G175	Cans (beverage)	22	0.55
G176	Cans (food)	3	0.06
	Total	5.01 %	32.96 %

particles per grid was estimated for the set of all scenarios according to Eq. (1):

$$N(i,j,t) = \sum_{s=1}^{S} \sum_{t=1}^{T} n(i,j,t) \tag{1}$$

where S is the number of scenarios, t is the time, T the simulation period and i,j the grid nodes.

Windage assignment for Set 1 and Set 2 was Cd = 0 % and Cd = 4 %, respectively. Both simulation sets were conducted using the transport module of the TESEO model (Abascal et al., 2007; Abascal et al., 2017a; Abascal et al., 2017b). TESEO is a 3D numerical model conceived to simulate the transport and degradation of hydrocarbons, as well as the drift of floating objects and people in marine environments, on both regional and local scale. The transport module allows including environmental conditions -wind, waves and currents-to compute particle trajectories. The transport model has been calibrated and validated by comparing virtual particle trajectories to observed surface drifter trajectories at regional and local scale (Abascal et al., 2009; Abascal et al., 2017a; Abascal et al., 2017b). Recently, TESEO has been also successfully applied to marine litter transport studies (Mazarrasa et al., 2019; Núñez et al., 2019). Pretests were performed to establish the numerical settings of the simulations in order to balance the number of particles and the time step for computing their transport. Finally, 30,000 particles were released per month - 20,100 and 9900 for Set 1 and Set 2 accordingly - ensuring a good performance of the model without compromising the computing time and the results. Pathways were calculated from the release location (Fig. 3) until the end of the simulation, allowing the position to be described in detail at temporal and spatial scale. Fishing-related FML items were treated as buoyant particles and advected by 2D surface ocean current fields. Wave effects were omitted.

The domain was divided into a regularly spaced grid of 61 × 133 elements and 0.08° × 0.08° spatial resolution (Δx). A land-sea mask was embedded in the model to undertake the beaching assessment. For each particle, the displacement was integrated with the time step (Δt) of 1800s, thus the particles will not displace more than one grid in one time step (Price et al., 2004; Abascal et al., 2010). As mentioned, 200 scenarios per month and 2400 in total were randomly selected. For each scenario, particles were initialized as an instantaneous release and run for 90 days as suggested as valid for basin scale by (Mansui et al., 2020). A turbulent diffusion coefficient of 1 $m^2 s^{-1}$ was set according to previously FML modelling studies carried within the BoB (Pereiro et al., 2019) to account for sub grid dispersion. Finally, the position of each particle along its trajectory and the density of particles per cell was saved every 12 h (Table 3).

Particles stranded in the limit of the coastline cells bordering land were treated as beached litter. Particles escaped from geographical limits of the study area - northern, southern and western boundary - were considered in order to quantify the accumulation rate of particles escaped. Once beached or escaped, particles were removed from further model computational steps.

The mean accumulation rate of beached, floating, and escaped particles was calculated by averaging the accumulation rate for each time step throughout the year during the integration time. The evolution of the accumulation rate was calculated based on a weekly assessment. The spatial accumulation was calculated by the end of the simulation (90 days-period). Concentrations in the MPAs were quantified as the ratio between the number of particles accumulated by the end of the simulation (n) and the MPA surface area (km^2). MPAs areas with spatial scale smaller than the grid were not included in the analysis.

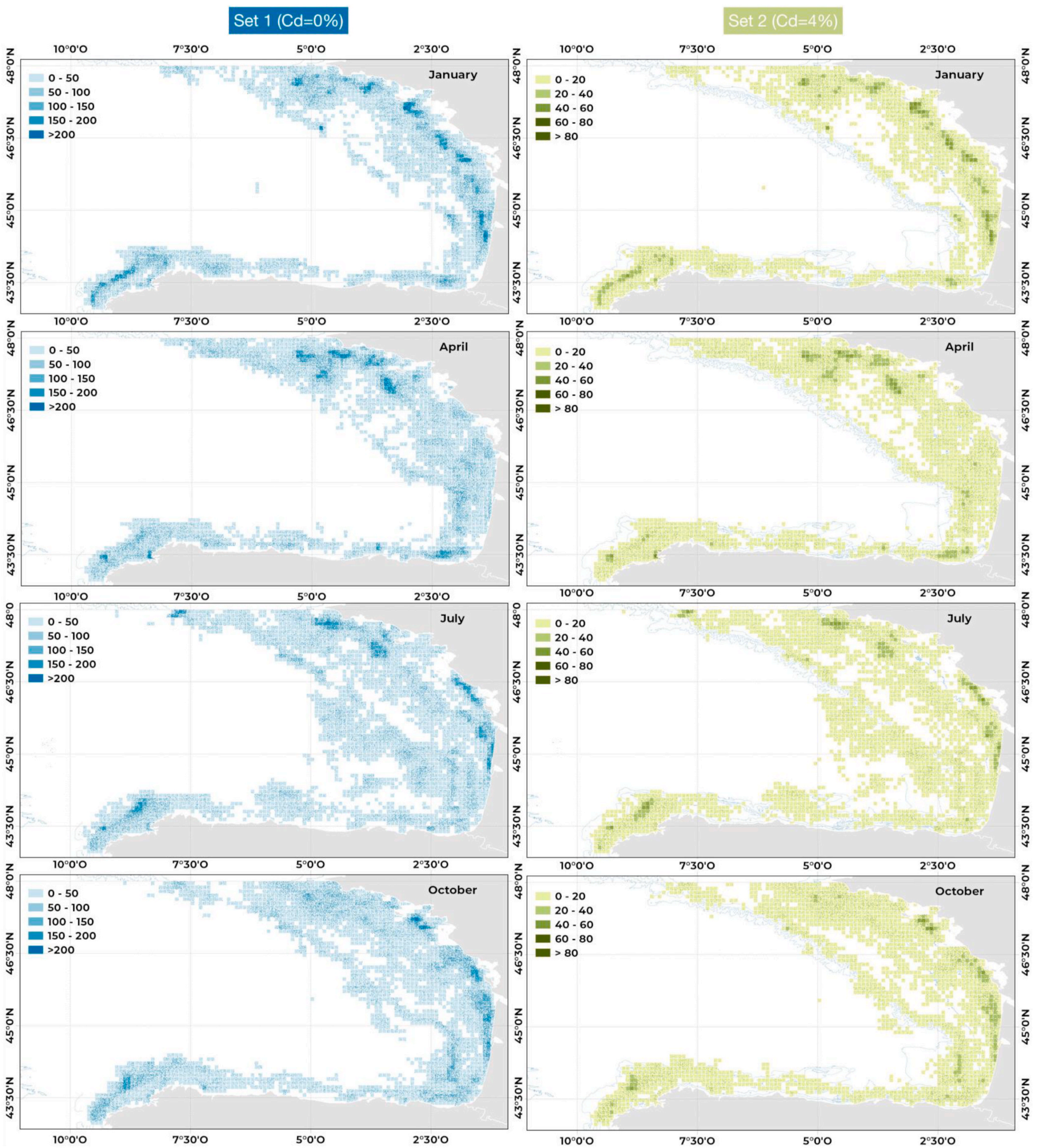

Fig. 3. Release locations for Set 1 (blue) and for Set 2 (green) initialized in January, April, July and October. Additional figures for the remaining months are available in Supplementary Figure S1 and Figure S2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)appsec1

4. Results

4.1. Temporal FML accumulation

4.1.1. Mean accumulation rate

Over 24 % of particles from Set 1 and 80 % from Set 2 beached at the end of the simulations (Fig. 4). For Set 2, beaching increased rapidly during the first-time steps and gradually levelled for the second half of the simulation period. At the end of the simulation, more than 55 % of particles from Set 1 remained floating at sea surface and less than 1 % from Set 2 still floated. No significant differences were observed amongst Set 1 (21 %) and Set 2 (19 %) in terms of accumulation of particles escaping the area. Particles from Set 1 were most likely to escape through the northern boundary (14 %) comparing to Set 2 (10

Table 3
Simulation, release, and physical parameter values corresponding to simulation Set 1 and Set 2.

	Simulation parameters			Release parameters		Physical parameters	
	Number of particles per month (total)	Integration time	Time step	Release locations	Release time	Turbulent diffusion coefficient	Windage coefficient (Cd)
Set 1	20,100 (241,200)	90 days	1800 s	Proportional to monthly fishing effort	Randomly selected by month	1 m^2/s	0 %
Set 2	9900 (1128,800)						4 %

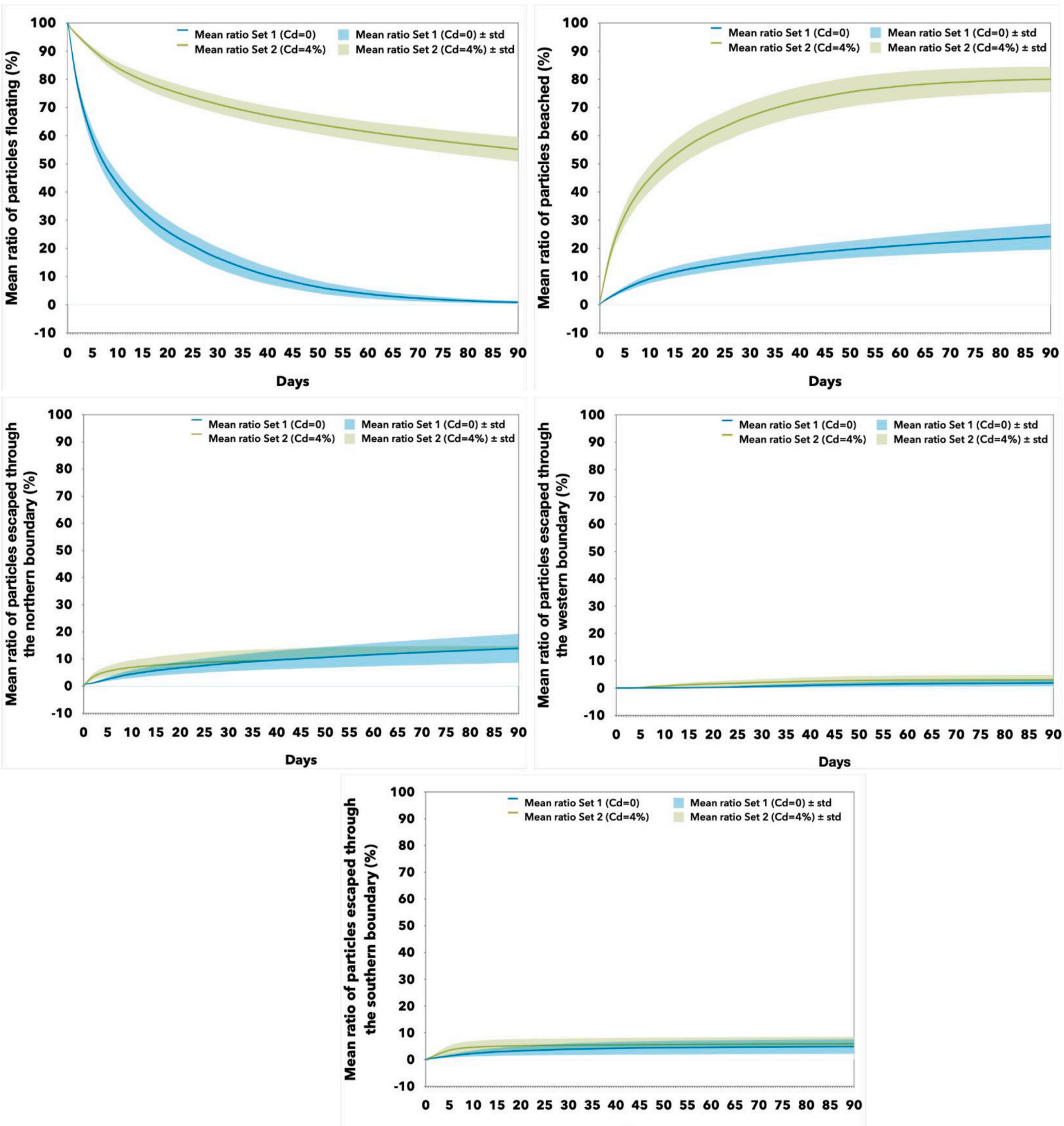

Fig. 4. Mean accumulation ratio for Set 1 (blue) and Set 2 (green) of floating, beached and escaped particles through the three open boundaries. The average was calculated per each time step of the integration time throughout the year. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

%); only 2 % and 3 % of particles ended up at the western boundary for Set 1 and Set 2 respectively. Less than 5 % of particles escaped from the BoB through the southern boundary for both sets.

4.1.2. Accumulation rate progress

High temporal variability was observed over the year on surface and coastal accumulation for both sets (Fig. 5). The accumulation rate for floating particles from Set 1 ranged from 85 to 89 % (minimum-maximum values respectively) after one week to 44–59 % by the end of the simulation period. In contrast, surface accumulation for particles from Set 2 varied from 48 - 57 % to 0.2–1.4 % for the same period. The most significant decrease for both cases occurred during summer.

Beached particles from Set 2 increased to 65–80 % after one month of simulation to subsequently stabilized over 80 % till the end of the simulation period. Beaching for particles from Set 1 increased from 6 to 10 % after one-week simulation to 20–35.5 % by the end of the simulation. Beaching was also significant during summer.

For both sets, particles escaped more easily through the northern boundary comparing to the other boundaries. In autumn and winter, between 3 and 10 % of particles from Set 2 and 2–4 % of particle from Set 1 escaped during the first week of simulation; the accumulation rate hardly increased in both cases above 4–21 % by the end of the simulation. It was observed that few particles escaped through the western boundary: only 0.15–3.3 % of particles escaped for Set 1 and 0.4 %–6.12 % for Set 2. The particles escaped mainly in winter and during the first weeks of the simulations. Similar rate of particles ranging from 1.8 to 9 % escaped through the southern boundary under the different windage conditions. In this case, particles mostly escaped by end of spring and during summer.

4.1.3. Spatial FML accumulation

A large number of particles from Set 1 continued floating in the BoB at the end of the simulations. However, particle from Set 2 were mainly transported by the wind towards the coast and finally beached (Fig. 6). The spatial distributions of modelled particles showed remarkable seasonality. Particles from Set 1 were more prone to remain in the sea surface in autumn and winter. Particles tended to accumulate towards the western Spanish coast (between 8°W 9°W) and on the eastern Spanish coast (between 2°W 4°W) throughout the spring. The eastern accumulation region gradually decreased in autumn though higher accumulation on the western coast was still present. Whether autumn and summer, accumulation both in the coastal area and sea surface scarced on the Spanish central zone (between 5°W 7°W). For Set 2, accumulation on the sea surface was almost non-existent. However, the strong influence of the windage on the coastal accumulation was clearly evidenced along the French shoreline, resulting in a larger particle concentration throughout the year comparing to the Spanish coastline. Autumn and winter fostered particle accumulation mainly in the French coastal areas from 44°N up to 47°N. However, during spring and summer particles also beached in the French southerly coast (between 43°N 44°N) and in the Basque coast (between 2°N 3°N). Isolated hotspots showed up on the eastern Spanish coast during this period.

4.1.4. FML concentrations in MPAs

MPAs over the continental shelf experienced higher concentration comparing to those sited over the abyssal plain (Fig. 7). The most frequent range of concentration for Set 1 and Set 2 was 1–50 particles/km^2. The mean particle concentration per MPA for Set 1 and Set 2 was 23.12 particles/km^2 and 28.29 particles/km^2, respectively. For Set 1, three of the five MPAs experiencing the highest mean particle concentration were located in France (*Île d'Yeu* - 216.77 particles/km^2, *Île de Groix* - 78.55 particles/km^2, and *Iroise* - 74.33 particles/km^2) and two in Spain (*Espacio Marino de la Ría de Mundaka* – 75.60 particles/km^2 and *Espacio marino de la Costa da Morte* - 48.82 particles/km^2); For Set 2, four of the five MPAs experiencing the highest mean particle concentration were located in France (*Estuaire de la Bidassoa et baie de Fontarabie* - 125.83 particles/km^2, *Île d'Yeu* - 124.65 particles/km^2, *Baie de Quiberon* - 117.70 particles/km^2, and *Île de Groix* - 93.81 particles/km^2) and one in Spain (*Espacio marino de la Ría de Mundaka-Cabo de Ogoño* - 101.40 particles/km^2). French and Spanish MPAs experienced higher concentration for both sets mainly by the end of summer and during autumn.

5. Discussion

Modelling approaches are crucial to accurately predict where marine litter will converge in the BoB, described as a regional hotspot of FML. Since information on the origins and the contribution of windage effect on FML circulation are not well known in the area, a better understanding of the relative importance of both parameters is needed. The results of this study provide initial insights of the influence of windage effect on simulated particles allocated as fishing related items and the estimation of their distribution patterns and concentrations in MPAs within the BoB.

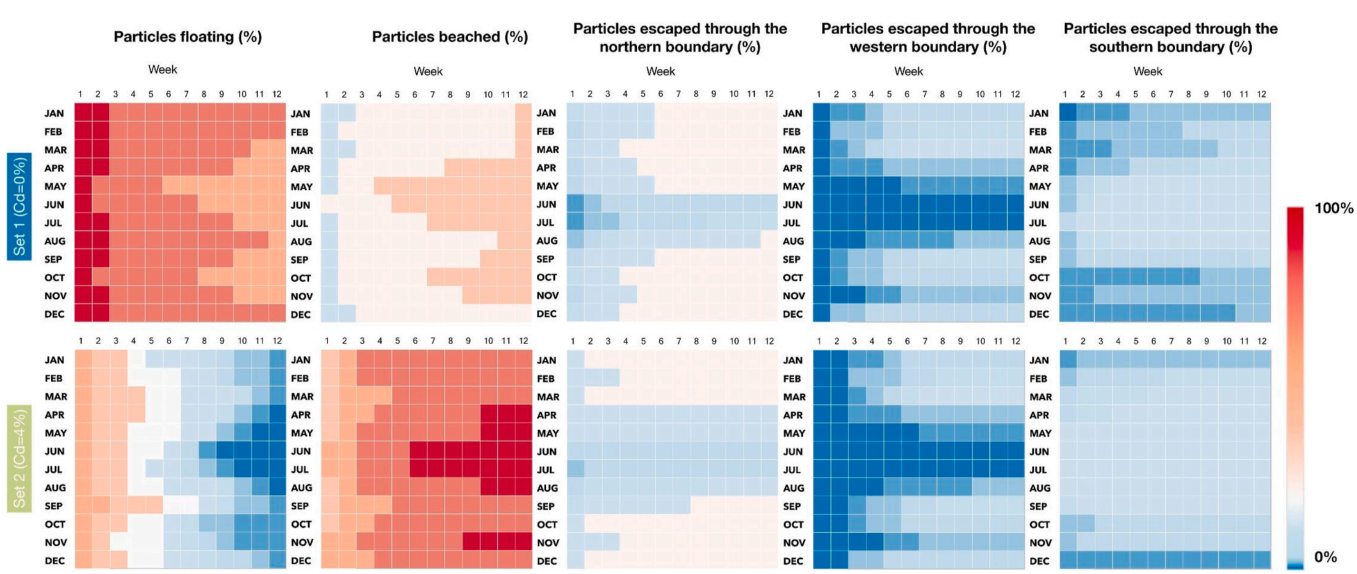

Fig. 5. Annual accumulation rate progress for Set 1 (figure above) and Set 2 (figure below) of floating, beached and escaped particles through the three open boundaries. The assessment of the accumulation rate was calculated every week during the simulation period (90 days).

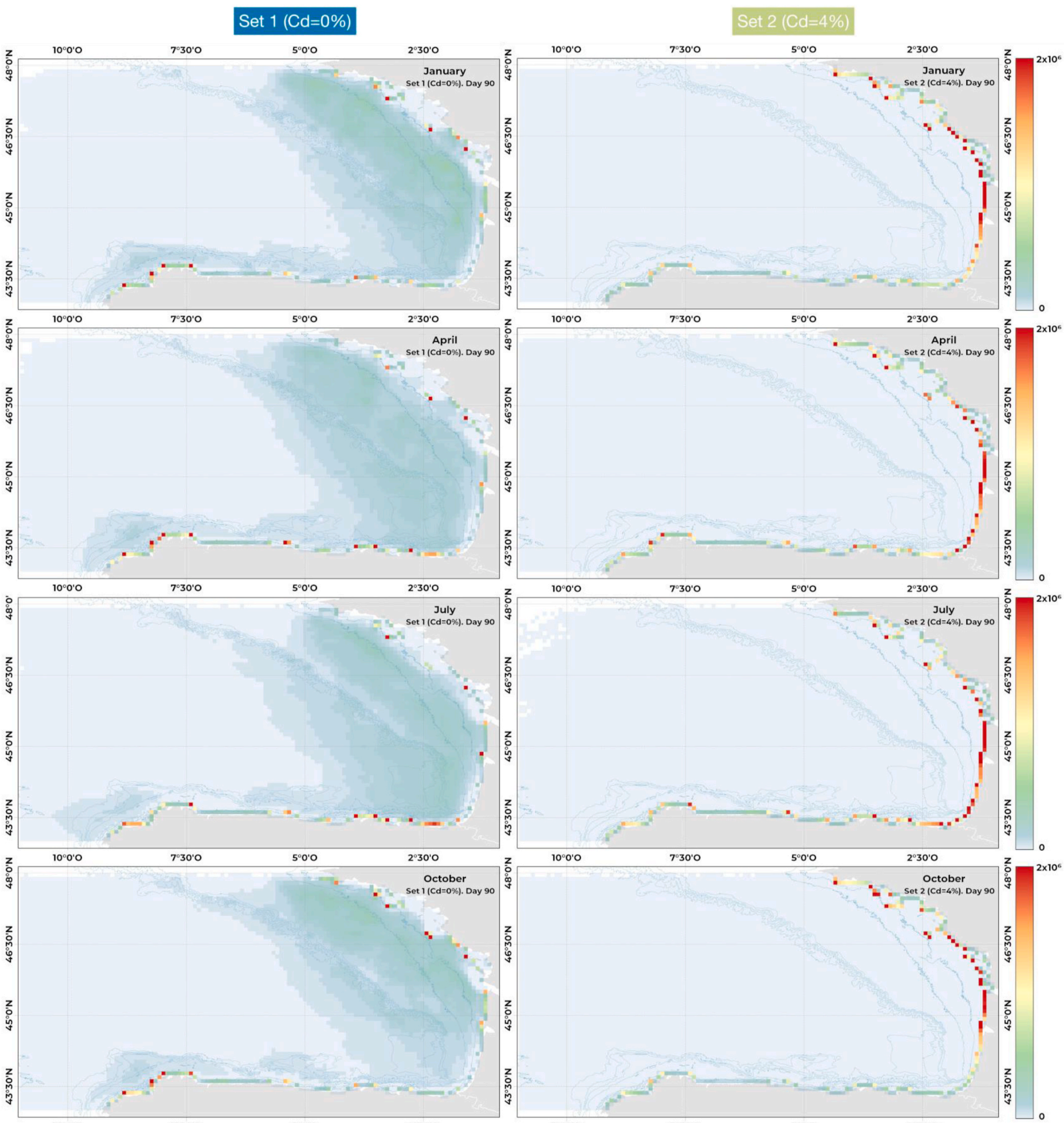

Fig. 6. Spatial particle accumulation for Set 1 (left) and Set 2 (right) after 90 days of simulation. The figures show the particle accumulation for the releasing initialized in January, April, July and October. Additional figures for the remaining months are available in Supplementary Figure S3 and Figure S4.

5.1. Assumptions on fishing sources

Contributions to measure the importance of sea-based sources in a given region, particularly fisheries, can be considered relevant since a growing number of studies link marine litter presence to areas of high fishing activity (Pham et al., 2014; Unger and Harrison, 2016; Richardson et al., 2019). This study combines fishing FML data from surveys with modelling approaches to explore for the first time the behaviour of fishing-related items within the BoB. However, there are two assumptions in the allocation of fishing sources that are important to consider. First, the existing data concerning the origin of FML are not evenly collected throughout the BoB. FML samples derive from litter windrows located in the south-eastern BoB (Ruiz et al., 2020). Sampling elsewhere is substantially more sparse and mainly limited to visual observations. Second, sampling activities in the litter windrows have limited temporal coverage. This hampers the interpretation of temporal trends in abundance and origins of fishing FML affected as well by seasonal changes in currents, winds, wave action, etc. Still, these data represent a potentially valuable information on fishing-related FML origins not available from any other source.

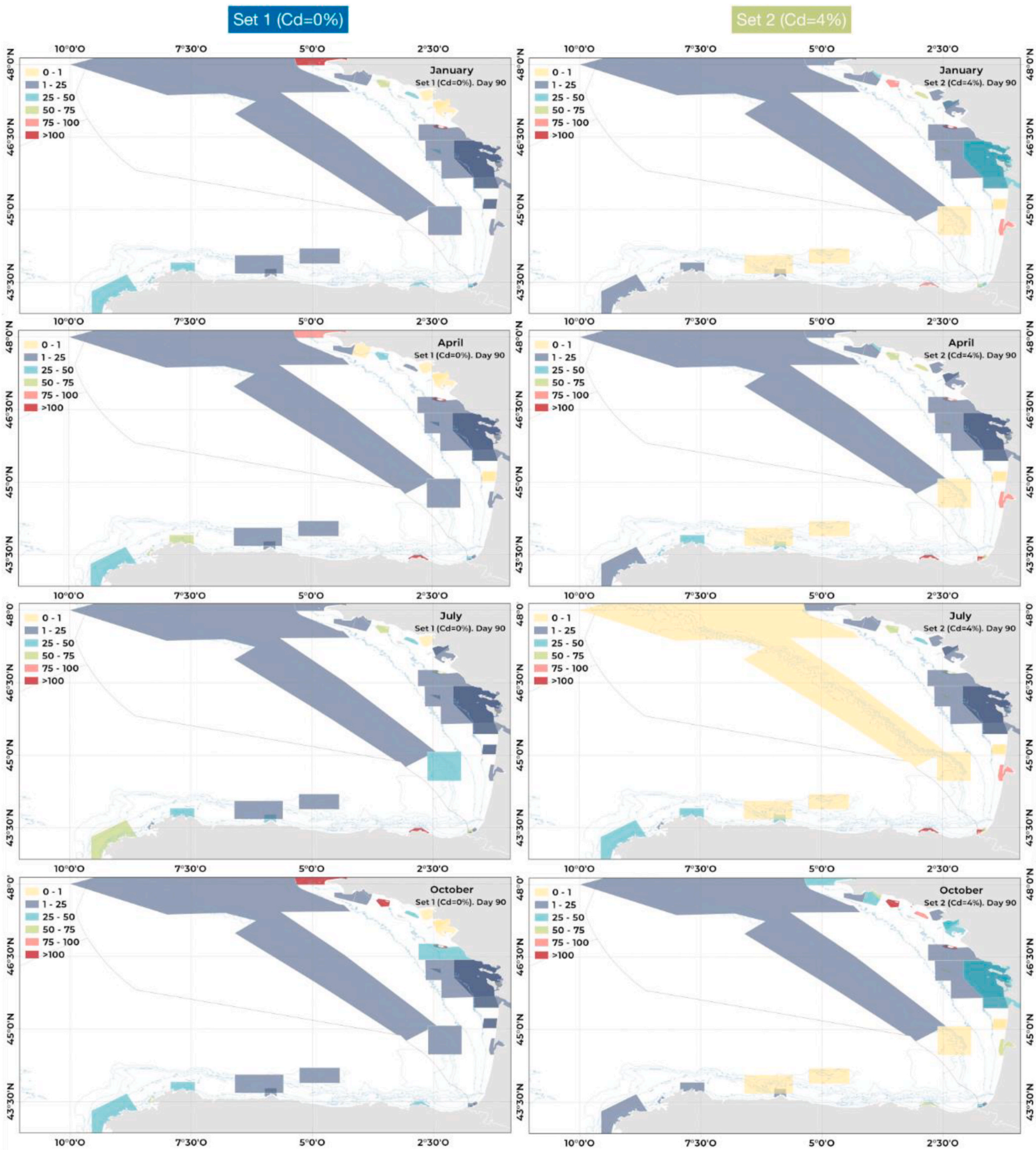

Fig. 7. Concentration within the MPAs for set 1 (left) and Set 2 (right) after 90 days of simulation. Concentrations in the MPAs (n/km2) were quantified as the ratio between particle accumulation by the end of the simulation and the MPA surface area. The figures show the particle concentrations for the releasing initialized in January, April, July and October. Additional figures for the remaining months are available in Supplementary Figure S5 and Figure S6.

5.2. Windage parametrization and FML distribution

This study allowed for distribution of low (Set 1) and high windage parametrized simulations (Set 2) to be compared. Results are consistent with previous studies documented in literature, which highlight the significant impact of windage effect on FML transport and accumulation (Breivik et al., 2011; Maximenko et al., 2018; Ko et al., 2020). Simulations underlined an asymptotic behaviour of particle accumulation over the integration time, regardless the windage coefficient (Fig. 5). At basin scale, a similar accumulation has been described for the Mediterranean Sea (Zambianchi et al., 2017). The mean rate of particles beached is far greater and occur faster for Set 2, particularly in summer (Figs. 5–6). During this period, winds tend to have a marked north/north-eastward component resulting in strongly beaching for the

French coast. Large surface accumulation rates are observed during winter for Set 2 (Fig. 6). Furthermore, particles are more likely to remain floating and accumulate in the French shelf instead of becoming beached or escaped. In winter, currents induced by IPC may result in stronger particle transport and accumulation from the Spanish towards to the French shelf (Fig. 7). Conversely, the circulation becomes weaker and equatorward from April to September. This flow can favour a higher retention mainly in the south-eastern continental shelf of the BoB, in line with results already described in the literature (Declerck et al., 2019; Pereiro et al., 2019). Results also showed that particles barely escape from the BoB and the direct effect of wind does not play a major role in this process. This agrees well with recently studies which stated that the BoB acts as trapping zone for FML, particularly for meso (5–25 mm) and macro (25–1000 mm) litter items (Rodríguez-Díaz et al., 2020). Particles mainly scape throughout the northern boundary mainly due to the effect of surface currents. During summer, the prevalence of north-westerlies winds may result in low number of escaped particles, particularly for particles from Set 2 (Figs. 5 and 6).

5.3. Model limitations

In addition to the assumptions concerning the temporal and spatial coverage of fishing sources, numerical simulations require simplifications of processes that influence their accuracy (van Sebille et al., 2018). In this study, once particles beached, it is assumed that it is its final destination. However, the state of particles at the shoreline can vary between beached and re-floated episodes. Particle experiences different behaviour depending on complex physical processes but how they contribute to the final particle state is still unknown (Hardesty et al., 2016; Carlson et al., 2017; Utenhove, 2019). Furthermore, few studies on the coastal contribution to marine litter fragmentation and sinking have been carried out so far. Therefore, no interaction between the surface and seabed within the shoreline have been considered. Wind-induced mixing of water can distribute FML from the surface along the water column. This vertical mixing has been addressed in previously studies focus on microplastic distribution (Kukulka et al., 2012; Kooi et al., 2016; YanfangLi et al., 2020). Vertical mixing is not included in this study since the application of the model is limited to macro litter items with strong buoyancy.

Based on previous studies that show the relevance of the wind drift and surface currents in the transport of floating objects in the study site (Abascal et al., 2009), waves were omitted as forcing of the numerical model. Usually, wind and waves effects are considered together and represented by the windage coefficient (Abascal et al., 2009; Pereiro et al., 2018). However, this approach remains appropriate only while the waves are directly related and propagate in the same direction as the local wind. Therefore, more research would be required to incorporate the wave-induced Stokes drift into the numerical model and to consider the effect of the swell on FML transport.

Despite waves can induce the transport close to shore and play an important role in coastal areas and especially in beaches, including dynamics due to waves and the high-resolution process nearshore are beyond the scope of this paper.

5.4. Implications for MPAs management

The recently adopted EU Biodiversity Strategy sets the goal to improve and expand the coverage of European MPAs from 10 % to 30 % for 2030 (EEA, 2018; Agnesi et al., 2020). Such political commitments require well-managed MPAs to avoid the impact of marine pollution. Monitoring tools and numerical approaches become crucial to determine the environmental status of the MPAs and to design effective measures to reduce litter input. In this study, concentrations obtained both for Set 1 (mean 23.1 particles/km^2 - max 125.8 particles/km^2) and Set 2 (mean 28.3 particles/km^2 - max 270.81 particles/km^2) showed lower values compared with previous data reported from Mediterranean MPAs. Average abundance from seasonal surveys performed by (Ruiz-Orejón et al., 2019) in *Menorca Channel* MPA (Balearic Islands) ranged from 373 items/km^2 to 1315 items/km^2 throughout the year. Though, these results account for the entire fraction of marine litter sampled and they are not limited exclusively to fishing-related items.

Likewise, French MPAs located in the continental shelf of the BoB experienced higher FML concentrations despite windage conditions. Vessel-based activities and a high proportion of the MPAs documented in this study are located in the same geographical area, mainly in the continental shelf. Since particles have been allocated based on the fishing effort, the proximity of the release locations to the MPAs may influence the final FML destination and concentration. If the release take place offshore and far from the continental shelf, the transport and distribution occur more gradually, mainly for Set 1. This scenario gives a larger time window to stakeholders to act. However, the proximity to the release locations constitutes a threat to the MPAs, particularly for French ones, as it reduces the response time to critical pollution events.

The evidence of harm from marine litter to biota has been collected over the past years, underlying the negative impacts on marine organisms and habitats conservation. Entanglement, ingestion, the transport of microplastic or invasive species are major examples of the adverse consequences of marine litter exposure. The mobility of FML under the influence of currents and wind and, particularly, of highly buoyant items poses an elevated risk, especially for French MPAs, undermining ecosystem services provided by the MPAs and, consequently, bringing losses to economic French and Spanish sectors such tourism, fisheries and aquaculture.

Research conducted so far to assess the influence of MPAs in the society have highlighted their positive effects on human well-being (Rasheed, 2020; Garcia Rodrigues et al., 2021). Since MPAs outcomes are positive for the relationship between humans and the environment, stakeholders in the BoB should explore integrating study results on marine litter abundance and distribution to foster comprehensive measures and enhance the governability for a maximum well-being impact.

Regional and local management actions to address sea-based pollution are necessary to tackle the problem at source. A dedicated database to identify which derelict fishing gears are predominant in the study area coupled with interviews of fishers can help improve fishery management scheme and regulation. Assist in the selection of an appropriate disposal site or provide tools for fishers to underpin monitoring and/or control of their gear(s) increase the opportunity of the fishing sector to intervene on the prevention of gear loss and cut down fishing and shipping related litter presence in MPAs.

Recent transboundary initiatives implemented in the area such LIFE LEMA project (https://www.lifelema.eu/en/) or the innovative FML-TRACK service (https://fmltrack.rivagesprotech.fr/) acknowledge the need to extend solution-oriented tools to tackle FML in the BoB, ensuring in this way a more effective MPAs conservation. It has emerged clearly the importance of modelling to improve capabilities to prevent and remove FML underpinned by the availability of open and quality assured oceanographic products such as those provided by Copernicus Marine Environment Monitoring Service (CMEMS). Modelling assessments coupled with complementary videometry approaches, which monitor and estimate riverine litter quantities released into the coastal area, support decision-makers on FML management in the south-east of the BoB (LEMA, 2020; Delpey et al., 2021). Since the outcomes delivered by models and videometry provide near-real time FML abundances and predictions on transport and distribution of FML, they should be taken into consideration by the competent French and Spanish authorities for evaluating possible environmental consequences for MPAs in the case of intentional and unintentional marine litter releases.

5.5. Recommendations for future research

Research on marine litter behaviour in the BoB is still in its early stage. One of the greatest challenges is actually create new insights on

FML circulation from fishing-related activities to prevent and mitigate its impact at basin scale. To address the gaps in the current knowledge, more observations of actual fishing FML abundances are needed. Besides, there is still much work to be done on explaining what kind of objects are released within the BoB since litter trajectories can be significantly altered by the wind conditions. Improved parameterizations of windage coefficient are crucial to better understand the modelled FML pathways and destiny. Despite a significant proportion of marine litter in the BoB may be sourced from the fishing sector, commercial and recreational shipping activities also contribute to marine litter in the area. Hence, shipping routes need to be included in future studies to give a full picture of the influence sea-based sources occurring on the BoB. The validation of computed particle trajectories and concentrations remains challenging due to the lack of observed data. Thus, further collection of field data and investment in FML monitoring are recommended. Long term, large spatial scale, standard and harmonised data are required to assess the performance of the results. Particle movement and distribution are more chaotic in coastal waters. This would need further investigation from Lagrangian analysis of high-resolution current and wind data to accurately address beaching and re-floating of litter processes. Using Lagrangian approaches to resolve the hydrodynamic connectivity in the BoB can provide also valuable information on the origin and age of the water masses within the MPAs to appropriately deal with the potential sources of FML at basin scale (van Sebille and et al., 2018). Lastly, efforts have been made over the last few years to confer the protected status of MPA to European areas of high ecological value, therefore, consistent data from monitoring enable also reasonable policy decisions for medium- and long-term strategies especially to those MPAs significantly impacted by FML.

6. Conclusions

Fishing sources have been considered in this study to assess FML circulation within the BoB under different windage conditions. Simulations allowed for studying the distribution patterns and concentrations of low and highly buoyant fishing-related items. Results demonstrate that windage effect shapes FML behaviour in the BoB and confirm the need to be incorporated in modelling simulations to fully understand FML transport and fate. The behavioral differences over spatial and temporal scale underline the high variability in particle accumulation and provide seasonal information to decision-makers on the likely fate of FML. Particular attention should be paid to the French coastline since high exposure to FML accumulation is expected mainly during summer season especially for highly buoyant items. Results lends weight to the argument that the BoB is an accumulation region for FML and strengthens the need to comply with prevention measures at source, particularly for fishing activities. Preventive and behaviour-changing measures become important in addressing fishing FML generation and disposal due to the combination of the geographical proximity between the area where fishing vessels operate, the coastal area and the MPAs. For highly buoyant items, mitigating measures should be rapid implemented to fit the limited time for intervention between FML realising and coastal and MPA arrival. Further simulations with more windage parametrization and experimental research (i.e: drifters) is recommended to provide new insights on FML behaviour and to validate the modelled results. Besides, monitoring efforts are required to provide the necessary information to implement and to assess the efficiency of specific measures for tackle FML in the BoB.

Author statement

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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.envpol.2021.118216.

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