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Validation of a Lagrangian model for large-scale macroplastic tracer transport using mussel-peg in NW Spain (Ría de Arousa)

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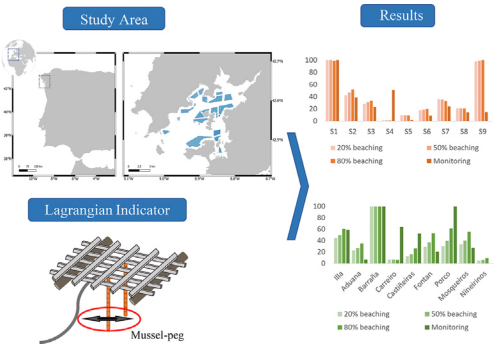
HIGHLIGHTS

- The study area orientation with respect to the intertidal movement plays a major role.
- Wind effect has a great influence on the distribution of marine debris accumulation on the Ria de Arousa.
- The beaching parametrization can represent different retention scenarios.

GRAPHICAL ABSTRACT



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ABSTRACT

Marine debris is a growing problem in recent years due to population growth around the world. The incorrect management of plastic waste causes these bodies reach the seas and oceans, becoming a worldwide problem. Once they reach the seas and oceans, they begin a long period of degradation, moving from a macro state (plastics whose diameter is greater than 0.5 cm) to a micro state (diameter less than 0.5 cm). The microplastics spread throughout the oceans, entering the food chain of marine species and, subsequently, of humans. Therefore, it is important to stop the problem while it remains at the macroscale. In this work, a validation of a recently developed Lagrangian computational model to track the movement of macro plastics in seas and oceans is presented. This validation is performed on a regional scale, in the Ría de Arousa, one of the most important estuaries for mussel cultivation in northwestern Spain. During mussel cultivation in rafts, a type of floating plastic stick are released, the mussel-pegs. The potential of this study is that we can compare the accumulation results of the model with the accumulation data collected on the Galician beaches. In a general framework, the influence of wind on the spatial distribution of the accumulations given by the model was observed. For the monitoring data, similar results were found for the accumulation trends over the entire total period. For the monthly representation, some discrepancies were observed. These differences can be attributed to particular synoptic situations, poor reproduction of the coastline or to the very orientation of the study area with respect to the intertidal dynamics.

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1. Introduction

Concern about marine litter has increased in recent decades (Rangel-Buitrago et al., 2020). This is particularly true for plastics (also referred to as plastic bodies or plastic debris), which are the majority of litter consisting of objects that have been manufactured or used by people before being dumped in rivers, seas and beaches (Williams and Rangel-Buitrago, 2019). These plastic bodies represent a huge problem for our oceans and coasts (Amelia et al., 2021; Krause et al., 2020), having a great impact not only on the environment, but also on the human and marine wildlife health (Karbalaei et al., 2018). As they can remain floating in the ocean for years, these plastics are broken down into small fragments by various agents (wind, salinity, solar radiation, temperature and mechanical stress due to currents and waves motion) as reported Min et al. (2020) and Wayman and Niemann (2021). It is possible to differentiate between macroplastics (whose diameter is greater than 0.5 cm) and microplastics (whose diameter is less than 0.5 cm). These small bodies enter the trophic chain of marine animals and then, humans. The effects over animal and human health are virtual unknown (Akdogan and Guven, 2019; Hwang et al., 2020). In addition, there are huge economic losses for marine-related sectors (Abalansa et al., 2020). The spatio-temporal monitoring of microplastics is difficult (Li et al., 2020; Carretero et al., 2022). Therefore, prevention is the first action required, focusing on the study of macroplastics in rivers and coasts in their initial state (Rangel-Buitrago et al., 2020).

Despite being one of the main pollutants in the ocean, the transport of marine plastics through ocean circulation remains poorly understood (Chassignet et al., 2021). Several factors can influence the understanding and description of the movement of this marine litter, as reported Van Sebille et al., 2020. Not only in terms of ocean properties such as temperature, salinity, or biodegradation (Cooper and Corcoran, 2012; Urbanek et al., 2018); but also depending on the characteristics of the plastic body (such as its weight, density and degradation). Studies have been done to detect microplastic acumulations by using satellite images. Davaasuren et al. (2018) uses SAR satelite information to detect these plastic patches over the oceans. Goddijn-Murphy and Williamson (2019) uses thermal infrared (TIR) sensing to try to control water pollution by plastics. They applied radiative transfer theory to estimate the surface fraction of water covered by plastic litter. Drifters tracking can also be useful to detect convergence zones depending on the oceanic dynamic (Maximenko et al., 2012). Another way to study the evolution of plastics is the detection on beaches. This type of study requires trained personnel as well as the determination of the type of plastic body to be studied. However, many inconsistencies can arise in this type of study, as the detection of plastic particles in sand may depend on multiple factors such as personal experience or visibility (Lavers et al., 2016). Moreover, in this kind of study the origin of the plastics collected on the beach is unknown. It is therefore critical to focus on the transport of macroplastics that move on the surface, before degrading and sinking. Actually, the most appropriate way to study the influence of plastics is the use of Lagrangian transport tools. Lagrangian methodologies are widely used in marine litter transport studies (Carlson et al., 2017). There are many studies using Lagrangian models in different parts of the world to track the movement of plastic in the ocean and sea (Chassignet et al., 2021; Politikos et al., 2020; Turrell, 2020; Khoirunnisa et al., 2020; Zambianchi et al., 2017; Sousa et al., 2021). These models are based on surface current models to define the movement of plastics, study their origin and their fate, since they can provide the position (x,y,z) at each time step. In this study, a Lagrangian model was considered to simulate the transport of the mussel-pegs along one of the most important estuaries of the Galician coast for the mussel farming industry.

Galicia has a coastline of 1195 km (as reported the Instituto Nacional de Estadistia, INE). Geographically, the Rías are one of the peculiarities of Galician coast (see Fig. 1). They are indentations in the coast where the sea flooded river valleys by lowering the land level (relative rise in sea level). These kind of estuaries are important for fishing, contributing to the fact that the Galician coast is one of the most important fishing and seafood areas in the world (Labarta et al., 2004). The estuaries are traditionally divided into Rías Altas and Rías Baixas, according to their position with respect to Finisterre as the most western cape of Galicia. In Galicia, the enormous importance of mollusc aquaculture, mainly mussels, makes it the most important economic activity in the community (Labarta et al., 2004; Labarta and Fernández-Reiriz, 2019). Mussels are cultivated in rafts (Fig. 2). These are floating nurseries consisting of a rectangular wooden structure to which the mussel ropes are attached. The wooden structures are attached to floating bodies that hold them on the surface of the sea, and also fixed to the seafloor by a chain (see Fig. 2). They are thus suspended cultures growing in the water column. The mussel spawn is wrapped around the rope with the help of a fine biodegradable rayon net, giving the mussel enough time to attach itself to the rope. After a few months, due to the considerable increase in weight of the mussels, it becomes necessary to divide the ropes, i.e. to make new ropes of lower mussel density. Then, every 30–40 cm of rope, wooden (in the past) or plastic (more common nowadays) sticks are placed between the strands of rope to prevent clusters of mussels from becoming detached as shown in Fig. 2 b. These mussel-pegs provide a better grip on the rope, prevent detachment and make it easier to fix the mussels. They are plastic pieces 225 mm long by 30 mm wide (see Fig. 2c). The work of stringing, unfolding and extracting the mussels means that the mussel-pegs, either whole or broken, are released and accidentally fall into the sea, becoming one of the most common types of marine litter in the Galician coast. Because the large extension of the crop, as well as the relevant quantity of these plastic sticks released into the water and their characteristics (they have a known origin, are easy to characterize and to count), they can be used as indicators of marine litter areas of accumulation. The study here presented is located in the Ría de Arousa as part of the Rías Baixas. This particular estuary is the most active indentation for the mussel production (Comeau et al., 2018).

Since there is no degradation of the mussel-peg from the time it is released until it reaches the coast, it can be considered as a macroplastic body. In addition, due to the collections of mussel peg on beaches, it is possible to know how this type of plastic accumulates along the coastline of the Arousa estuary. Therefore, the main objective of this study is to know whether a Lagrangian model can provide a good estimation on the accumulation of marine litter along the coastline in a small region with the dynamics of the Ría de Arousa. A similar study was carried by Declerck et al. (2019) and Carlson et al. (2017) by using drifter trajectories and floating macro debris respectively. In the present work, a new tool recently developed by the Instituto Superior Técnico de Lisboa and the University of Santiago de Compostela, the MOHID-Water Lagrangian model was used. The methodology of which is described in the Methods section. Although the Illa de Arousa is part of the Ría de Arousa, from here on we will refer to the Ría de Arousa as the inland coastal region, excluding the Illa de Arousa.

The objective of this study is to determine whether the mussel-peg is a good Lagrangian indicator. Then, could the methodology here be used to validate the recently developed MOHID-Lagrangian tool and to determine accretion zones? This study provides new insight for Lagrangian study in high resolution areas where the orientation and characterization of the study area plays an major role.

2. Methods

2.1. Study area

The Ría de Arousa (Fig. 1b) is located at the northwest coast of the Iberian Peninsula (Fig. 1a), being part of the Rías Baixas of the Galician coast. It is the largest estuary on the south Galician coast, with a surface area of 230 km^2 approximately. It can be subdivided into two zones: the inner zone (98 km^2), more exposed to fluvial processes, shallower and more isolated habitats, and the outer zone (132 km^2), with greater interaction with oceanic processes (Otto, 1975; Rosón et al., 1995; Álvarez-Salgado et al., 1996), deeper and more exposed habitats (Outeiro et al., 2018). The average sea level oscillation is around 2.5 m, making it a meso-tidal estuary

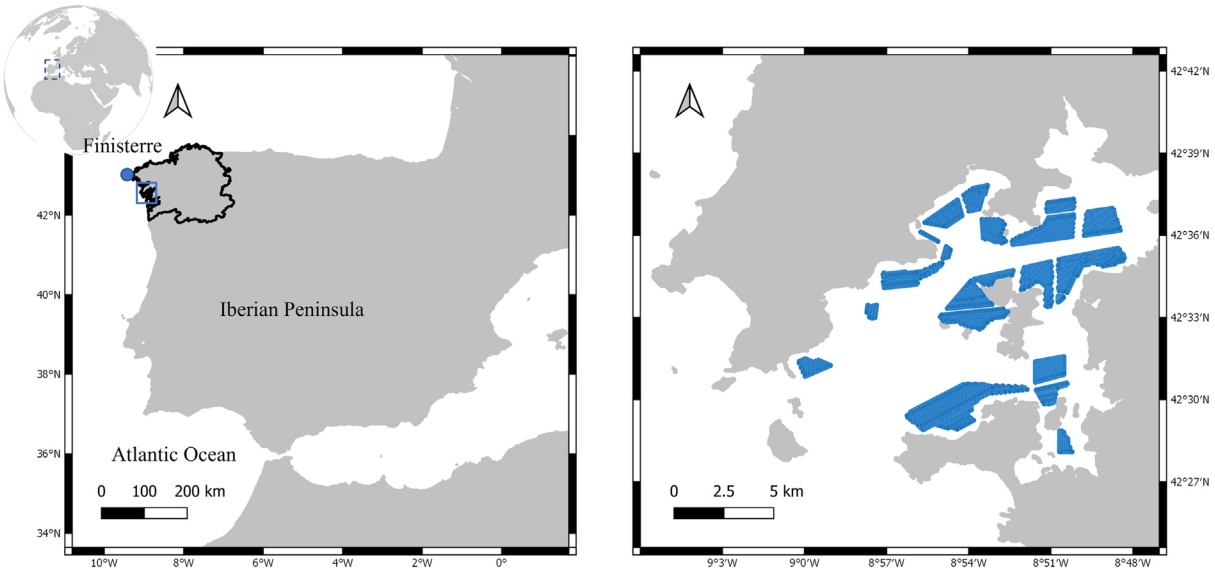

Fig. 1. Maps showing the Galician coast (solid black line on the left map) and the Ría de Arousa (blue square on the left map); and the spatial distribution of the mussel rafts (blue dots on the right map).

(between 2 and 4 m tidal range). The average wave height ranges between 1 and 2.5 m for the spring and summer seasons, while for the autumn and winter months, this value oscillates between 3 and 5 m (Conselleria de Medio Ambiente, 2010). These variations in sea level height give rise to cyclical movements of incoming and outgoing water, called tidal currents, which can be of great intensity.

The Ría de Arousa as a partially mixed estuary (Rosón et al., 1995; Dyer, 1973) and average the currents over several tidal cycles because the residual circulation obtained is positive in two layers: an inflow current of salt water through the bottom from the ocean and an outflow current of brackish water through the surface. In the Ría de Arousa there are also several sources of stratification: freshwater inputs, heat flow through the atmosphere-ria interface and water exchanges between the shelf and the estuary. All of these give rise to longitudinal density gradients, which act as drivers of the positive circulation described above. Winds also have a great influence on the variability of the residual circulation both on the shelf and in the estuary, which can lead to three different scenarios: (i) reinforced positive circulation when winds from the north dominate, (ii) a situation of relaxation in transition periods with a very slow positive circulation maintained for days, and (iii) an inverse or negative circulation favored by winds from the south. In addition, depending on its bathymetry, the Galician coast can be characterized in different ways. Although it is possible to distinguish between 11 types of pure typologies, the enormous variety on the Galician coast and the changing hydrodynamic conditions give rise to the appearance of an extensive series of intermediate typologies. In particular, the beaches of the Ría de Arousa are small, of great typological variety, and numerous due to the intense fracturing of the terrain (Conselleria de Medio Ambiente, 2010). In particular, this estuary is dominated by shelf beaches, which means that there are rocky intertidal zones that influence the dynamics. Computationally, depending on the grid mesh, rocky areas may not be represented so Lagrangian particles move freely without beaching, or at least be delayed by the presence of obstacles. Fig. 3 shows the navigation charts of the study areas. As it can be seen, most of them have rocky intertidal zones just in front of the collection area, but for Barraña and Aduana regions. For the case of Porco beach (Fig. 3 e.vi) the collection area is located on the left side of the buffer, in front of the Puntal de las Sinas. Computationally, this effect can only be parameterized in the MOHID-Lagrangian by the beaching factor and the beaching level.

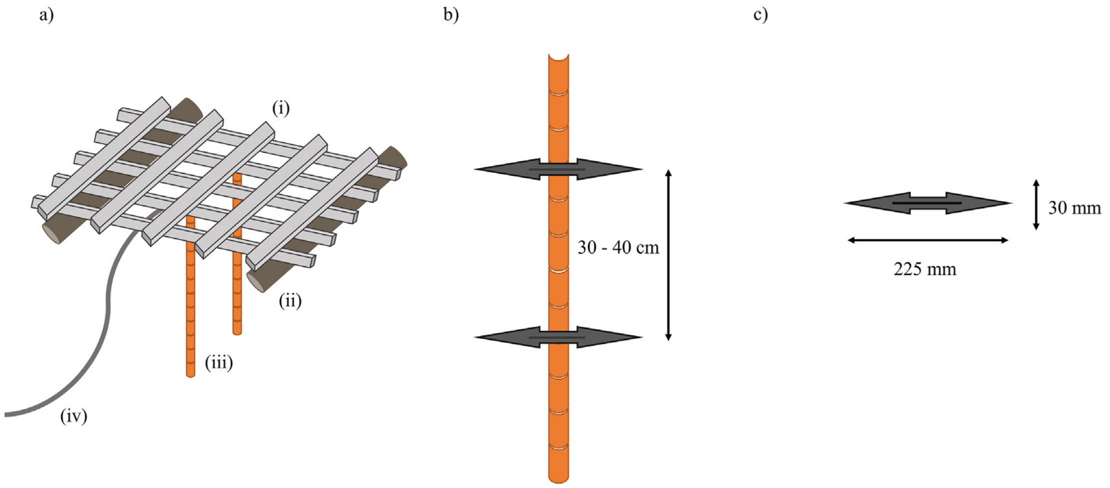

Fig. 2. Schematic of a mussel cultivation raft. (a) Shows the main components of the pan: (i) wooden structure, (ii) floats, (iii) cultivation ropes and (iv) anchoring. (b) Shows the arrangement of the mussel-peg on the rope and (c) the dimensions of the mussel-peg.

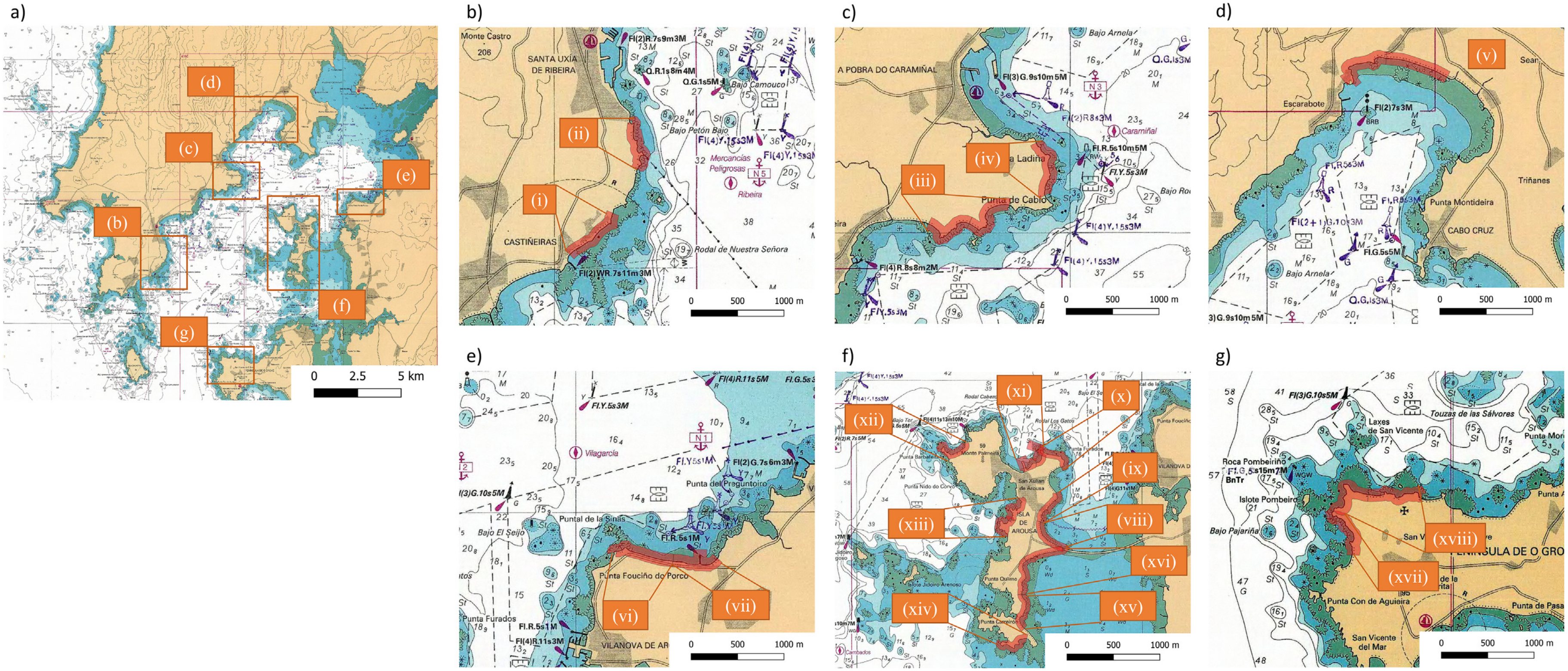

Fig. 3. Navigation charts of the Ría de Arousa (a). Going from south to north and from west to east in each image, the shaded areas correspond to: (b.i) Mosqueiros, (b.ii) Fontán, (c.iii) Illa, (c.iv) Nineiriños, (d.v) Barraña, (e.vi) Porco, (e.vii) Aduana, (f.viii) S1,(f.ix) S2, (f.x) S3, (f.xi) S4, (f.xii) S5, (f.xiii) S6, (f.xiv) S7, (f.xv) S8, (f.xvi) S9, (g.xvii) Castiñeiras and (g.xviii) Carreiro.

2.2. Input data. Hydrodynamic model

The MOHID-Lagrangian model (www.mohid.com) was employed, a recent Lagrangian tool developed for the dynamic study of marine transport. In particular, it was used it to track forward in time the transport of marine debris in the oceans and to estimate its accumulation along the coast. It is a complete high-resolution Lagrangian tracking model that can function as a library for the MOHID Water modelling system or as a stand-alone program. Working independently, our Lagrangian model will be forced with the current values obtained using the MOHID-Water 3D hydrodynamic model (Martins et al., 2001) to reproduce the current, salinity and temperature in the RV. This operational system is daily executed by MeteoGalicia (www.meteogalicia.gal) to obtain the advective contribution. The output results has a 300 m of horizontal resolution and the vertical discretization consists by two domains with an interface at 8.68 m. While the upper domain is composed by 11 sigma layers, having a high resolution in the top layer accounting for the wind influence, the bottom domain has 16 z-level layers. The WRF model (Weather Research and Forecasting Model) provides the surface boundary condition, applied to the Rías Baixas area with 1.3 km horizontal resolution. A detailed examination of this model operated by MeteoGalicia can be found in Huhn et al. (2012) and Venâncio et al. (2019). Furthermore, the model also contains the Verdugo-Oitabén rivers discharges through the SWAT model. Besides, ROMS coastal model is also used as boundary conditions.

2.3. Lagrangian model

To track particles, MOHID-Lagrangian module uses the concept of tracer, whose position (x,y,z) is well-known at each time step. The movement of the tracers depends on the velocity from the hydrodynamic module, the wind from the surface module and the random velocity from the waves action. The velocity field is interpolated from the hydrodynamic eulerian velocity field to obtain a new grid with a resolution set by the user. To calculate the position of the particle, this velocity field and a diffusive term are integrated as:

$$\frac{dx_i}{dt} = v_i(x_i(t), t) + D_i \tag{1}$$

where v_i is the velocity field at a t instant and x_i position, and D_i is the diffusion velocity, calculated as de Pablo et al. (n.d.) described. The strength of this module lies in the parameterization of beaching. It is possible to give a threshold depth value above which the particle is stranded in the sand, as well as a probability that the particles will be stranded. These two arguments can account for different scenarios in which accumulation can occur. Another robustness of this model is that it can be separated the accumulations on the coast according to the emission sources. This means that the influence of each emission source can be separately evaluated.

In this study, three different scenarios were considered (see Table 1 in the Supplementary material). First, the effect of accumulation along the entire coast is calculated for a time period of 1.5 years (from October 1, 2018 to April 1, 2020). Within this period, three different wind orientation situations were selected. For each, percentiles P25, P50, P75 and P95 were calculated with respect to the maximum accumulation of all segments. This makes it possible to distinguish between high and low accumulation zones and to show the spatial distribution of marine litter within the Ría de Arousa. The second scenario takes place in the Illa de Arousa from October 1, 2018 to June 1, 2019; and the third scenario, from October 1, 2020 to April 1, 2021, takes place along the north of the Ría de Arousa shore. These two last time periods have been chosen according to the two beach monitoring data here presented. To estimate the accumulation ratios along the coastal line, the shore of the Ría de Arousa is divided into 427 segments (see Fig. 4). These segments (also called buffers) have 1000 m length by 100 m of width each. These dimensions has been set to ensure the best reproduction of the coastline, since a lower resolution cannot ensure the correct definition along the coast. Because some study regions are composed of different beaches within one single shore segment, especially in the second case, the study regions were joined by segments, here referenced as S1, S2, S3, S5, S6, S7, S8 and S9 (see Fig. 3 f). In the third scenario, nine beaches were selected. A total of 18 study areas are available for comparison of simulated and experimentally collected data. Since the extent of the buffer may be larger than the extent of the shore where collections take place, the estimated accumulation will be greater than the actual accumulation. Therefore, the results obtained from the simulation are corrected using an area factor. This factor is calculated as the ratio of the monitored beach area to the computational buffer area.

The simulation domain cover from 9.15°W to 8.15°W and from 42.2°N to 42.6°N with a 200 m spatial resolution and 3 h temporal resolution. According to the mussel raft distribution, the emission points were established at the same location (see Fig. 1c). For the entire simulation period, Lagrangian particles are released from all emission points every hour. Mussel-pegs collected on the sampling beaches can come from other estuaries with shellfish activity. To consider this effect, two emission points were also considered at the northern and southern edges of the simulation domain. For each polygon, emission points are assumed every 140 m along the polygon geometry. In the case of external sources, we define a regular emission with an area of 9 km^2. Because the diversity of beaches in the Ría de Arousa, simulations have been carried out varying the probability of stranding. This is intended to simulate three possible retention scenarios. The 80% beaching factor reflects areas of high retention, 50% beaching factor reflects medium retention and 20% beaching factor reflects areas of low retention, mainly rocky ones. Then, trends were calculated using relative accumulation (%RA) for each beach. For each study area, the mean accumulation every 4 h is obtained. This is intended to smooth possible atypical effects due to particular synoptic weather conditions. For each time period considered, the total accumulation (A_{TOT}) and the maximum accumulation between the whole considered study areas (A_{MAX}) are obtained. The relative percentage for each region is obtained by dividing the accumulation of that area by the maximum accumulation as,

$$\%RA = \frac{A_{TOT}}{A_{MAX}} \tag{2}$$

2.4. Observational data. Beaches collection

The monitoring data presented here is part of one of the strategies of the CleanAtlantic project. This project aims to protect biodiversity and ecosystem services in the Atlantic Area by improving capacities for monitoring, prevention and removal of macro marine litter. The project also contributes to raising awareness and improving marine litter management systems. As part of this project, a study has been conducted to analyze different strategies for identifying marine debris accumulation areas that can be incorporated into monitoring, cleanup and collection protocols. One of the strategies tested was the use of mussel rafts as an indicator of plastic debris accumulation. These indicators, along with other measures and proxies, (i.e., oceanographic currents, socioeconomic data), can be used to detect the presence of marine litter in each habitat and spatial and temporal trends in accumulation (GESAMP).

Therefore, the sampling plan was designed with the intention to determine the main regions of litter accumulation along the island's coastline and whether there are any specific locations that stand out from the rest. The chosen beaches met the following requirements (1) to be formed by sand or gravel and exposed to the open sea, (2) to be accessible to the samplers throughout the year, as well as to facilitate the removal of marine litter, and (3) not to be subject to other litter removal activities. A weekly frequency was established, and data collection was always conducted one hour after high tide to avoid sampling being affected by the rising tide. At each collection, the number of mussel-pegs found, both whole and broken, was counted and removed from the beaches. The sampling of all selected beaches was carried out in two campaigns: A) Illa de Arousa: carried out between October 2018 and April 2019. The points located in A Illa de Arousa

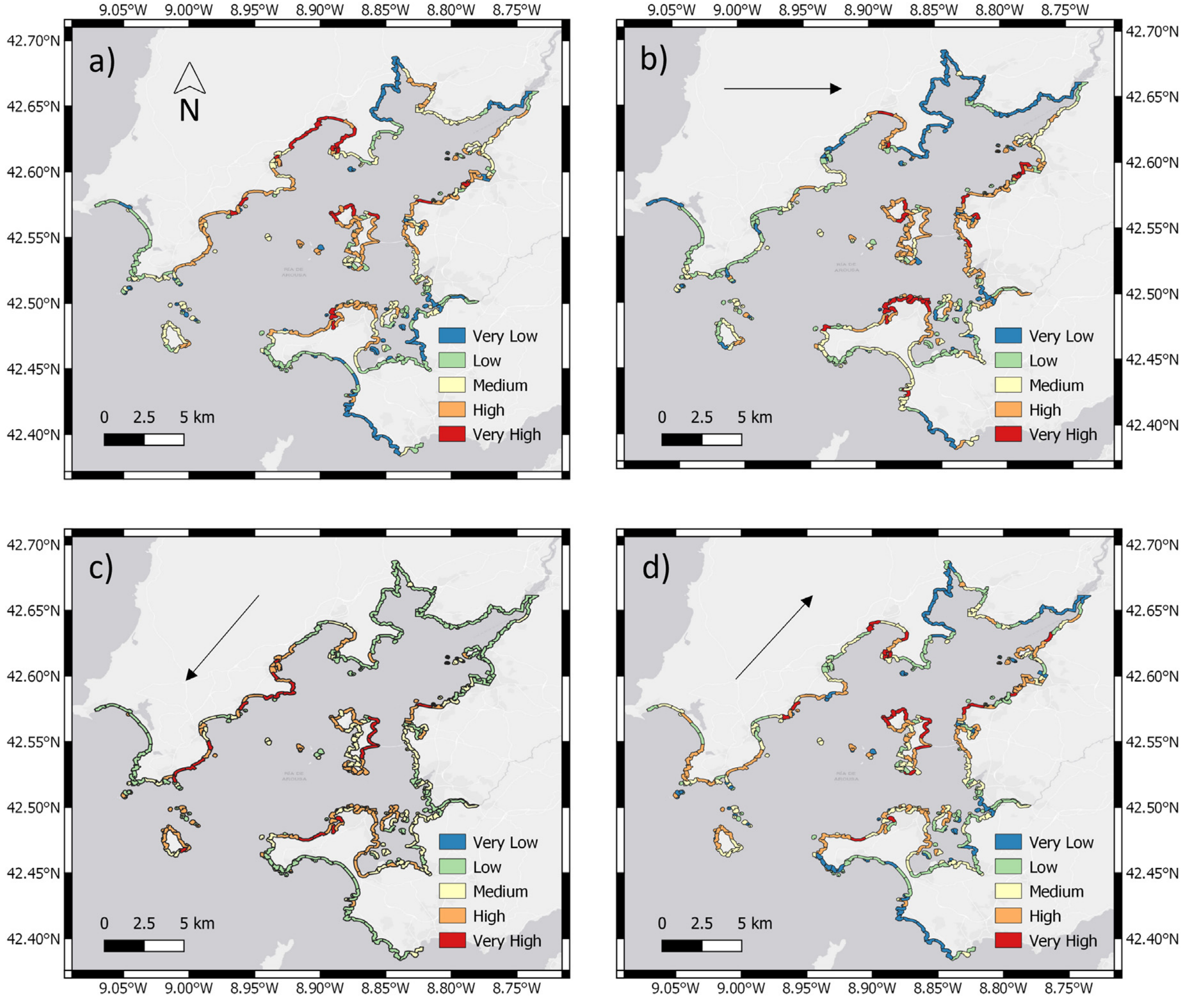

Fig. 4. Accumulation ratios in the Ría de Arousa along the 427 segments for a period of one and a half years (from 2018 October 1 to 2020 April 1) obtained from the computational model. The classification 'very low' corresponds to accumulation values below P25; 'low', between P25 and P50; 'medium', between P50 and P75; 'high', between P75 and P95; and 'very high', above P95. The black arrow shows the wind direction. a) Considers the whole time period, b) corresponds to an easterly wind on the 30th January 2019, c) corresponds to a southeasterly wind action on the 7th May 2019 and d) corresponds to a northwesterly wind action on the 10th January 2019.

were sampled as part of a citizen science project. B) Ría de Arousa: carried out between October 2020 and Mars 2021. The points located on the coast of this estuary were sampled by expert technicians in coastal sampling who usually carry out both sampling work on the selected beaches and advice to the shellfish sector as part of their daily duties.

3. Results and discussion

Fig. 4a shows the spatial distribution of accumulations for an emission period of one year and a half obtained from the computational model. Knowing the temporal distribution of accumulations for each coastal segment, the total accumulation was calculated. The P25, P50, P75 and P95 (25th, 50th, 75th, 95th percentiles) were used to establish the thresholds for very low, low, medium, high and very high accumulations. The areas with the lowest debris accumulation rate are the outermost, i.e., those most exposed to oceanic action. On the other hand, greater accumulations appear towards the inner part of the estuary. Given that the currents enter from the south, in a northeasterly direction, and drain towards the north in a northwesterly direction, the main accumulations appear in the coastal segments oriented towards the south and southeast, coinciding with this movement. This map (Fig. 4) shows two clearly defined accumulation zones. One in the northeast of the estuary and the other in the northwest of the central island (A Illa). Likewise, the entire intermediate inner region shows high accumulation values above P50. Turning now to the study of wind action, Fig. 4b corresponds to an easterly wind, Fig. 4c considers a southeasterly wind action and Fig. 4d considers a northwesterly wind action. These three situations demonstrate the significant influence of this agent. Thus, an easterly wind situation will cause a greater accumulation on the coastline with the same orientation. In the case of a predominantly northeasterly wind, the drainage of the estuary is favored. Therefore, the innermost zone registers a lower accumulation, while the outermost regions with the same orientation register higher accumulation values. For the last situation, a predominantly southwesterly wind favors the high accumulations on beaches with the same orientation and located in the interior region.

This effect is smoothed in the simulation results, since the average accumulation every 4 h has been calculated for the set of buffers; and then the temporal accumulation per buffer has been estimated. The results are presented in two perspectives: (1) for the whole simulation period and (2) separated by months.

3.1. Illa de Arousa

Comparing now the monitoring data with the simulated data, the results can be separated by segments. For the first time period (from the 2018 October 1 to 2019 May 1), Fig. 5 shows the results for nine different coastal line segments. It is important to note that the comparison refers to trends, not to net data, i.e. both data series (simulated and observational) have

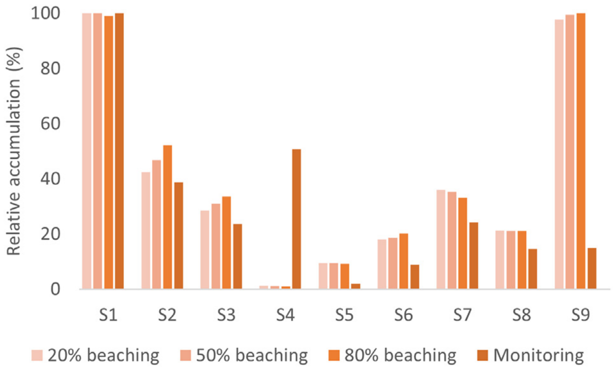

Fig. 5. Comparison of trends in the accumulation of mussel-pegs for different shore segments in the Illa de Arousa from October 2018 to April 2019. Simulations have been performed for different beaching values: 20% (light orange), 50% (medium orange) and 80% (dark orange). The monitoring data are shown in brown.

been normalized according to the maximum found in each study region. In all of them the stranding factor has been varied to see which one estimated a better accumulation. As can be seen, in the cases where it differs, the 20% stranding factor fits better. Since the Illa de Arousa area is a mostly rocky area (see Fig. 3f) it is highly unlikely that mussel-pegs reach sand areas. However, it can be stated that the computational model is able to reproduce the general trend of accumulation in the studied areas, with the exception of S4. In this case, the buffer used for the accumulation count does not reliably reproduce the shoreline. Because the spatial resolution of the buffers along the coastal line, there are cases where the shore profile is not well enough replicated. In the case of S4, the buffer orientation is slightly different from the actual orientation of the monitored beach. This orientation causes the simulated circulation to barely reach this region, so that a smaller number of particles are always found. Finally, it was calculated the relative contribution of the two external emission sources. In this case, only 3% of the particles that have reached the coast come from external sources. This makes sense, since these sources will affect the outermost regions, which are the most influenced by oceanic action. So it makes sense that only a small fraction of the particles emitted by these sources will be stranded on the coast.

Fig. 6 shows the monthly comparison between simulated and monitoring data. This higher temporal resolution shows more discrepancies than in the previous representation. Here it is important to identify the causes that can produce disparity between simulated and monitoring results. The first and most important is the relationship between the study area orientation and the intertidal motion. The more the beach is oriented towards the tidal movement, the larger the number of computationally accumulated particles is. However, the bathymetry of the region can lead to accumulation values below the computational estimation. Since the rocky regions near the coast may act as low retention factors, the monitoring data on the beach may be lower than expected. In the case of the Illa, this is what happens in S2, S3, S5, S6. All these regions are heavily affected by intertidal motion. This means that the greater the number of particles passing through an intermediate zone, the greater the accumulation recorded in that zone, since 80% of the particles present are stranded on the sand (in the case of setting the stranding at 80%). This fact is clearly more accentuated in S7 and S9 due to the fact that their southern orientation results in a higher number of particles being received in both regions during rising tides. Fig. 3f shows that all areas of the island have rocky intertidal zones that will have an effect on the monitoring data at the beaches, as this value is usually lower than that estimated by the model. In cases where the collection value is higher, it may be due to a particular synoptic situation on the particular collection day. Being the westernmost area of the Iberian Peninsula, Galicia, and in particular the west coast, often suffers from various atmospheric phenomena coming from the North Atlantic. Specifically, in the month of October 2018, two hurricane events reached the coast of Galicia, leading to an anomalous synoptic situation. The month of November 2018 was characterized by the appearance of a great storm, causing atypical wind situations. Finally, the month of December 2018 was characterized by high altitude squalls during the first 20 days of the month. All these synoptic situation can affect the monitoring data. The case of S4, as mentioned above, presents a representation problem, since the orientation of the buffer representation means that hardly any particles reach this area. Finally, S1 and S8 are the best estimated regions during the whole period. Respecting to the beaching parameterization, in this particular study, no differences were observed.

3.2. *Ría de Arousa*

For the Ría de Arousa, the same trends as in the previous subsection were calculated. For the accumulation over the entire simulation period, similar results are found in the trend of the simulated data with reference to the sampled data (see Fig. 7). Barraña beach reaches the maximum accumulation value both in the simulation and in the beach collections, while the minimum value is estimated for Nineiriños by using both methodologies. For this beach, the monitored data show a concentration of 0.31% with respect to the total litter collected on all beaches sampled. It is possible to find a clear disparity between simulation and observation for Carreiro beach. In particular, this beach is located in a highly exposed area of the estuary to oceanic action. In addition, its position makes it possible that the accumulations observed on the beach come from points outside the estuary, particularly from the mussel cultivation areas of Ría de Pontevedra. Although this fact has been tried to overcome this fact with two external emission sources, the percentage of particles reaching the coast from external sources is only 3%. Here, the behavior of beaching for the last study regions is similar to the previous case. The highest values of relative accumulation occur for a beaching value of 80% while the lowest values are recorded for a beaching of 20%.

The importance of beach orientation in relation with the intertidal motion is observed in Fig. 8 for the monthly accumulation. This is the case for the Illa and Fontán beaches. The values estimated by the model are higher than those collected on beaches because the intertidal movement makes it difficult for mussel-pegs to accumulate on these beaches. Oceanic influence must also be taken into account. As in the previous case, in the regions more exposed to oceanic circulation the model will present a lower accumulation value. Computationally, for the Carreiro and Castiñeiras regions this behavior is found. However, in the case of Carreiro, high accumulation values are recorded in the beach collections. This is due to the fact that, despite being in one of the outermost areas of the Ría, its orientation does not favor the estuary dynamics to clean this area. Moreover, being a rocky area, the dynamics in this region will be slower in reality. This is not the case for the model. In the case of Castiñeiras, its orientation makes the oceanic action have a greater effect, so the accumulation values are low in both methods. Moreover, it may happen, as in the case of Aduana, that anthropogenic constructions such as a dyke are not included in the coastal management plans, so they are also not taken into account in simulations of this type. However, in reality, these types of constructions have an effect that is reflected in the monitoring data. Therefore, the Lagrangian model on this beach always reports larger values than those actually found in the collected ones. Finally, for identations that do not present any of these factors, as it is the case of Barraña and Porco, the monitoring data on the beach can be well reproduced computationally. During this study period, the months of January and February were characterized by the occurrence of storms that affected the region. In these two months, Galicia suffered from four different strong squalls. In our comparison, both months stand out for having disparities between simulated data and monitoring data. With respect to beaching, it can be concluded that no significant differences can be seen in most cases. However, in those cases in which the circulation favors the appearance of a greater number

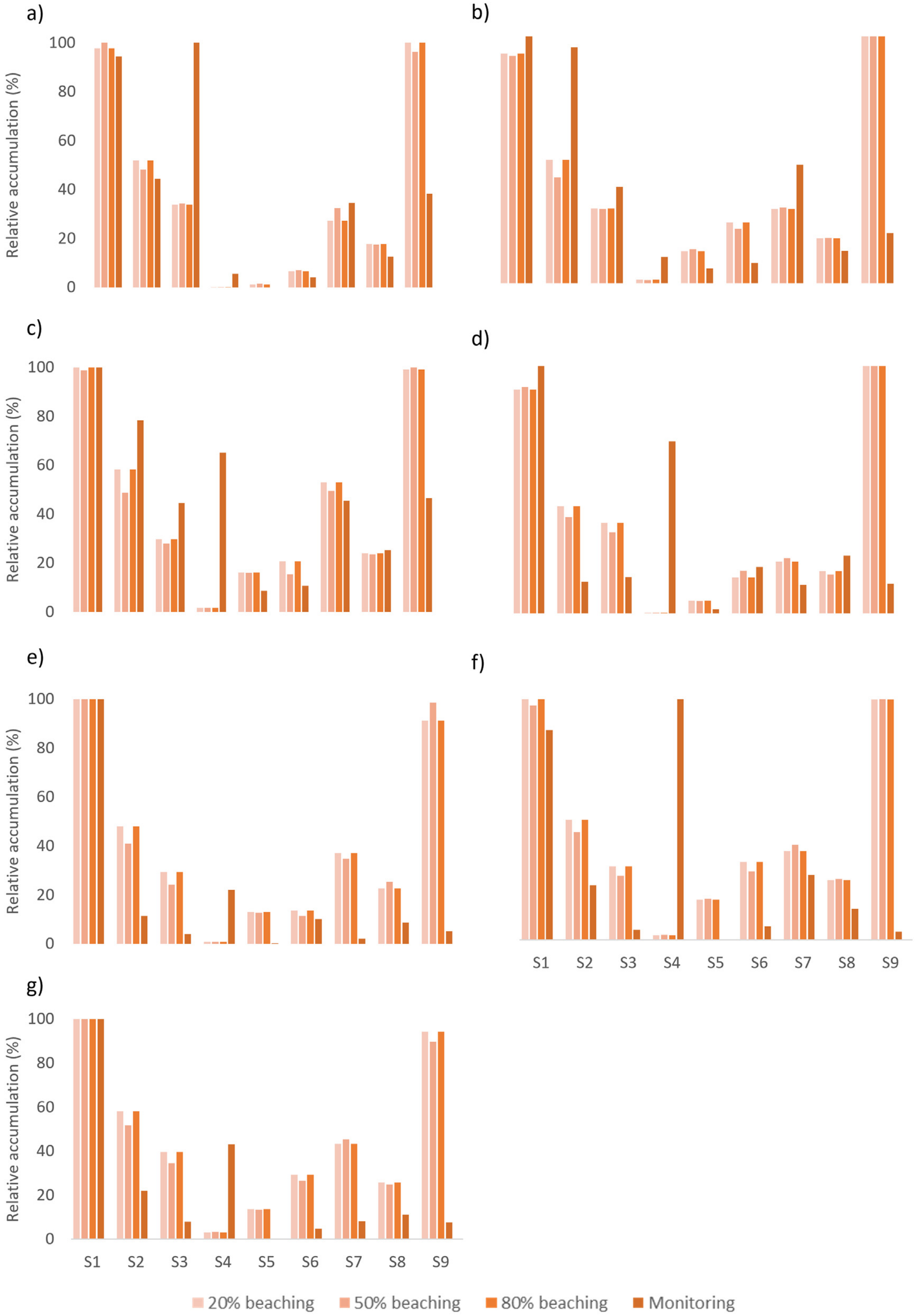

Fig. 6. Comparison of trends in the accumulation of mussel-pegs for different shore segments in the Illa de Arousa for a monthly representation from October 2018 to April 2019. a) October 2018, b) November 2018, c) December 2018, d) January 2019, e) February 2019, f) Mars 2019, g) April 2019. Simulations have been performed for different beaching values: 20% (light orange), 50% (medium orange) and 80% (dark orange). The monitoring data are shown in brown.

of particles over a given study region, the percentage established must be taken into account, since the higher the percentage, the greater the disparity between results with different beaching may appear, as in the case of Porco beach in the months of October and March.

These results indicate the MOHID-Lagrangian model is able to estimate reasonably well the accumulation of sticks both on the Illa de Arousa and on the Ría de Arousa. There are particular cases, such as some synoptic situations, which cause disparities between the model results and the

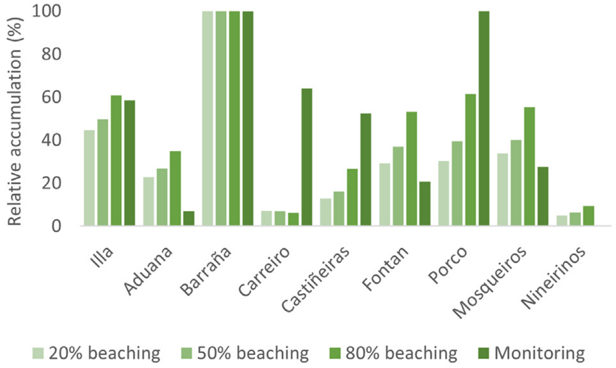

Fig. 7. Six month comparison of trends in the accumulation of mussel-pegs for different shore segments in the Ría de Arousa, from October 2020 to March 2021. Simulations have been performed for different beaching values: 20% (light green), 50% (medium green) and 80% (dark green). The monitoring data are presented in darkest green.

monitoring data collected on the beach. Another source of disparity is the bathymetry of the accumulation zones, where a high resolution model should be implemented.

4. Conclusions

The growth of plastic inputs into the seas and open ocean is a major problem. However, floating plastic debris can be used as an ideal tracer to determine areas of accumulation as well as their points of origin. This type of study is possible through the use of Lagrangian methods. This paper presents a recently developed Lagrangian tool that has been validated using a floating plastic; mussel-pegs. Note that, although the data validation of these models has to be done on a regional scale, they can be implemented on an international scheme. Furthermore, the robustness of this study lies in the fact that the emitting sources are well known. For this reason, it is feasible to use such monitoring data to validate the MOHID-Lagrangian model. However, the precise computational reproduction of this situation is complex, since the actual emission from the rafts is unknown, as mussel sticks are not emitted at each mussel collection and the mussel collection is not performed periodically. In addition, the residence time of the mussel sticks is not determined and it is not possible to differentiate whether the origin of a particular plastic stick comes from the raft of this estuary or from another. Furthermore, the whole receptor points are equally probable to receive marine litter accumulation, i.e. all shoreline segments can record accumulation with the same probability. Thus, the model ignores rocky regions. Therefore, it is possible to find accretion zones in rocky regions where no real accretion occurs. In addition, during sampling, the safety of the samplers was always the top priority. Thus, sampling was always conducted during daylight hours and was suspended in cases where safety could be compromised (adverse weather conditions and COVID protocols) However, as it is based on the opportunity given by citizen science and the sampling work of the professionals, the records were made weekly on different days of the week. This means that, in this case, it will be more difficult to characterize the possible weather situations represented by the experimental data. For each of the beaches sampled, a specific form was developed to record information on mussel-pegs accumulation areas. In addition, the samplings were completed with photographs to verify the reliability of the data. All these factors can have an impact on the comparison results.

In this study it has been used a regional Lagrangian model to study the accumulation of marine litter in the Ría de Arousa. Three different time scenarios have been simulated: (1) one and a half years to see the global trend; (2) seven months to compare with the monitoring data in the Illa de Arousa and (3) six months to compare with the monitoring data in the Ría de Arousa.

This kind of studies are highly relevant to test whether computational models, in this case the MOHID-Lagrangian, are capable of reproducing the observational results. The first results show the spatial distribution of marine litter in the Ría de Arousa. Using the P25, P50, P75 and P95, the accumulation zones along the coastline can be qualitatively differentiated. The areas most exposed to oceanic action are those with the lowest accumulation ratios. Due to the circulation of currents, the largest accumulations occur at the outermost of the currents in the estuary. It was also found that wind has a great influence on the modelling. The accretion zones vary depending on the wind direction. As for the comparison between the model and the monitoring data collected on the coasts, highly favorable results have been found for both study periods. In both scenarios it was possible to reproduce the general trend of each area for the entire time period with the exception of two regions in the case of the Illa, and one in the case of the Ría.

In the case of the Illa, these two disparities are directly related to the orientation of the buffer with respect to the dynamics of the estuary. In one case, the computational exposure to the dynamics of this region does not correspond to the real one, favoring the arrival of fewer particles in this study area. In the other case, the orientation of the buffer is totally favorable to the oceanic circulation, which causes a high number of particles to be stranded in this area. A similar monthly behavior is found for all the study zones, except for the months of November and December. In these cases, the influence of North Atlantic hurricanes could be the cause of these anomalous behaviors.

For the Ría, the overall trend is well reproduced by the Lagrangian model, with the exception of Carreiro beach. The large variability of this region makes it, in a computational sense, one of the cleanest areas in this study. However, its particular orientation makes the accumulations monitored in this beach higher than expected. On a monthly basis, the importance of the orientation of the beach with respect to the intertidal dynamics is also observed. Thus, the importance of taking into account a correct reproduction of the coastal profile is also highlighted.

Although the results obtained in this study have been satisfactory, we would like to conclude this article with a series of recommendations for the design of future studies, as well as for monitoring data. The knowledge of the study area is important to evaluate whether it can be represented faithfully in a computational way. Spatial resolution problems can lead to unexpected and erroneous results, as it was our case with the S4 segment. The computational orientation of the corresponding buffer caused that only few particles reached this region, while a more favorable orientation and closer to the real one, the accumulation in this area could have been better estimated. As has been shown, bathymetry plays a major role and it must be considered for the correct interpretation of the region dynamics.

In addition, it is important to take this type of comparison with caution, given that computationally we obtain a continuous time series of marine debris accumulation at the shoreline. However, the results obtained in the collection correspond to certain situations that depend on multiple factors and that may not be representative of the temporal trend of accumulation in a particular region. These factors can be classified as environmental and human variables and both can have a detrimental effect on the obtained results. Environmental factors are impossible to control, but it is important to keep them in mind when analyzing the results. As we have seen, synoptic situations are key to locate potential marine litter accumulation areas so the establishment of consolidated campaigns that consider these conditions to define the monitoring periods is highly recommended. Human interference is easily controllable. We would like to highlight some indications to be taken into account in future studies. Must be ensured that the total of the planned samples are carried out at the scheduled date and time. All sampling must be gone on the same day and after the peak of high tide, preferably two hours later. This ensures that all floating particles

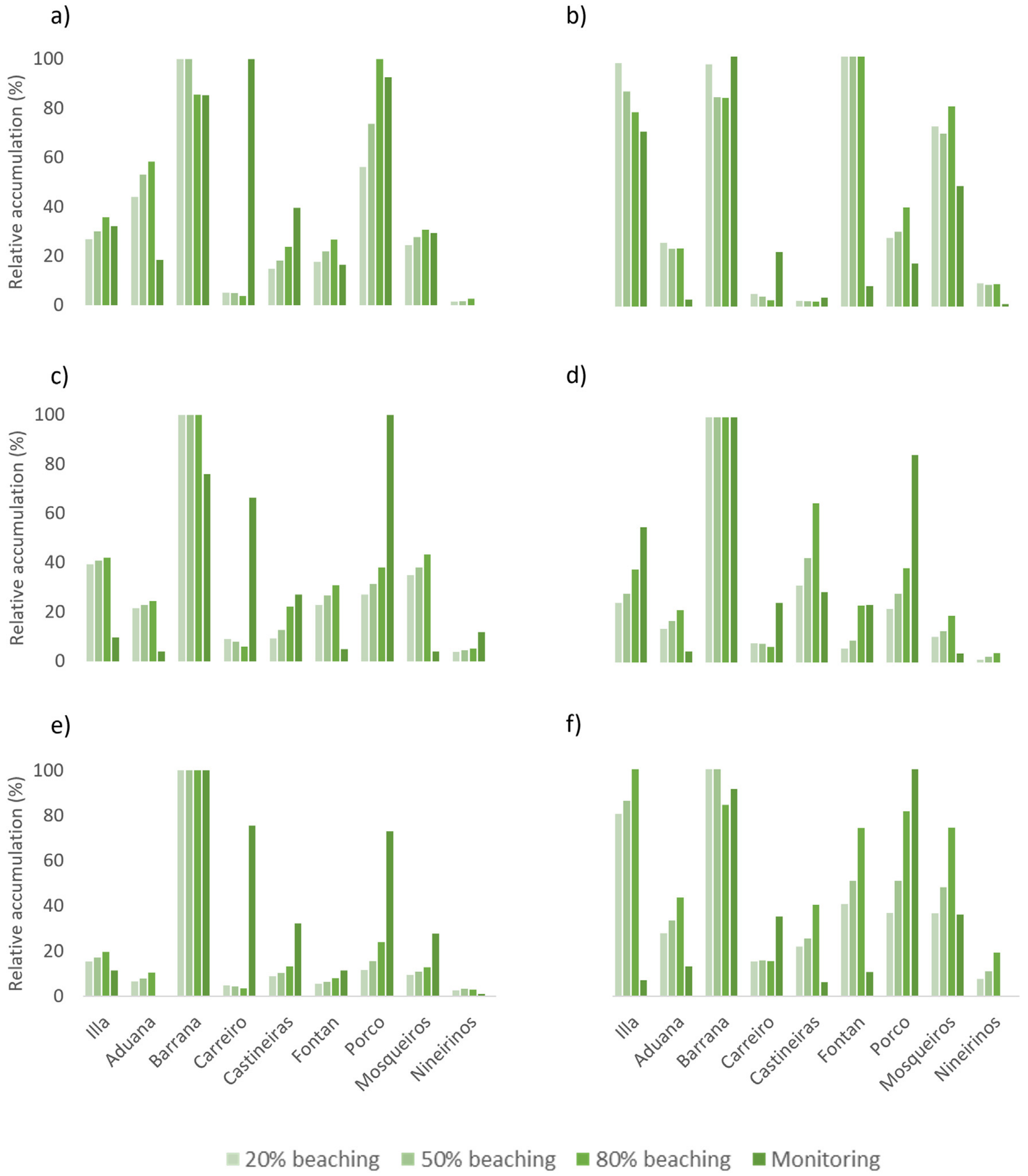

Fig. 8. Six month comparison of trends in the accumulation of mussel-pegs for different shore segments in the Ría de Arousa for a monthly representation, from October 2020 to March 2021. a) October 2020, b) November 2020, c) December 2020, d) January 2021, e) February 2021, f) Mars 2021. Simulations have been performed for different beaching values: 20% (light green), 50% (medium green) and 80% (dark green). The monitoring data are presented in darkest green.

have beached. It is also remarkable that the sampled objects must be removed once they have been counted, to be sure that the monitoring data collected over the time provides an estimation of the flux of debris onto the shoreline.

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CRediT authorship contribution statement

Sara Cloux: Methodology, Validation, Formal analysis, Writing – original draft. **Silvia Allen-Perkins:** Validation, Formal analysis, Resources, Data curation. **Hilda de Pablo:** Methodology, Writing – review & editing, Supervision, Funding acquisition, Project administration. **Daniel Garaboa-Paz:** Conceptualization, Software. **Pedro Montero:** Conceptualization, Resources, Data curation. **Vicente Pérez-Muñuzuri:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition, Project administration.

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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