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Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach

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Abstract: Plastic pollution has been observed in many marine environments surrounding the Iberian Peninsula, from the surface water to deeper waters, yet studies on their pathways and accumulation areas are still limited. In this study, a global ocean reanalysis model was combined with a particle-tracking Lagrangian model to provide insights into the pathways and accumulation patterns of microplastics originating in southern Portuguese coastal waters (SW Iberian). The study investigates microplastics floating on the surface as well as submerged at different water depths. Model results suggest that the North Atlantic Gyre is the main pathway for microplastics in surface and subsurface waters, transporting the microplastics southwards and eastwards towards the Mediterranean Sea and the Canary Islands. Currents flowing out of the Mediterranean Sea act as the main pathway for microplastics in deep waters, transporting the microplastics along western Iberia. An average residence time of twenty days in the coastal waters suggests that microplastics do not accumulate close to their sources due to their relatively fast transport to adjacent ocean areas. Notably, a significant proportion of microplastics leave the model domain at all depths, implying that SW Iberia may act as a source of microplastics for the adjacent areas, including the Mediterranean Sea, Morocco, the Canary Islands, Western Iberia, and the Bay of Biscay.

Keywords: microplastics; pathways; accumulation; SW Iberia; numerical model

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1. Introduction

Plastic pollution is internationally recognized as one of the most pressing threats to the ocean due to its persistence, its toxicity, and its effects on marine ecosystems and humans [1]. In fact, plastic items are estimated to account for up to 80% of marine litter [2], with the greatest portion of marine plastic items found in microscopic sizes (<5 mm), known as microplastics [3]. Microplastics originate from the direct release of manufactured microparticles used in various products (e.g., microbeads), or from the fragmentation of larger plastic litter in the environment. A primary concern regarding marine microplastics is their potential risk to marine organisms. Due to their small size, microplastics are easy to ingest accidentally by a wide range of marine organisms, from plankton to whales, and they can thus enter and accumulate along the food web [4]. Microplastics also have an indirect impact on the ecosystem since they adsorb and may concentrate pollutants from the surrounding water, exposing those who ingest them to harmful substances [1].

After entering the ocean, microplastics are readily transported for long distances due to the action of winds, waves, and ocean currents. As a result, they can be found in all oceans, from the poles to the equator, and from the shoreline to the deep sea [4]. According to recent estimates, there are approximately 51 trillion pieces of microplastic floating in the world's upper ocean [5]. Despite this high amount, floating plastics at the ocean surface only account for about 1% of the total estimated quantity of global marine plastic [5], with 99% found at the subsurface and at the bottom of the ocean. These plastic particles leave the ocean surface through several possible pathways, including beaching, sinking, and settling through the water column to the sea floor [6]. This vertical transport of plastic particles is controlled by their physical properties (size, shape, and density). However, these properties can change over time in the marine environment due to a variety of factors, including biofouling, weathering, mechanical deterioration, and other external variables [7]. Thus, the fates and pathways of microplastic particles that have sunk through the water column may be affected by various ocean circulations at different depths [8]. Although the subsurface and deep waters are important regions of microplastic accumulation, the distribution and transport of microplastics in these areas remain poorly understood due to a variety of reasons, such as the significant costs and operational challenges associated with acquiring samples from deep-water environments [6].

Advances in numerical modelling have counterbalanced the lack of relevant field observations of microplastic pollution in the ocean. Typically, high-resolution ocean models are employed to provide ocean current fields to particle-tracking Lagrangian models, which simulate the dispersal of virtual particles, including microplastics originating from known sources, such as urbanized cities, rivers and fishing areas. Such modelling approaches have provided useful information on the transport, accumulation zones, and potential origins of microplastics in marine environments [3,9–15]. However, most of these models focus only on the transport of microplastics at the sea surface, omitting their dynamic behavior in the marine environment (e.g., sinking, fragmentation, biofouling) as well as their differentiated transport at different depths. Few previous studies have considered particle characteristics such as density, size, and shape in their models, concluding that different classes of plastics can have different sinks, trajectories, and residence times [13–15].

On the Iberian coast, microplastic pollution is an issue of growing concern [16]. Some numerical models have been applied to assess the transport and sources of marine plastic litter items in Iberian coastal waters, whether in their larger or smaller form, and to make predictions regarding their potential accumulation zones [11,14,17,18]. However, information on the transport of microplastics along the Portuguese coast remains poorly described, particularly in the southern region.

In this context, the present study uses a numerical modelling approach as a tool for assessing microplastic pollution in a broad area surrounding the Iberian Coast, encompassing the Madeira and Canaries archipelagos. The approach uses 3D reanalysis of an ocean circulation model coupled to a particle-tracking Lagrangian model to characterize the transport and fate of microplastics originating on the southern Portuguese coast over an 11-year period. The model was applied to evaluate the transport of microplastics at different depths in order to answer the following research question: how does general ocean circulation affect the transport and distribution of microplastics originating from the SW Iberian coast?

2. Methods

2.1. Study Area

The Algarve coast, which stretches along the Iberian Peninsula's southwestern region, is an ecologically important region with extensive national parks and high biodiversity. This coastal region is home to a population of more than 450,000 people and contributes significantly to Portugal's seafood production through fishing and aquaculture [19]. Additionally, it is one of Europe's most popular destinations for sun, sea, and sand tourism. Considerable concentrations of microplastics have been reported in this region at the sea surface and sea floor, and in coastal zones and biota [16,20–22]. In a recent study on the Algarve coast, microplastic concentrations were found to be higher in deep offshore water samples than in coastal surface water samples [22]. However, information about their sources, how they are transported, and where they accumulate is still largely unknown.

In terms of oceanic conditions, the surface circulation off the Iberian coast shows a complex pattern determined by the eastern part of the North Atlantic Gyre, which consists of three main large-scale currents: the Portugal Current (PoC), flowing from the north; the Azores Current (AzC), flowing from the west; and the Canary Current (CaC), flowing to the south [23] (Figure 1). The Portugal Current lies on the upper layers (0–500 m) off the Iberian west coast and flows southwards year round from 50° N to 35° N [24]. Only part of this flow continues southwards into the CaC, while the rest enters the Gulf of Cadiz flowing towards the Strait of Gibraltar in a shallow surface layer (Figure 1), where it is known as the Gulf of Cadiz Current (GoC) [25]. Due to the many similarities between the two, some studies have classified the PoC as a component of the CaC, while others, such as [23], identify it as a unique current.

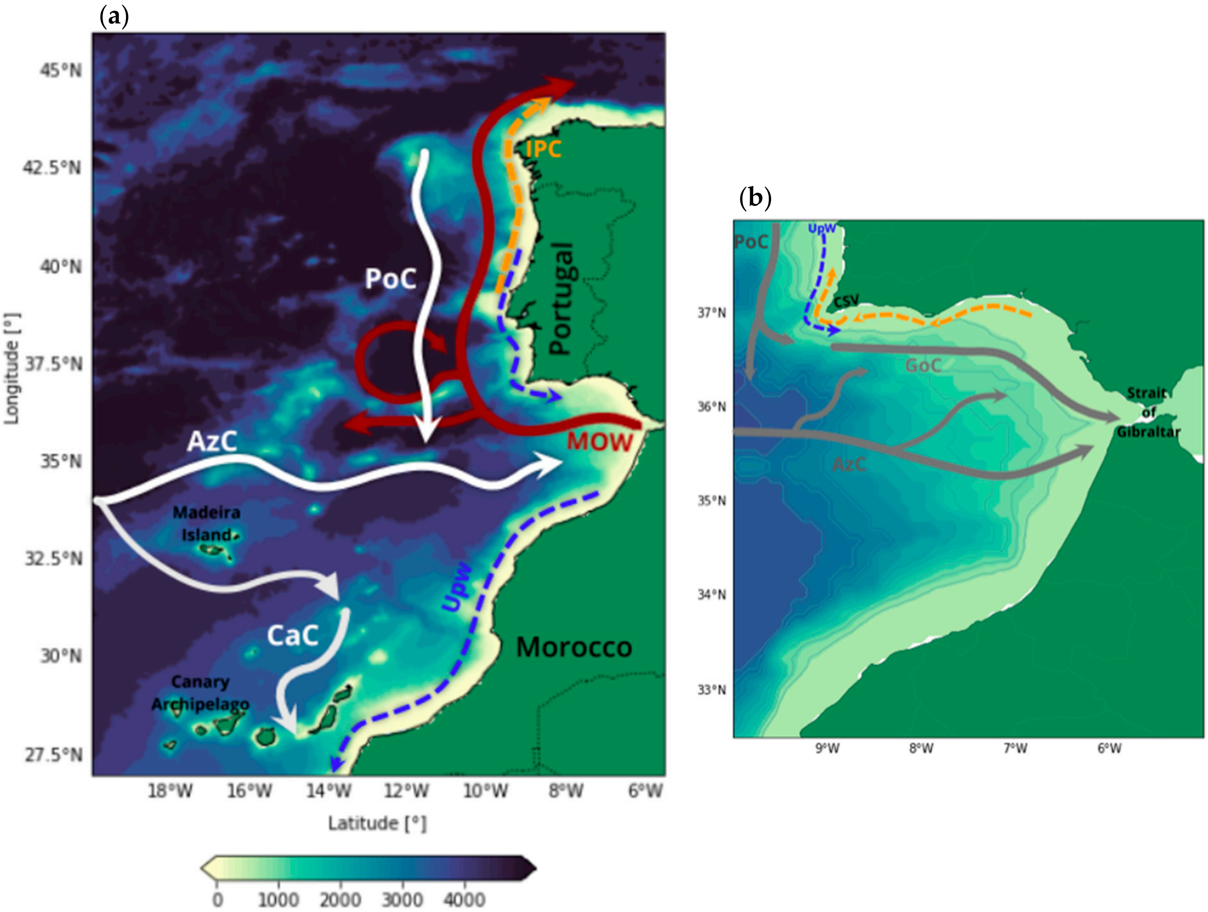

Figure 1. Schematic representation of the general circulation in the Iberian and Canary Current system (**a**) and upper general circulation of the southwest Iberian region (**b**). AzC—Azores Current; CaC—Canary Current; GoC—Gulf of Cadiz Current; IPC—Iberian Poleward Current; MOW—Mediterranean outflow water; PoC—Portuguese Current; UpW—upwelling coastal circulation; CSV—Cape St Vincent.

The Azores Current originates from the southern branch of the Gulf Stream and splits into two branches around the Madeira Islands; one part continues eastwards entering the Gulf of Cadiz, while the other turns southwards merging into the Canary Current (CaC). The CaC flows south along the African coast and through the Canary Islands, from 30° N to 10° N, reaching a depth of 300 m [26]. Like the PoC, the CaC is wide (1000 km) and slow, and it flows year round towards the equator [26].

Moving towards the coast, Moroccan and Iberian surface circulation is mainly influenced by upwelling phenomena driven by seasonal northerly winds. This region is part of the Canary Current upwelling system, which is one of the four major eastern boundary current systems. Upwelling is permanent over most of the Moroccan coast (21–35° N); however, it is less intense and more seasonal north of the Canary Islands (~26° N) [27]. Along the Iberian coast, seasonal variability is observed, with a southward upwelling jet occurring through the spring and summer (May to September) under the influence of northerly winds [28]. During the winter, the dominant wind direction changes and poleward flow becomes a conspicuous feature along the Iberian shelf edge and slope at all levels between the surface, due to the Iberian Poleward Current (IPC), and deeper waters, which carry Mediterranean outflow water between 500 and 1500 m [28]. Furthermore, observations have shown highly energetic mesoscale features at the surface, such as filaments extending off Cape St. Vincent on the southwestern Iberian coast, as well as off Cape Ghir in Morocco [28,29].

Mediterranean water flows into the Gulf of Cadiz and the Atlantic Ocean through the Strait of Gibraltar at a depth of 300 m in what constitutes the Mediterranean outflow water (MOW). This salty and denser MOW cascades down into the Gulf of Cadiz where it divides into two branches after passing Cape St. Vincent (Figure 1). One branch flows northward along the western slope of the Iberian Peninsula at a depth of 1000 m, while the second branch is deflected westwards towards the northeast Atlantic Ocean [29]. Furthermore, the MOW enters the Tagus Basin (36.5–39° N) and turns anticyclonically, generating a water mass reservoir [29]. The MOW has also been reported southwest of the Iberian Peninsula, mainly through the influence of Mediterranean eddies, also known as meddies. Meddies are mesoscale vortices formed by the sharp bend of the bathymetry in the proximity of Cape St. Vincent and Portimão Canyon, as well as Lisbon and Setubal Canyon. After detachment from the continental slope, these meddies travel predominantly west-southwest [30].

2.2. Marine Microplastic Model

2.2.1. Lagrangian Model and Forcing

Simulations of microplastic transport were performed with OpenDrift (Release v. 1.5.6), an open-source Lagrangian model framework developed in Python by the Norwegian Meteorological Institute [31]. In this work, the particle trajectories are integrated using a Runge–Kutta second-order scheme based on the combination of ocean currents and atmospheric forces [31]. The position of a particle in each vertical layer is updated horizontally, as follows:

$$x(t+dt) = x(t) + u(x,y,t) * dt + R_x * \sqrt{2 * \frac{K_h}{dt}}$$

$$y(t+dt) = y(t) + v(x,y,t) * dt + R_y \ * \sqrt{2 * \frac{K_h}{dt}}$$

where (x, y) define the horizontal position of the particle, dt is the time step, (u, v) are the current velocities at the designated depth in x, y directions provided by the hydrodynamic model, K_h is the horizontal diffusion coefficient, and R_x, R_y are random numbers uniformly distributed between -1 and +1. This last term in the equations approximates the effect of turbulent diffusion on the particles. Furthermore, this work employed the wind effect on the upper circulation that is already incorporated in the hydrodynamic model.

2.2.2. Model Settings

Simulations were performed over a period of 11 years (2010–2020), coupling external hydrodynamic forcing to the particle-tracking Lagrangian model in two dimensions. Daily mean current data from CMEMS GLORYS12V1 Global Ocean Physics Reanalysis, produced by the Mercator–Ocean system, was used as the hydrodynamic forcing for the OpenDrift model. This ocean model was driven at the surface by the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim atmospheric reanalysis [32]. In addition, the GLORYS12V1 combines observations from satellites and in situ instruments, numerical modelling, and data assimilation to provide a more accurate past state of the ocean [32].

The model domain covers parts of the northeastern Atlantic Ocean from the Canary Islands (27° N) to the Iberian Peninsula (42° N), and from 20° W to the Mediterranean Sea

(5.5° W), with a horizontal grid resolution of 1/12°, which corresponds to approximately 8 km, and 50 vertical levels (from 5500 m deep to the surface) [32]. In this study, a constant horizontal diffusion coefficient of K_h = 1 m/s was applied in the trajectory of each particle at each time step. This value has been shown to be well suited for studying the transport of particles in the study region [17].

The effects of sinking, sedimentation, and biofouling are important for microplastic transport, since they produce a change in buoyancy, and thus influence the vertical position of a particle in the water column. In recent years, much effort has been made in estimating the sinking behavior of microplastics [33–35]. However, how these processes occur in nature is still not fully understood, and parameterizations are not yet robust enough to be applied with confidence in microplastic models [7]. As a consequence, vertical movements were not considered in this work. Instead, a sensibility study was conducted using three scenarios, each of which used a different predefined depth to simulate the release and drift of particles (described below).

Three scenarios with different depths were analyzed using a sensitive approach to study the distribution of the particles in the model. These three depths were selected based on the distinct ocean circulation pattern of the study area described in the literature. For the first scenario, particles were discharged in the surface layer of the ocean (up to 1 m depth), where the circulation of the study area is driven by winds. For the second scenario, called here subsurface, particles were discharged at a depth close to the thermocline, here defined as a 30 m depth, following [28]. At this depth, the circulation is affected by a combination of atmospheric conditions and ocean currents. In the last and deepest scenario, particles were discharged at a depth of 800 m in order to study the impact of the Mediterranean outflow water (MOW), the dominant factor affecting circulation over the Iberian Peninsula between 500 m and 1500 m [29].

Due to the lack of field data on the concentration of microplastics and their horizontal and vertical distribution in the coastal waters of SW Iberia, the number of particles released in this case was determined based on a good compromise between computational time and model accuracy. Therefore, for the surface and subsurface depths, 49 particles were released daily at 49 locations along the SW Iberian coast (Figure 2a). These discharges represented microplastics originating from land- and sea-based sources along the coast, such as ports, as well as from shipping, tourism, and fishing activities. For the 800 m depth simulation, 48 particles were released from 12 points further out from the coast (Figure 2a) to ensure that deep-water circulation was the main factor affecting the particle transport. These particles represented those that sank due to different plastic properties as well as changes in their buoyancy during physical and biological processes, including biofouling, aggregation with other particles, and degradation. In total, 186,298 particles were released over the 11-year simulation for each of the upper two depths, while 182,496 were released for the 800 m layer. The particle discharges are summarized in Table 1.

Table 1. Configuration of point discharges of particles at each depth layer in the ocean model.

Release Depth (m)	0	30	800
Time step	daily	daily	daily
Horizontal diffusion coefficient Kh (m^2/s)	1	1	1
Source location	49 points of emission	49 points of emission	12 points of emission
Number of particles	49	49	48

To assess the potential accumulation zones, this study used the residence time to determine the time required for pollutant particles to leave a region of interest. Such information is critical for gaining a better understanding of potential places with a higher risk of microplastic threats to the ecosystem. In this study, residence time was defined as the number of consecutive days a particle spent in each of the five sub-regions depicted in Figure 2b: southern Iberian coastal waters (S-coast); western Iberian coastal waters

(W-coast); western Iberian offshore waters (W-Off.); SW Iberian offshore waters (SW-Off.); and southern Iberian offshore waters (S-Off). These sub-regions were chosen to comprise the coastal and offshore waters of southern and central-western Portugal.

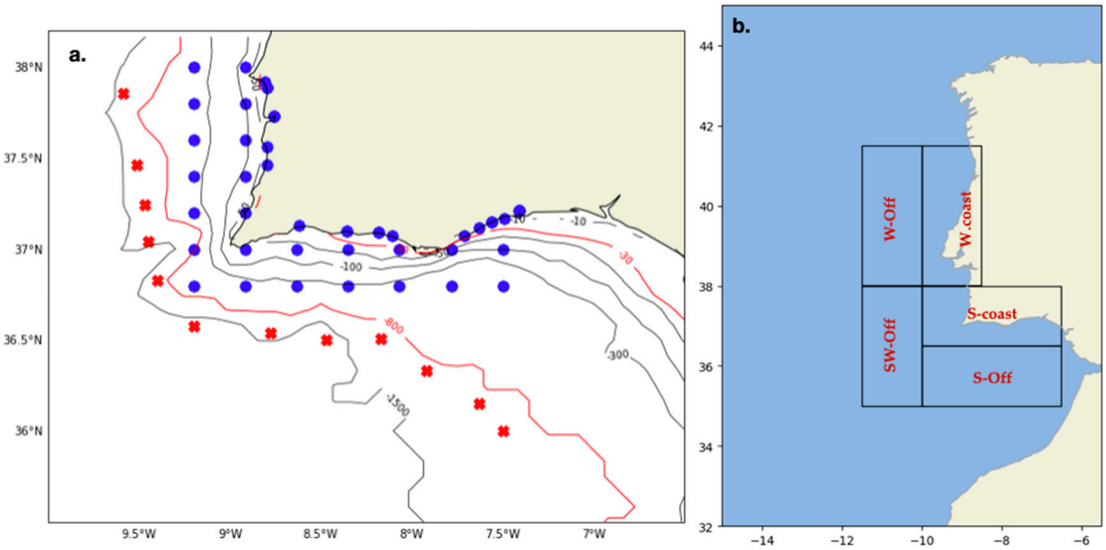

Figure 2. (**a**) Microplastic inputs around the SW Iberian coast for each designated depth: surface and 30 m depth as blue circles and 800 m depth as red crosses. Bathymetry is displayed as black isolines from 0 to 1500 m, and red isolines for 30 and 800 m. (**b**) Marine waters of the Iberian Peninsula were grouped into five monitoring boxes: southern Iberian coastal waters (S-coast); western Iberian coastal waters (W-coast); western Iberian offshore waters (W-Off.); SW Iberian offshore waters (SW-Off.); and southern Iberian offshore waters (S-Off.).

3. Result

3.1. Pathways and Travel Times of Microplastics in the Water Column

The potential pathways of microplastics originating on the SW Iberian coast for each of the three simulated depths (surface, subsurface, and deep-water) are shown in Figure 3. These pathways are conceptualized as "cumulative particle concentration": the proportion of particles detected in each 0.8° grid cell and normalized per 100,000 emitted particles. Normalization was used to make the results independent from the total number of particles released. Furthermore, the concentration of particles crossing each cell was plotted on a logarithmic scale for better visualization.

The simulation results shown in Figure 4 represent the travel time of the marine microplastics originating from the SW Iberian coast. These maps show the time required for the particles to be transported away from the Iberian coast towards nearby neighboring regions at three different depths. Here, the travel time was evaluated by averaging the age of the particles detected in each grid cell of the model with reference to the time of particle release.

In general, Figures 3 and 4 suggest that the main pathways and travel times of particles differ between the three simulated depths. These differences were more noticeable in the deep-water simulation, where most particles traveled northwards along the western Iberian shelf and particles reached the northern Iberian waters 16 months after their release. In addition, a large number of particles appeared to concentrate between 36–39° N for a few months before slowly moving westwards and reaching remote Atlantic waters 20 months after release. Microplastics in the surface and subsurface, on the other hand, moved predominantly eastwards towards the Strait of Gibraltar, reaching Mediterranean waters within three (surface) and six (subsurface) months of their release. In addition, it is possible to observe a southward flow that transported particles towards Madeira Island and the Canary Islands within 10 months of their initial release, while particles at the subsurface took twice as long to reach this area.

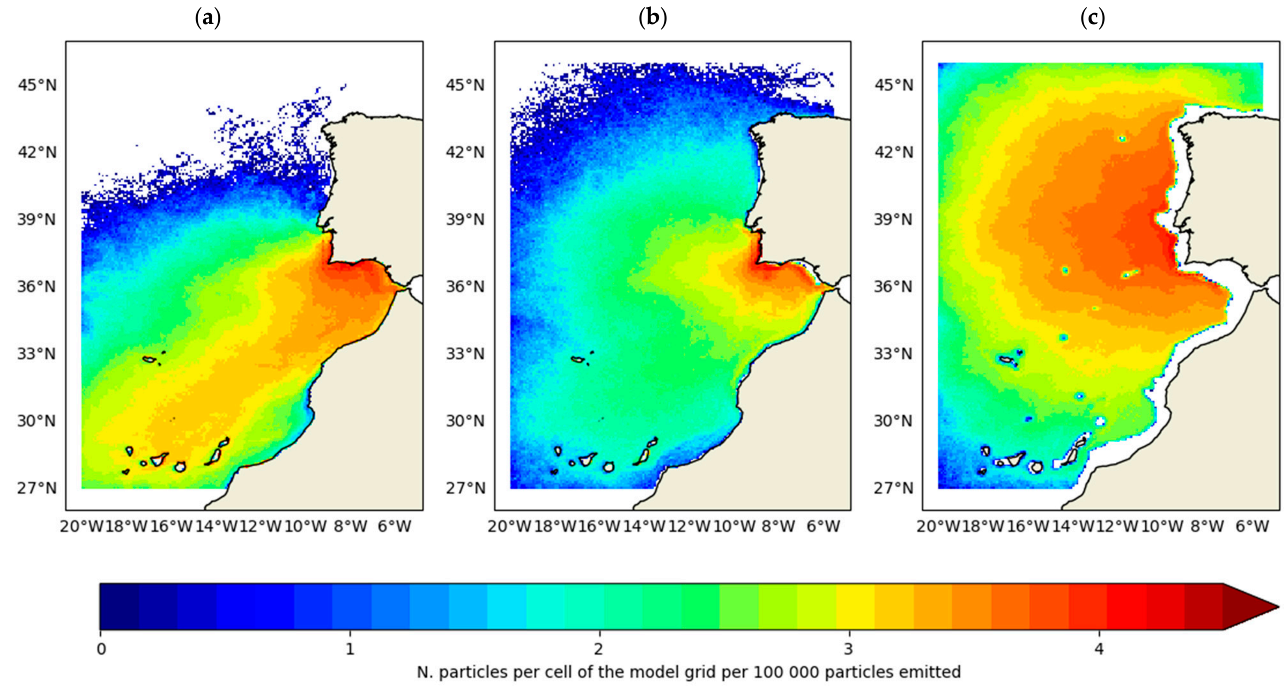

Figure 3. Maps showing the cumulative particle concentration per 100,000 particles detected in 0.8° grid cell on a logarithmic color scale for particles carried by currents (**a**) at the surface (left box), (**b**) at a depth of 30 m (middle box), and (**c**) at a depth of 800 m (right box).

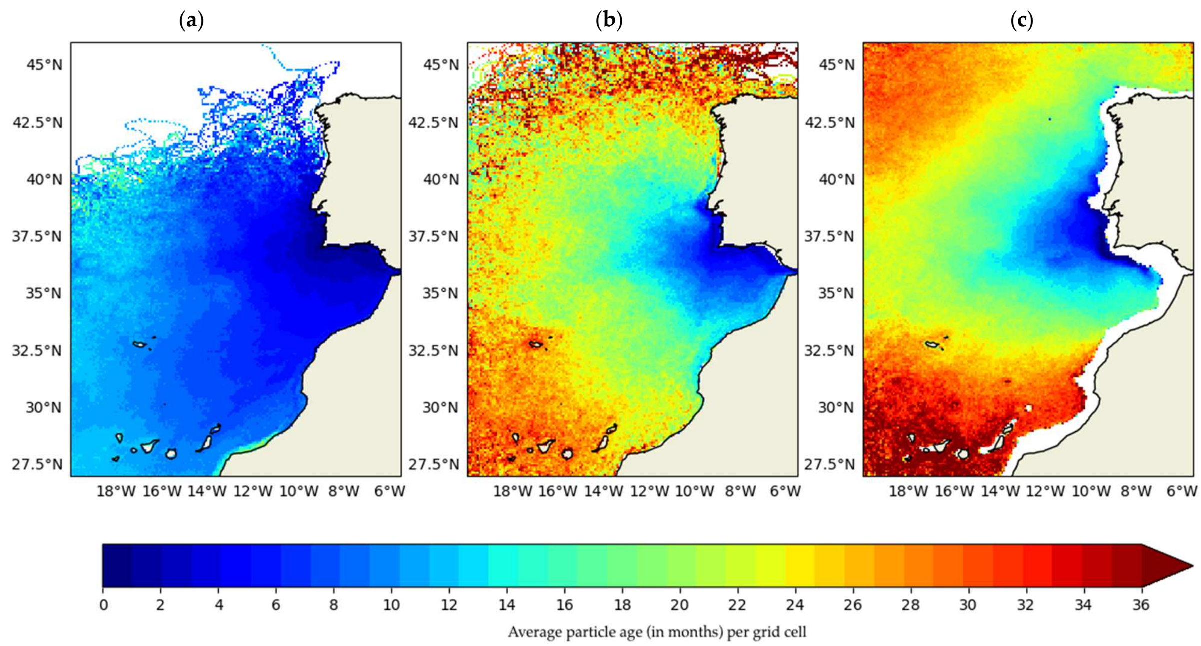

Figure 4. Average age of particles (**a**) at the surface (0 m depth), (**b**) subsurface (30 m depth), and (**c**) deep-water (800 m depth) levels during the entire simulation period, detected in 0.8° grid cells. Color scale is divided into two-month intervals.

3.2. Residence Time of the Microplastic Particles

The presence of possible accumulation zones of marine microplastics in SW Iberian waters was explored by determining the residence time of microplastics simulated in surface, subsurface, and deep waters. According to past studies, residence time is a useful indicator in Lagrangian models for evaluating the time that particles remain in an area, and consequently, the accumulation zones of marine litter in different coastal waters [17]. Such information is important for assessing the areas that could be more affected by pollution threats. In this study, the residence time was defined as the number of consecutive days that a particle remained in a certain region over the 11-year period. Figure 5 shows the residence times in days calculated individually for each of the five monitoring boxes (i.e., S-coast, W-coast, W-Off, SW-Off, and S-Off) in Figure 2.

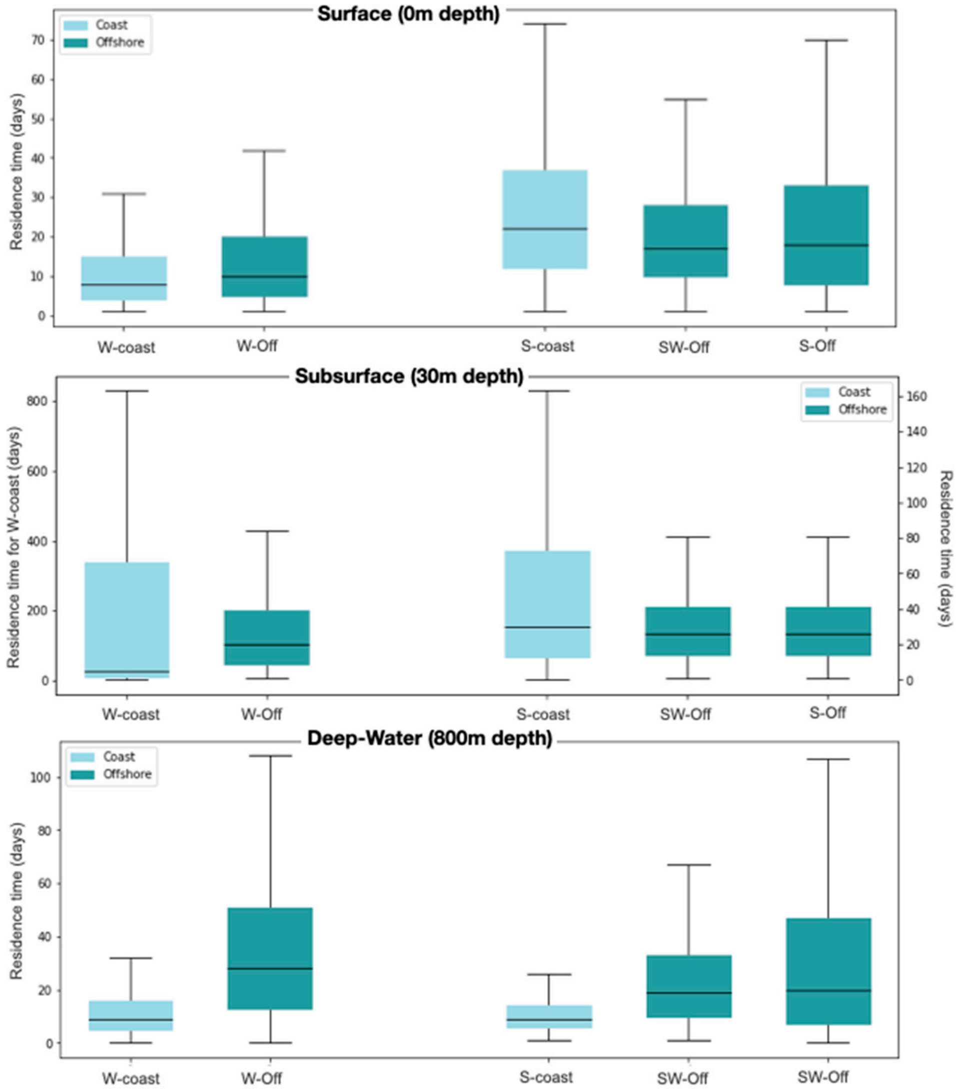

Figure 5. Residence time (in days) of particles calculated for each of the five sub-regions according to Figure 2b (W-coast, W-Off, S-coast, SW-Off, and S-Off) for the simulations at the surface (top box), subsurface (middle box) and deep-water (bottom box) levels. Note the different axis scales.

Furthermore, the concentration of marine microplastics from the SW Iberian coast which crossed the western, eastern, northern, and southern boundaries of the model domain (Figure 6) was used in this study to assess the potential transfer of microplastics from the SW Iberian coast to neighboring regions, such as the North Atlantic Ocean, the Bay of Biscay, and the Mediterranean Sea. Table 2 shows the proportion of particles which crossed each of the model's boundaries for each simulation depth. These values are expressed as fractions of the total number of particles released.

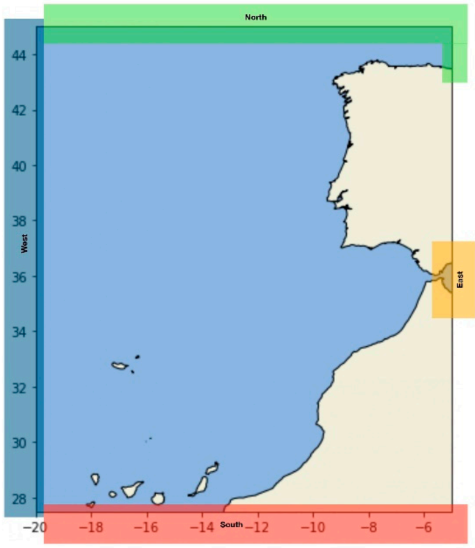

Figure 6. Map of the model domain and the location of each designated boundary: north (green box), south (red box), west (blue box) and east (yellow box).

Table 2. The fraction of particles crossing the northern, southern, eastern, and western boundaries of the model, at the surface, a depth of 30 m, and a depth of 800 m. The boundaries are show in Figure 6.

Release Depth (m)	0	30	800
North	0%	0%	18%
South	20%	1%	0%
West	29%	1%	22%
East	48%	28%	0%

4. Discussion

The model results suggest that the vertical position of the microplastic particles has a significant impact on their pathways and fates. For example, microplastics with a density lower than that of seawater, such as polypropylene and polyethylene, the world's most common plastics, floated at the surface during the 11-year simulation, being transported either southwards or eastwards by the North Atlantic Gyre as shown in Figure 1. Within this system, the Portuguese Current (PoC) and its associated branches acted as the dominant transport pathways for the microplastics, transporting most of them southwards along the SW Iberian coast. Some of the particles continued further south into the North Atlantic Ocean, reaching the Madeira and Canary Islands. Meanwhile, many other particles entered the Gulf of Cadiz, being transported eastwards towards the Strait of Gibraltar via the eastern branch of the PoC, known as the Gulf of Cadiz Current, as well as via the eastern branch of the Azores Current. According to [25], these two branches are the principal causes of Atlantic water entering the Mediterranean through the shallow surface layer. The dynamics of this region are complex, being highly influenced by the transient character of the upwelling regime [23,28,36]. The forcing fields used, being hourly reanalyzed, captured this transient behavior. Moreover, the predominant export of microplastics at the surface and subsurface towards the Mediterranean is consistent with previous studies using in situ data which have shown that eastern Gulf of Cadiz and Western Mediterranean coastal surface waters have been exposed to higher concentrations of microplastics than other Iberian coastal regions [37].

The present results suggest that, qualitatively, the pathways of microplastic particles at the surface and subsurface (30 m depth) follow a similar pattern, with a high concentration of microplastics drifting eastwards over the southern Iberian shelf. However, models show that microplastics at a depth of 30 m are less dispersed throughout the NE Atlantic. In fact, less than 1% of microplastics at the subsurface travelled southwards towards the Canary

Islands region, compared with ~20% of floating particles (Figure 3a,b). These disparities in dispersion can be attributed to the exposure of floating microplastics to wind-driven currents. Wind-driven currents are generally limited to the highest layer of the ocean, above the thermocline, which in the SW Iberian Peninsula is between 30 m and 60 m deep [28]. Previous studies have reported the importance of the inclusion/absence of wind forces in the transport of macro and microplastic litter in marine waters [11–14,18]. It is important to recall that the effect of winds on circulation discussed in this paper is already included in the global ocean model used in this model (GLORYS12V1).

In deep waters, represented here by a depth of 800 m, a high proportion of microplastic particles are transported northwards and westwards along the Iberian basin, as depicted in Figure 3. In general, the buoyancy of microplastics is determined by particle density, and particles with a density higher than that of sea water tend to sink through the water column until they reach neutral buoyancy conditions, at which depths they are then transported [38]. For example, plastics such as polyvinyl chloride (PVC) and polyethene terephthalate (PET) possess densities greater than that of the surface water and are thus more prone to submerge. In addition, biofouling attached to naturally buoyant plastics may increase their density, causing them to submerge [34]. Naturally, these high-density particles are exposed to the Mediterranean outflow water (MOW) circulation, which is a deep current flowing from the Mediterranean Sea towards the Atlantic Ocean through the Strait of Gibraltar at a depth between 500 m and 1500 m [29]. Moreover, the simulation results suggest a high concentration of microplastics in the vicinity of the western Portuguese continental slope and Tagus Bay, between 33° N and 39° N (Figure 3c). This high concentration might be explained by the presence of an anticyclonic gyre, known as the MOW reservoir, centered in the Tagus Basin [29]. Therefore, this study reinforces the importance of including distinct circulations at different depths in microplastic models to gain a better understanding of their spatial distribution and fate.

It is well known that once microplastics are in the ocean, they are subject to a variety of environmental agents that may change their properties (size, shape, and density) through fragmentation, biofouling, and other processes (see review in [7]). These changes in the microplastic properties can lead them to sink through the water column. Consequently, their dispersion will be affected by differences in circulation at various depths. For example, microplastics at the surface and subsurface take approximately three and six months, respectively, to reach the Strait of Gibraltar, and biofouling processes can take six weeks to cause the particle to sink through the water column, though this time can vary depending on particle type and seawater properties [39]. It is reasonable to expect that because of the biofouling process some microplastics may not reach Mediterranean waters, but rather might be returned and distributed along the Iberian Peninsula via the MOW circulation. This could explain the high concentration of microplastics of low density observed in deeper water off the coast of southern Portugal [22]. Given the effect that vertical position has on the transport of microplastics from SW Iberia, sinking, biofouling, and settling processes must be included in future microplastic modelling studies. Although estimating these processes is challenging, many efforts have been made with experimental studies of how sinking and biofouling processes affect the behavior of microplastics in the natural environment [13]. Studies in this field should continue in order to improve the parameterization of the physical, chemical, and biological processes (diffusion, degradation, sinking, biofouling, washing, and deposition) that affect microplastic behavior [33–35], and consequently to improve the accuracy of their simulated pathways.

Microplastics originating in SW Iberian coastal waters tended to be carried far from their sources in a short period of time, as illustrated by the travel time of particles in Figure 4. In fact, the model suggests that microplastics at the surface, subsurface, and deep-water levels were transported to the open ocean or nearby coastal regions in less than three months following their release. In addition, once in the open sea, microplastics at the sea surface take a similar amount of time (~10 months after release; Figure 4a,b) to reach Madeira and the Canary Islands, despite the fact that the SW Iberian is physically closer to

Madeira than the Canaries. This similarity highlights the significance of assessing particle travel time in conjunction with particle paths (Figure 4b), since the combination can reveal the predominant direction taken by particles. Moreover, microplastics at the subsurface level take significantly longer (32 months after release) to reach the same archipelagos. This time discrepancy may be related to the decrease in wind influence and current speed at subsurface depths [11,12].

The microplastic model predicts that particles that enter the surface waters of the SW Iberian coast (S-coast, SW-off, and S-off; Figure 2b) remain for an average of 20 days before being transported away (see Figure 5). Figure 5 also suggests that the residence time is about 10 days shorter in the western sub-regions (W-coast and W-Off; Figure 2b). Such a short residence time is likely related to the Iberian coast's upwelling regime, which is often more frequent and intense along the west coast than along the south coast [36]. Moreover, given the short residence time and the large microplastic outflow fluxes shown in Figure 3, it is reasonable to expect that microplastics would not remain long enough to accumulate in the SW Iberian surface waters. This finding is consistent with the low levels of microplastics detected in previous studies along the surface waters of the SW Iberian Peninsula [22].

Particles suspended in the water column at depths of 30 m and 800 m show similar average residence times of ~20 days in the SW Iberian sub-regions (S-coast, SW-Off, and S-Off), except for the S-coast sub-region, where the residence time of 10 days in deep waters is much shorter (Figure 5). This difference in time might be related to the shallow bathymetry along the coast causing a faster deposition of the particles at the sea floor, and consequently deactivating them from the simulation. These results imply that a high number of microplastics in deep waters remain on the seabed. However, a previous study identified a higher concentration of microplastics in deep waters, and a low concentration in the sediments along the SW Iberian coast [21,22]. This nonconformity between model results and field surveys may be related to a variety of parameters that were not taken into account in this model, including bottom deposition, settling, and resuspension. Further studies are thus needed.

The potential transport of microplastics from the SW Iberian coast to neighboring regions is assessed by the results shown in Table 2 and Figure 6. A significant amount of microplastics were carried far from sources located along the SW Iberian coast into the open sea and adjacent regions, where high levels of plastic pollution already exist. For example, 98% of the microplastic released at the surface were transported out of the model area, 48% of which reached Mediterranean waters and 20% of which reached the region around the Canary Islands. These results imply that the SW Iberian coast is an important source of microplastics for the Mediterranean Sea, which is one of the most plastic-polluted areas in the world, as well as a hot spot of marine biodiversity [40]. On the other hand, the deep-water simulation results showed that 18% of microplastics originating from SW Iberia made their way into the Bay of Biscay. A previous study recently described the Bay of Biscay coast as being exposed to marine litter from distant sources transported by poleward alongshore circulation [17]. These results support that argument. The opposite effect, i.e., the impact of SW Iberian waters on microplastics released outside the domain, was not addressed in this study and will be the next focus of our investigations.

5. Conclusions

In this study, a Lagrangian modelling framework was established to track microplastics originating from the SW Iberian coast over the 2010–2020 period, focusing on three depths: the sea surface, subsurface (30 m depth), and deep water (800 m). Despite the model limitation, this study provides useful information on the pathways and fate of microplastics originating from the SW Iberian coast. Model analyses conclude that microplastics at different depths follow different pathways. Most of the microplastics in the surface and subsurface levels were quickly transported offshore, where many of them eventually reached Mediterranean waters, while many others reached the Canary Islands. In contrast, microplastics suspended in deep waters were partially transported northwards over the western Portuguese continental slope.

Due to this dynamic, no permanent accumulation zones (hot spots) were identified. Nevertheless, regions around the Iberian Peninsula may present temporal accumulation of microplastics originating from the SW Iberian coast, in particular at subsurface and deep water levels close to the western Portugal shelf. Overall, the model also predicted that a considerable proportion of particles escaped far from the SW Iberian coast, implying that the study area is an important microplastic source for the Northeast Atlantic, western Mediterranean Sea, and to a lesser extent for the Bay of Biscay.

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