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Lagrangian tracking of long-lasting plastic tags: From lobster fisheries in the USA and Canada to Macaronesia

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ABSTRACT

Plastic waste from the fishing industry, particularly lobster trap identification tags from the USA and Canada, poses a significant threat to marine ecosystems due to its resilience. This study unveils a novel link between North American fisheries and the appearance of these plastic tags in Macaronesia. Collected in the Azores and Canary Islands, these tags offer a unique insight into the sources and spatio-temporal scales of marine plastic pollution. Ocean model data indicates the Labrador Current and Gulf Stream as key forces transporting these tags. Virtual particle simulations show a small fraction reaching Macaronesia (4.12 % in the Azores, 0.76 % in the Canary Islands), suggesting real ocean drift. The Azores, with more collected tags, are more susceptible, and tags can reach Macaronesia in under a year. These findings underscore the urgency of better waste management and emphasize the role of citizen science in monitoring and combating marine pollution.

1. Introduction

The rise in plastic production, driven by increased demand and population growth, has led to a surge in plastic waste accumulating in the oceans (Campillo et al., 2023; Ostle et al., 2019; Wayman and Niemann, 2021). A significant portion of the plastic waste in the ocean, ranging between 4.8 and 12.7 million metric tons per year, originates directly from land-based sources (Jambeck et al., 2015). However, without downplaying their importance, it should be noted that these values may be subject to greater uncertainty as pointed out by other authors (Mai et al., 2020; Weiss et al., 2021). Also, a relevant portion of the plastic in the oceans originates from sea-based sources, which is estimated in 6.4 million tonnes per year considering only the marine plastic litter generated in fishing activities (GESAMP, 2021). Among sea-based sources are specific industries, such as fisheries, in which utilised plastic materials are designed to endure harsh conditions for extended periods in the sea, posing a significant threat to marine ecosystems due to their high resistance and potential harm (Gilman et al., 2021).

Oceanic islands, in particular, suffer from the pressure of this contamination, being typically polluted by plastic items coming from far away sources and highlighting the importance of understanding the origin of these debris in order to improve waste management strategies (Lavers and Bond, 2017; Monteiro et al., 2018; Pham et al., 2020; Rodríguez et al., 2020). Items with labels offer the advantage of being easily traced back to their origin, acting as tracers and aiding in the identification of primary pathways, estimation of time frames, and assessment of interconnections among different regions. A compelling application of traceability for plastic debris in the ocean lies in the use of identification tags. These tags are commonly found in various daily activities, particularly those involving registration, regulation, or control, such as fishing. In the fishing industry, these tags play a crucial role in licensing, serial numbering of fishing gear, identifying areas of use, and recording dates. Consequently, the wealth of information associated with these tags makes them ideal tracers, allowing for the estimation of their geographical origin and approximate travel times once they are collected elsewhere. This information may be used to perform a Lagrangian approach and release virtual particles, devoid of physical size, into velocity fields generated by numerical models, observational measurements (e.g., geostrophic velocities derived from satellite altimetry), or high-frequency radar measurements (Hurlburt and Hogan, 2000; van Sebille et al., 2018, 2020; Werner et al., 2007).

Over the past few years, a substantial number of plastic tags from

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lobster fisheries in the USA and Canada have been found on various beaches in the Macaronesia region, particularly in the Azores and Canary Islands (Cividanes-García, 2022). These debris are no exception, containing all the information mentioned above and offering a perfect case study for improving our understanding of the oceanic dynamic connectivity between the northeastern coast of the North American continent and the Macaronesia region in a Lagrangian framework.

The lobster fishing areas of the USA and Canada span from Cape Hatteras along the coast to the Gulf of Saint Lawrence, covering a distance of approximately 200 km from the coast (Department of Marine Resources, 2022; Government of Canada, 2011, 2013; NOAA Fisheries, 2023). For further information about the lobster fishing management areas, please visit the links.[1] Each year, around 5–6 million lobster traps are released with identification plastic tags that must be replaced every season (Department of Marine Resources, 2022; Government of Canada, 2011, 2013; NOAA Fisheries, 2023). The large number of tags used annually for the identification of lobster traps makes many of them vulnerable to accidentally ending up under the influence of sea currents. Given the importance of near-surface currents in influencing the trajectories of these plastic tags, a brief summary of the main currents along the potential paths followed by these tags is presented. The first current interacting with these fishing areas is the Labrador Current. Originating from the Hudson Strait at 60°N, this subarctic current flows southeastward over the continental shelves and slopes until it reaches the Tail of the Grand Banks of Newfoundland at 43°N. At Hamilton Bank, on the southern Labrador Shelf, the current bifurcates into two branches: a small inshore branch carrying approximately 15 % of the transport and the mainstream, which remains over the upper continental slope, transporting roughly 85 % of the total flow (~4 Sv) (Lazier and Wright, 1993). The subarctic flow of the Labrador Current continues southwestward after passing the Grand Banks. Part of this flow enters the Gulf of Saint Lawrence through the Laurentian Channel Mouth, resulting in a cyclonic circulation inside (El-Sabh, 1976; Urrego-Blanco and Sheng, 2014), while the remainder continues flowing to the Nova Scotia Shelf and enters the Gulf of Maine (Lynch et al., 1996) (Fig. 1). The Gulf of Saint Lawrence, Nova Scotia Shelf, and the Gulf of Maine form an interconnected estuarine-shelf system (Urrego-Blanco and Sheng, 2014).

South of approximately 40°N, the main southward flow interacts with the upper boundary of the North Atlantic Subtropical Gyre (NASG), primarily characterised by the Gulf Stream (GS). Dominating the western-northwestern region of the gyre, the Gulf Stream exhibits an intense flow transporting up to 100–105 Sv (1 Sv = 10^6 m^3 s^{-1}) at 55°W (Gula et al., 2015; Rossby et al., 2014; Tychensky et al., 1998) (Fig. 1). The Gulf Stream bifurcates into two primary branches: the first branch generates the North Atlantic Current (NAC) with a northwestward transport rate ranging between 20 and 27 Sv (Daniault et al., 2016; Krauss, 1986), while the second branch forms the Azores Current (AC) with an eastward transport rate of 10–12 Sv towards the Macaronesia region (Frazão et al., 2022; Klein and Siedler, 1989; Tychensky et al., 1998).

Macaronesia encompasses the archipelagos of Azores Islands, Madeira, Canary Islands, and Cape Verde. The Azores Islands, situated between 36° and 43°N and between 25° and 31°W, lie within the flow of the Azores Current. The AC displays prominent meanders and loops, accompanied by mesoscale eddies of typical radius sizes around 80 km (Caldeira and Reis, 2017; Käse and Siedler, 1982; Siedler et al., 1985). The recirculation in the Canary Basin exhibits a three-banded structure, observable throughout the year (Fraile-Nuez et al., 2010; Klein and Siedler, 1989; Volkov and Fu, 2010, 2011). One of these branches extends into the Gulf of Cadiz (Candela, 2001; Sala et al., 2015), while the easternmost branch contributes to the Canary Current (CC) between Madeira and the African coast (Machín et al., 2006; Pérez-Hernández et al., 2013; Stramma, 1984). The CC flows relatively weakly, transporting approximately 3–4 Sv in a southwesterly direction parallel to the African coast (Pelegrí et al., 2005). The CC also receives contributions from the Portugal Current (PC), which flows southward off the Iberian Peninsula, although this interaction is more discernible during the summer and autumn seasons (Machín et al., 2006; Pérez-Hernández et al., 2013).

In this oceanographic context, the present study aims to highlight the oceanic connection that exists between the fisheries of the northeastern coasts of the USA and Canada and plastic waste received in Macaronesia. To carry it out we designed a set of experiments where virtual particles were released and tracked both forward and backwards in order to account for the major ocean circulation pathways influencing the spread of these tags prior to their arrival in Macaronesia. Additionally, these experiments were analysed to assess the model's ability to accurately capture the time scales of the phenomenon, comparing the results with the observational data.

2. Material and methods

2.1. Collection of plastic tags

The recurrent observation of these plastic tags has been undertaken by the Marine Ecophysiology group (EOMAR) from the Universidad de Las Palmas de Gran Canaria and OKEANOS from the Universidade dos Açores – Instituto de Investigação em Ciências do Mar. These groups have conducted periodic samplings since 2016 in the Canary Islands and Azores Islands, respectively.

To expand the plastic tags database even further, a citizen engagement initiative has been implemented, allowing individuals to report the discovery of lobster trap tags. The response has been remarkable, with tag findings connecting both sides of the Atlantic Ocean at subtropical and subpolar latitudes, contributing valuable data to the research efforts. Fig. 2 provides an overview of the locations where EOMAR, OKEANOS and citizens have gathered these plastic tags in Macaronesia.

Each tag attached to the traps features a printed code (Department of Marine Resources, 2022; Government of Canada, 2013). This printed code provides valuable details, including the fisherman's license number (the trap's owner), the Lobster Management Area, the sequential tag number, and other relevant information (Personal Communication with managers of Fisheries, June 15, 2022). However, it's worth noting that while the fisheries in the USA provide the year in the printed code, the fisheries in Canada use a colour code system that follows a 3-year cycle, leading to some uncertainty in assigning the specific year of use, which it is not printed on the tags (Government of Canada, 2013). In both cases, USA and Canada, lobster fishing is allowed year-round, so that the exact date within the year loses relevance for our study (Government of Canada, 2011; NOAA Fisheries, 2023). Two examples of lobster plastic tags are shown in Fig. 3.

2.2. Particle tracking algorithm and velocity field

The virtual particle tracking algorithm utilised here is based on a first-order differential Eq. (1), solved using the 2nd order Runge-Kutta method.

$$\frac{d\vec{x}}{dt} = \vec{v}(x, y, t), \tag{1}$$

where $\vec{v}(x, y, t)$ is the velocity of the ocean currents at position and time (x,y,t), along with an initial condition $x(t_0) = x_0$. For further details of this method, we refer to the literature (van Sebille et al., 2018; Nordam and Duran, 2020).

This approach allows for the tracking of virtual particles through a sequence of linearly interpolated 2-D velocity fields (Andruszkiewicz

[1] USA: https://www.fisheries.noaa.gov/resource/map/lobster-management-areas.Canada: https://lobstercouncilcanada.ca/all-about-lobster/sustainability/.

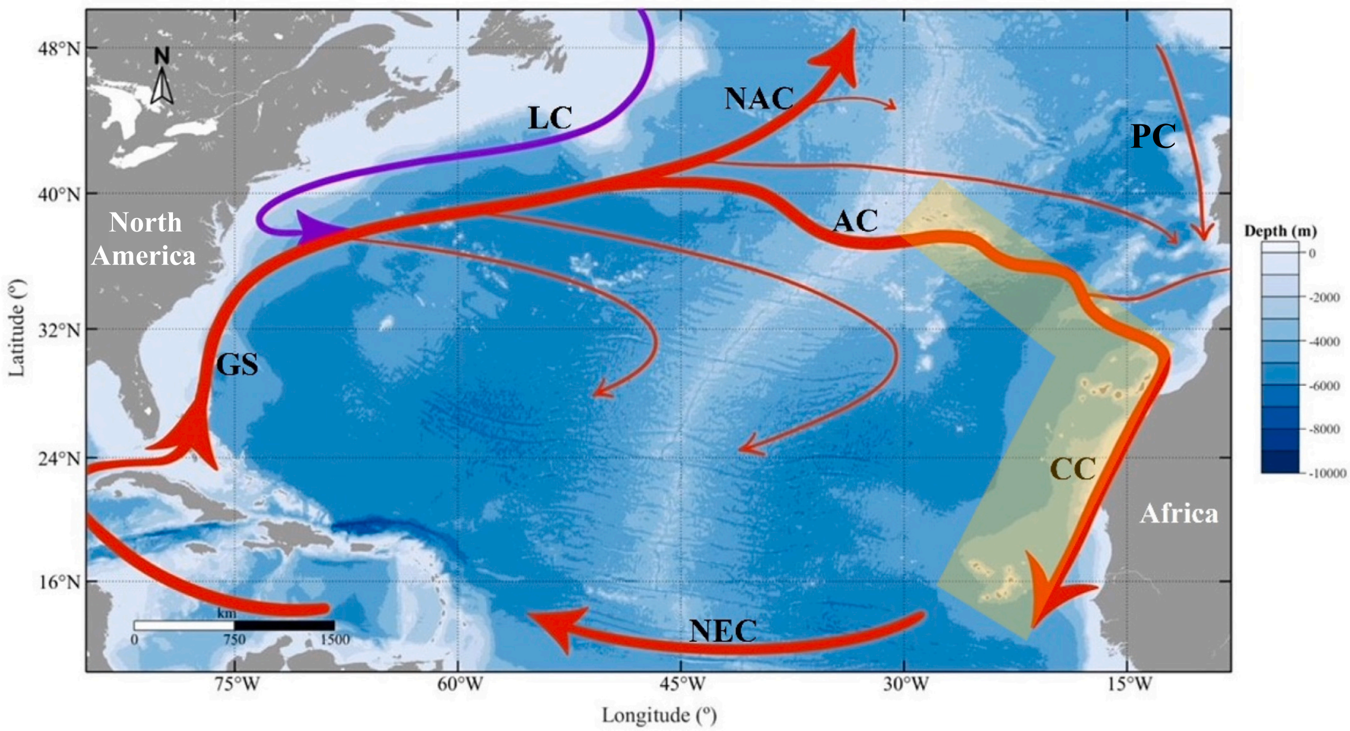

Fig. 1. Surface circulation of the North Atlantic depicted in a sketch (arrows) overlaid on a bathymetric map presented in shades of blue. The main components of the circulation are indicated by the following acronyms: Labrador Current (LC), Gulf Stream (GS), North Atlantic Current (NAC), Azores Current (AC), Portugal Current (PC), Canary Current (CC), and North Equatorial Current (NEC). The yellow semi-transparent polygon highlights the location of the Macaronesia archipelagos, including the Azores Islands, Madeira, Canary Islands, and Cape Verde. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2019; Nordam and Duran, 2020). Notably, we have not considered sinking in this model since the plastic lobster tags are not affected by biofouling, thus maintaining their positive buoyancy (Kooi et al., 2017; Onink et al., 2019).

With this principle it is possible to find the position of particles in the following time steps of a simulation based on the already mentioned velocity fields. In this algorithm, particles which exit the domain or reach the land will stop and maintain their last position until the end of the simulation, without beaching parameters.

To obtain the total velocity[2] field required for the simulations, we used the "Global Ocean Physics Reanalysis" numerical model, denoted as GLORYS12V1. This product is a CMEMS global ocean eddy resolution reanalysis, with the NEMO platform as its core component. Surface data from the ECMWF ERA-Interim and ERA5 reanalyses were used to force the model. GLORYS12V1 has a horizontal resolution of 0.083° (1/12°) and covers the temporal extent from January 1st, 1993, to December 31st, 2020. For our purposes, we focused solely on daily surface data (Drévillon et al., 2022), and we will refer to this product as GLORYS.

2.3. Grids for particle release and forward/backward simulations

The tags will be spread throughout the North Atlantic, and for this study two different approaches were adopted focusing on those heading towards Macaronesia, where beaches have been sampled to build our current database. Firstly, to simulate the trajectory of plastic tags from the lobster fishing regions (Fig. 1) to the Macaronesia archipelagos, we defined a grid of virtual particles covering all the fishing areas and let the particles perform forward trajectories. The grid featured a separation of 0.12°, totalling 9460 particles.

Secondly, to determine the potential origins of plastic tags found in the Macaronesia archipelagos, we established two separate grids of virtual particles to track backward trajectories: one covering the Azores Islands and the other covering the Canary Islands. On these grids the selected resolution was 0.1°, totalling 2244 particles released in the Azores Islands grid and 2191 particles for the Canary Islands grid. Here it is important to notice that the difference in number of particles between both grids is due to the different shape of the mesh used on each one. The locations of these particle release grids are shown in Fig. 4.

3. Results

3.1. Tags analysis

The number of tags collected is presented in Fig. 5, distinguishing between three different origins: USA, Canada and of unknown origin. While the origin for a large quantity of tags could not be identified, the majority of the tags came from the USA. The analysis poses a significant challenge in retrieving accurate information on the year and location of use by fisheries. As mentioned in the Material and methods section, tags from USA contain the year of fishing printed on them, allowing us to determine in which year each tag was released. In contrast, since this information is not available for the Canadian tags, only the US tags have been considered for the purpose of quantifying tag arrivals by year (Fig. 6).

Analysing USA tags revealed that the year 2007 had the most tags in the database, indicating that they came from lobster traps deployed in that year. Notably, some tags arrived at the Macaronesia archipelagos in <2 years, highlighting the potential for relatively rapid transit of these plastic tags across the Atlantic Ocean.

Given that the 2007 fishing year is the one for which the most tags

[2] We refer to total velocity as the sum of geostrophic and ageostrophic currents.

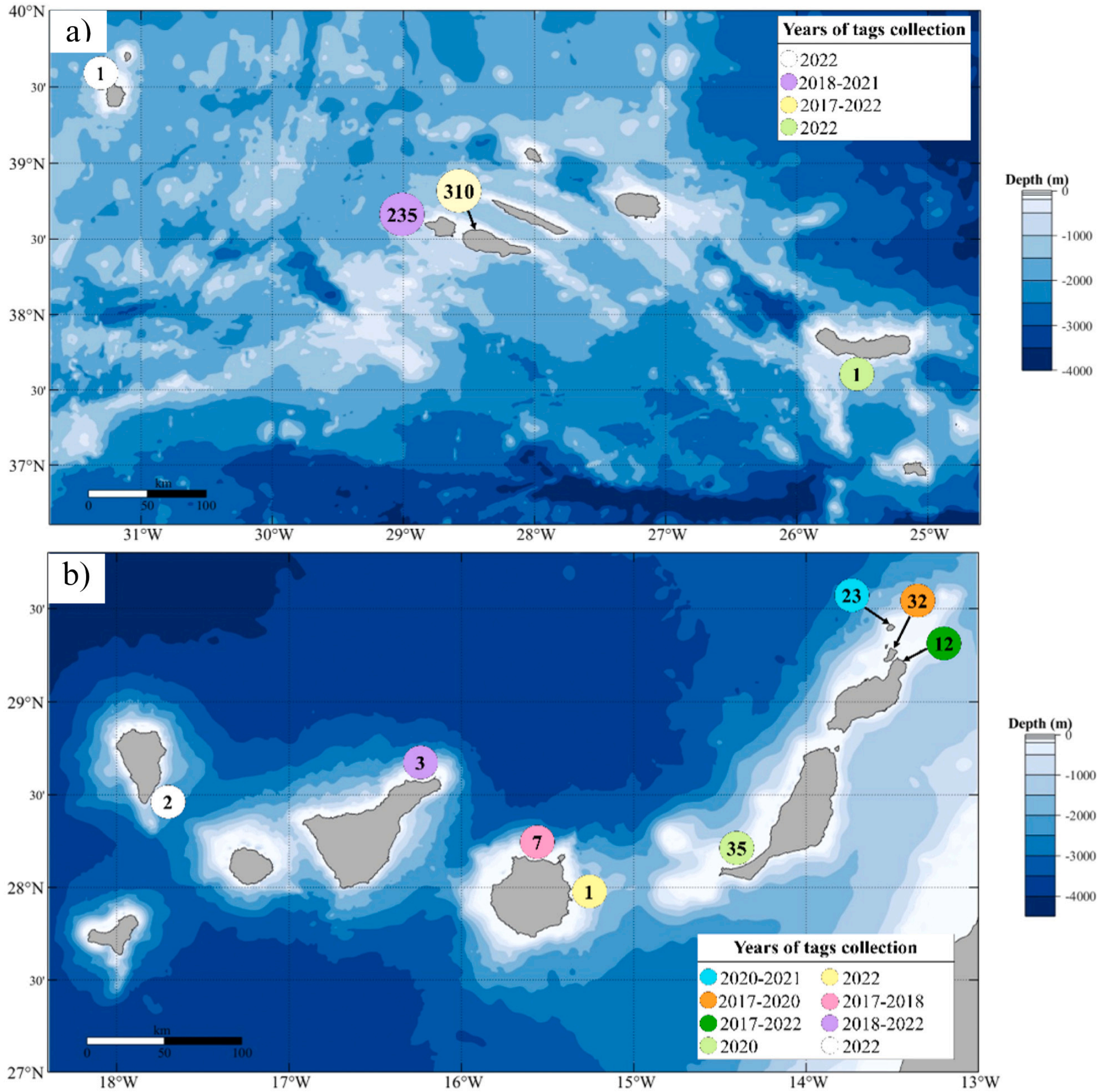

Fig. 2. Distribution of plastic tags collected on beaches in the a) Azores Islands and b) Canary Islands. The dots on the map indicate the number of plastic tags gathered on each beach, with their positions aligned based on the orientation of the respective beach.

have been found in Macaronesia, in order to reconstruct the possible trajectories of these tags, we conducted forward simulations starting in 2007. It is important to note at this point that for the selection of the year of the simulations, we rely solely on the number of tags received per year of origin. For this we know that the number of licences[3] varies little significantly over the years and the sampling efforts have been constant since its inception. After a series of sensitivity tests (not shown), we decided three-years of simulations represented an appropriate run length which provides the virtual particles with enough time to distribute widely over the basin. Accordingly, the forward simulation that we present starts on 01/01/2007 and the backward simulation starts on 31/12/2009. In both cases we worked with a single experiment. These numerical experiments utilised the total velocity fields from GLORYS, encompassing both geostrophic and wind-driven velocities.

By running these simulations, we aimed to gain a comprehensive understanding of the potential trajectories and dispersion patterns of plastic tags released from the lobster fisheries in 2007. The inclusion of both geostrophic and wind-driven velocities allows us to account for the complex oceanic dynamics and atmospheric influences that may have driven the movement of these plastic tags across the Atlantic Ocean.

3.2. *Distribution of virtual particles*

Instead of focusing on individual trajectories, our primary interest lies in understanding the overall distribution of virtual particles within the domain. To achieve this goal, we conducted a post-simulation analysis, counting particles in $0.25^\circ \times 0.25^\circ$ bins after the three-year period. This analysis provides a comprehensive view of the main pathways and particle density, which are crucial in identifying areas with the potential for marine pollution accumulation or dispersion.

[3] https://www.maine.gov/dmr/fisheries/commercial/fisheries-by-species/lobsters/maine-lobster-fishing-license-and-trap-tag-counts.

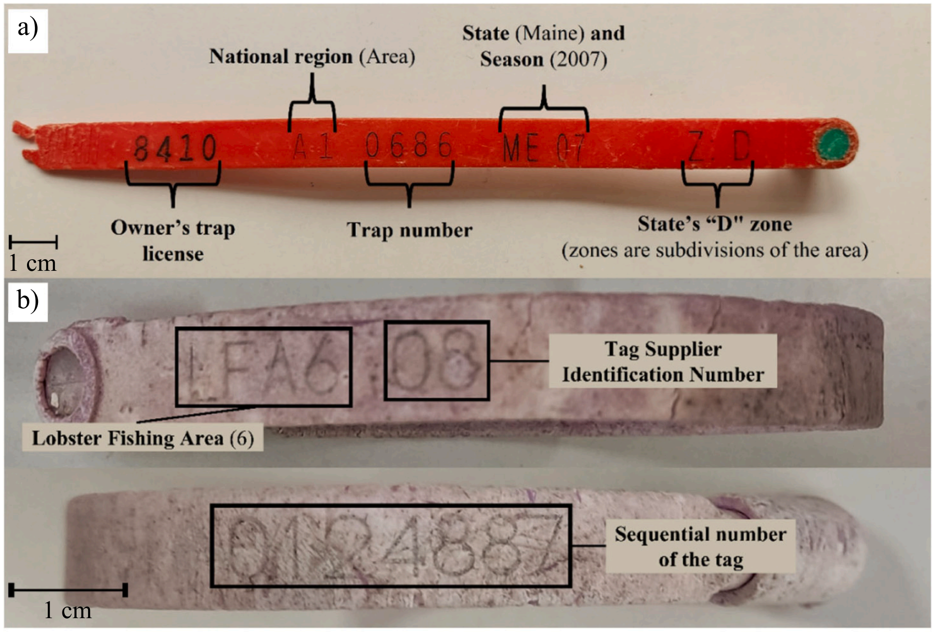

Fig. 3. Examples of lobster trap tags from a) the USA and b) Canada codes. The Canada plastic tag is presented in two pictures to ensure all printed information is highlighted.

3.2.1. *Forward simulations*

In the forward simulations, virtual particles were released in the fishing regions of the USA and Canada. The objective was twofold: to identify the primary pathways that plastic tags are likely to follow before reaching Macaronesia and to pinpoint the key areas where particle retention is most prominent. Fig. 7a illustrates the particle density across the entire domain of the simulations, offering valuable insights into the distribution patterns and potential areas of accumulation or dispersion for marine pollution.

Particles are broadly distributed across the full domain of the subtropical gyre, encompassing the coasts of North America, Western Europe, Northwestern Africa, and notably, Macaronesia (Fig. 7a). An outflow to the north is observed between 30°W and 15°W, above approximately 50°N, indicating the presence of the North Atlantic Current. Two main areas exhibit high particle density: the centre of the basin embedding the Azores Islands in the east, and the fishing regions of the USA and Canada in the west. The Canary Islands and Cape Verde appear, by comparison with the latter, less polluted in virtual particles. Another notable feature is the low particle density along the path of the Gulf Stream, which may initially seem counterintuitive, given its role as a major pathway for water mass transport from the western to the eastern side of the basin.

The low particle density along the Gulf Stream path can be attributed to the manner in which virtual particles released in the fishing regions disperse from the western basin of the North Atlantic Ocean and initiate their journey towards Macaronesia. As these particles gradually exit the fishing regions of the USA and Canada, they join the Gulf Stream between 65°W and 50°W at 35°–40°N, where the current experiences increased variability due to its meandering and the presence of numerous mesoscale eddies (Muglia et al., 2022). Thus, the Gulf Stream, in its most intense part, acts as a barrier between the fishing regions and the centre of the subtropical gyre.

3.2.2. *Backward simulations*

In the backward simulations, virtual particles were released in the Macaronesia region to identify the main pathways of particles arriving at Macaronesia and to trace back their potential source areas of marine pollution (Fig. 7b). Unlike the forward trajectories, backward simulations reveal distinct patterns. The majority of particles departing from the Azores Islands tend to flow upstream along the upper branch of the North Atlantic Subtropical Gyre, influenced by the Azores Current and the Gulf Stream. The distribution of particles captures their origin coming from the northwest. This is supported by the highlighted domain of the Labrador Current near Newfoundland (−52°W/47°N approximately), and a narrow band with high particle density from 85°W to 65°W denoting the source waters coming from the Gulf Stream. Thus, for the grid covering the Azores Islands, the Gulf Stream appears to be the primary source pathway for particles arriving at the Azores.

On the other hand, the main source pathway of particles departing from the grid covering the Canary Islands is oriented towards the Iberian Peninsula and the Northwestern African coast, subsequently turning westward at approximately 45°N.

3.3. *Quantitative analysis of particle landing*

We present in Table 1 a quantitative overview of the processes described in the previous sections based on the numerical simulations in Fig. 7. By analysing these results, we gain valuable insights into the patterns of particle accumulation and dispersion, particularly in regions such as the Azores and the Canary Islands. The quantitative analysis also enables us to understand the relative frequency of particles arriving at these locations and their potential sources. Furthermore, it allows us to identify the main regions from which marine pollution is likely to reach the Macaronesia archipelagos.

In the forward simulations, the data from GLORYS reveal a significant disparity in particle distribution between the Azores archipelago and the Canary Islands. The percentage of particles reaching the Azores is approximately five times higher than those reaching the Canary Islands: 4.12 % and 0.76 %, respectively.

Similarly, in the backward simulations, a comparable pattern emerges. The percentage of particles originating from the Azores and arriving at the fishing regions is about ten times higher for the period 2009–2007, compared to those from the Canary Islands: 22.52 % and 2.29 %, respectively.

These findings underscore the pronounced oceanic connectivity between the Azores archipelago and the surrounding areas, indicating a higher likelihood of particle accumulation and retention in the Azores region. Conversely, the relatively lower percentages observed for the

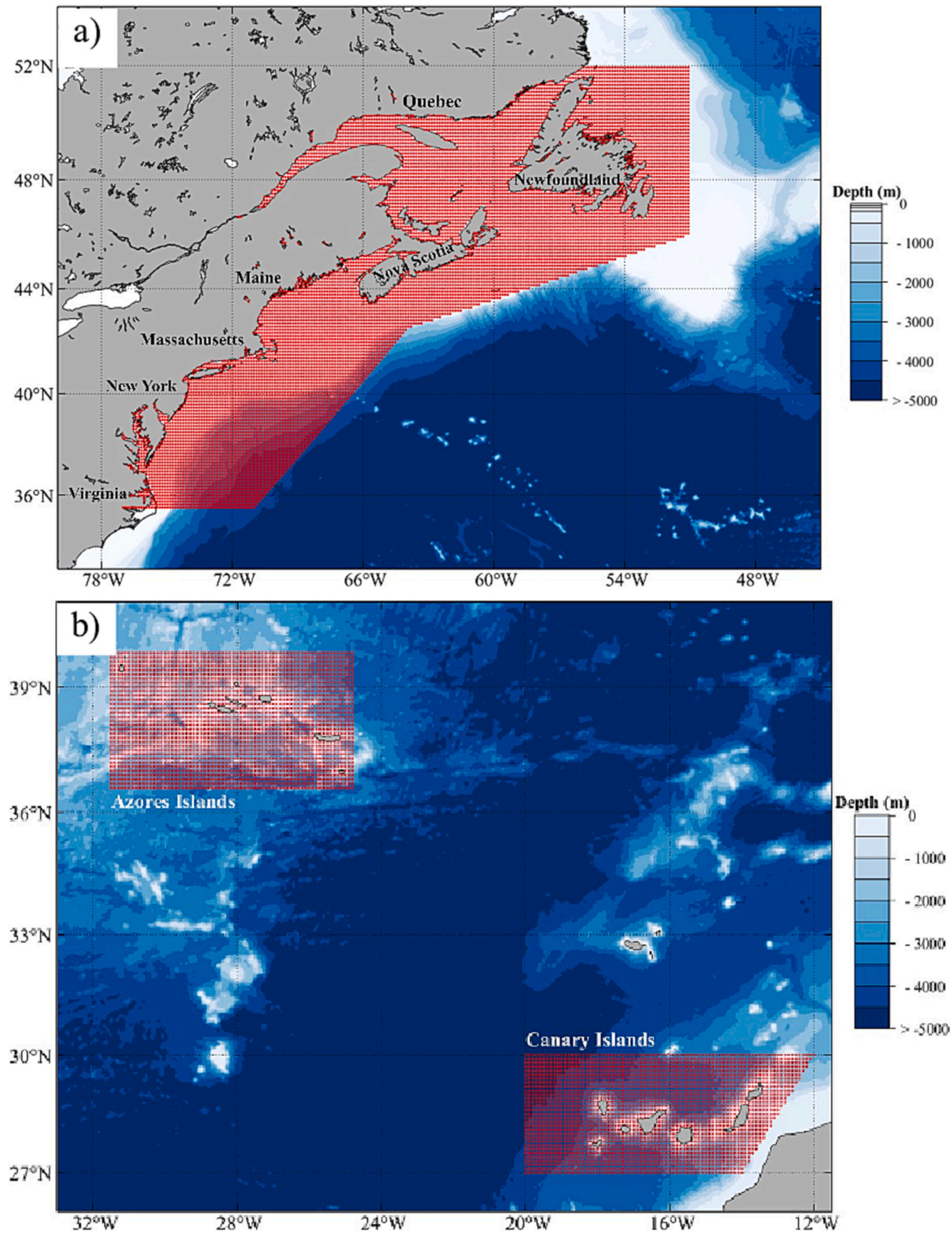

Fig. 4. Grids with the initial position of the virtual particles with a resolution of a) 0.12° and b) 0.1°.

Canary Islands suggest a less significant contribution to the marine pollution arriving at the easternmost Macaronesia archipelagos.

The data in Table 1 enhances our understanding of the spatial distribution and source pathways of plastic tags on the Macaronesia region, providing a quantitative view of the potential impact of marine plastic pollution arriving to this area.

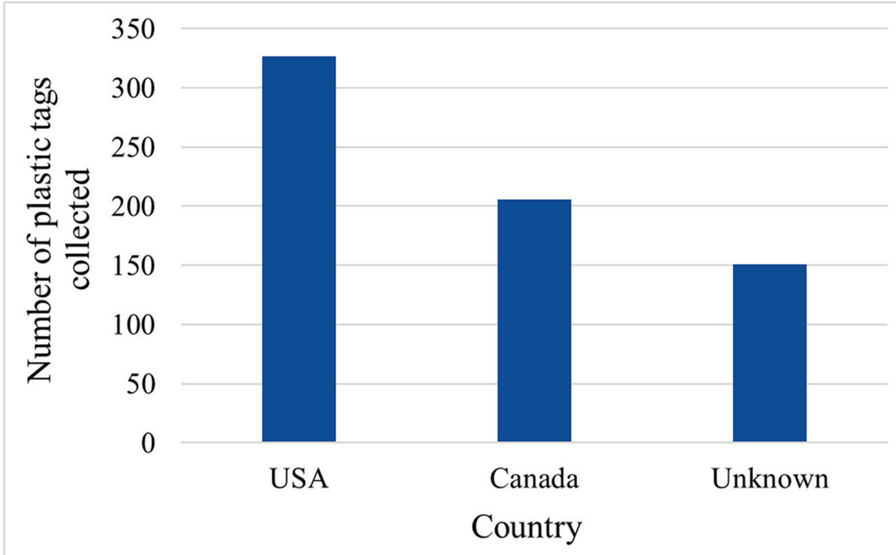

Fig. 5. Number of tags collected from each country.

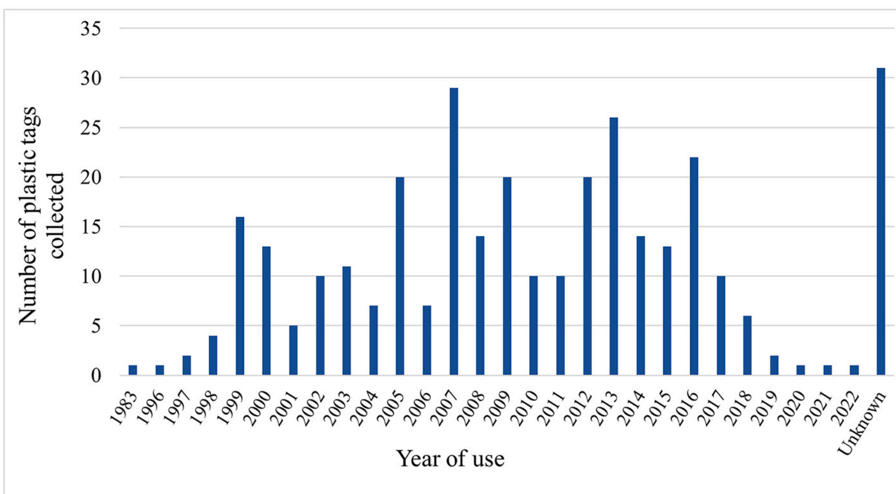

Fig. 6. Distribution of tags collected per fishing season in the USA fishing regions. USA tags with unclear printed codes were classified as originated from an unknown year.

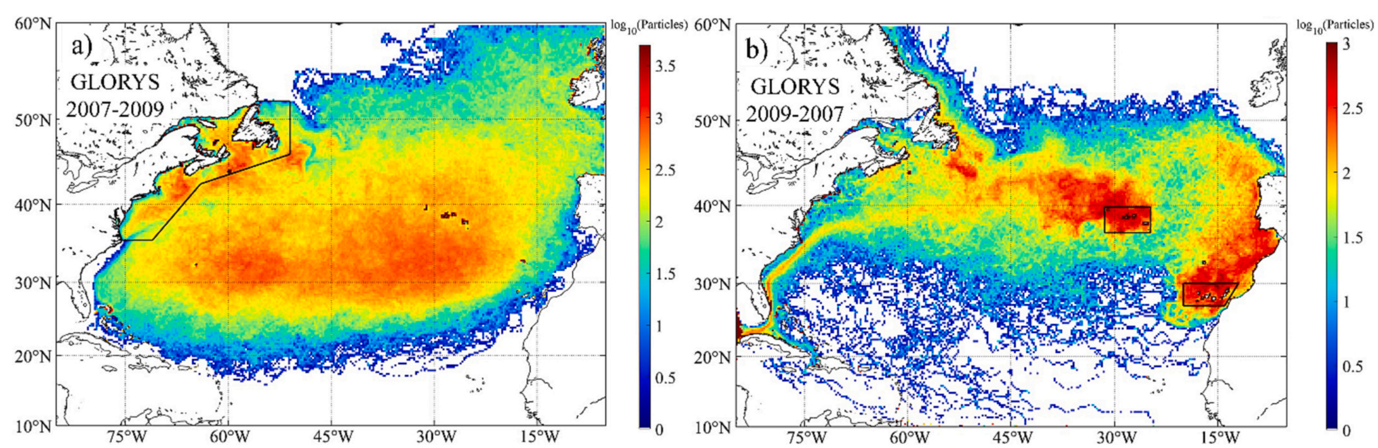

Fig. 7. Number of particles resulting from cumulative sum up of the number of particles per grid cell every time step during the 3-year simulation of a) forward simulations and b) backward simulation. The black polygons indicate the particle releasing area. The resolution of the initial particle positions was 0.12° in forward simulation and 0.1° in backward simulation. Shades of colours follow a logarithmic scale.

Table 1
Percentage of particles (respect to the total released particles) located in the different areas of interest at the end of the forward and backward numerical simulations. Acronyms stand for: Az (Azores Islands), Can (Canary Islands). The area considered for each analysis is the same of particles initial grids, as presented in Fig. 7.

	Time range	Initial grid resolution	Az arrivals (%)	Can arrivals (%)	Az – fishing regions	Can – fishing regions
Forward	1/1/2007–12/31/2009	0.12°	4.12	0.76	–	–
Backward	12/31/2009–1/1/2007	0.1°	–	–	22.52	2.29

3.4. Assessing the arrival timeline of plastic tags

After departure from the fishing regions (forward experiment), we tracked the time taken for the fastest virtual particles to reach Macaronesia. The entrance into Macaronesia follows the arrival of a given particle to either the Azores Islands' or Canary Islands' boxes as defined in Fig. 4(b). As one could expect, the Azores Island appears more directly connected to the fishing regions than the Canary Islands, provided that the time travel for the fastest virtual particle was about half the time than its analogous took to reach the Canary Islands (168 days against 360 days).

Like messages in bottles at the mercy of currents, bearing the date imprinted at the moment they were set adrift in the sea by their senders, plastic tags from lobster traps tell the story of the North Atlantic Subtropical Gyre in an unprecedented manner. Nevertheless, the interpretation of this information is not straightforward, as it is associated with several uncertainties. Firstly, we are uncertain about the time elapsed between the deployment of the trap at sea and the moment the tag was released. Secondly, we lack knowledge regarding the time the tag spent on the arrival beach before being detected. Consequently, from an observational perspective, we can only indicate a timeline underestimation of the tags that arrived faster in Macaronesia, considering that the actual times were likely shorter. Table 2 presents the arrival times for these tags, which departed from Maine, Rhode Island, and Massachusetts in 2018, 2020, and 2022, respectively; and arrived on the shores of Cofete beach (Canary Islands), Faial (Azores), and Pico (Azores) in less than a year. These observational values align with those obtained from simulations mentioned in the previous paragraph.

4. Discussion

The increasing presence of plastic in marine ecosystems highlights the urgent need for improved waste management practices in today's society. However, these new challenges also offer an opportunity to reinvent ourselves and develop innovative tools to expand our knowledge in oceanography and address the issue of marine pollution. Plastic debris, owing to its resistance and durability, serves as a unique tracer, providing valuable insights into physical dynamics and transport pathways in the ocean (van Sebille et al., 2018). In this work, we introduce, for the first time, the oceanic pattern linking the northeastern coast of the USA and Canada to Macaronesia.

This study focuses on a specific case of plastic tags, which act as perfect tracers due to the information printed on them, revealing their origin. The arrival of plastic tags from lobster traps in Macaronesia, originating from the northeastern USA and Canada, indicates the existence of transport pathways connecting these regions. Analysing these pathways is crucial to increase our understanding of the sources of marine litter affecting this area.

Virtual Lagrangian trajectories have been employed by several authors to determine the exposure or distribution of marine pollution (Delpeche-Ellmann and Soomere, 2013; Liubartseva et al., 2018; Mohtar et al., 2018; van Sebille et al., 2015), demonstrating the effectiveness of this tool as a complementary instrument to fieldwork (Hurlburt and Hogan, 2000; Werner et al., 2007). In a real case like the one presented here, the combination of forward and backward simulations provides a comprehensive explanatory vision, enhancing our understanding of oceanic connectivity and plastic transport (Cardoso and Caldeira, 2021; Mohtar et al., 2018; Sala et al., 2015).

During the forward simulations, particles released in the fishing regions of the USA and Canada exhibited considerable variability, dispersing across a vast area of the North Atlantic and arriving to the coasts of North America, Western Europe, Northwestern Africa, and Macaronesia. These results support the hypothesis that plastic tags from lobster traps reaching Macaronesia were transported by ocean currents from their source areas, the fishing regions of the USA and Canada.

As shown in Fig. 7a, regions with higher particle density after three years of simulations were identified within the Gulfs of Maine and Saint Lawrence, characterised as areas of high residence time (Koutitonsky and Bugden, 1991; Manning et al., 2009), and the central domain of the North Atlantic basin. This might potentially explain why a higher number of plastic tags were found in the Azores Islands compared to the Canary Islands, located farther east (Fig. 3).

Interestingly, a low particle density signature southeast of the fishing regions corresponds to the Gulf Stream. When particles exit the fishing regions, they encounter the highly variable velocity field of the Gulf Stream, causing their dispersion in different directions. Some particles follow the Labrador Current before being influenced by the northern edge of the Gulf Stream (~35°N) and transported northeastward. Others flow eastward directly from the fishing regions, influenced by the eastern branch of the Labrador Current at ~45°N (Fig. 1). At approximately 45°W, a significant portion of particles flows northward, following the North Atlantic Current, consistent with previous results (Cividanes-García, 2022) and supporting the presence of lobster plastic tags in the Northern North Atlantic Ocean.

In the backward simulations (Fig. 7b), the low density of particles observed along the Gulf Stream for the forward simulations is now characterised by high values. This shift results from the backward simulations tracing all potential sources of marine pollution arriving at Macaronesia.

The dispersion of particles originating from the east, outside the influence of the Azores Current, is reduced, leading to increased particle density along the Gulf Stream and the Labrador Current. This outcome indicates that the Gulf Stream is one of the primary sources of virtual particles arriving at the Azores Archipelago. For the Canary Islands, particles do not originate directly from the Azores Current northwest of the archipelago. Instead, their origin appears to be located in the eastern margin of the North Atlantic, as suggested by the relatively high density of particles northwest of the Iberian Peninsula (Fig. 7b). These results align well with previous studies employing similar procedures (Cardoso and Caldeira, 2021; Sala et al., 2015). The pattern observed in the

Table 2
Summary table of the arrival timeline of the fastest three plastic tags to reach the Azores and the Canary Islands from the fishing regions.

Country of origin	Federal fishing zone	State code	State	Year	Found (island)	Found (year)
USA	A1	ME	Maine	2018	Fuerteventura	2020
USA	A3	RI	Rhode Islands	2020	Faial	2020–2021
USA	A3	MA	Massachusetts	2022	Pico	2022

backward simulations offers a plausible explanation for the higher number of plastic tags collected in the Azores Islands compared to the Canary Islands (Fig. 3 and Table 1), indicating a different distribution of plastic tags within Macaronesia, consistent with the forward simulations.

The interaction with the coasts where fisheries are located is less prominent in backward trajectories compared to the high particle density observed along the Gulf Stream. This observation is likely due to the fact that the lobster fishing regions of the USA and Canada are not the primary source of plastic pollution to Macaronesia (Cardoso and Caldeira, 2021). However, they still contribute a considerable percentage as highlighted in Table 1; a concerning quantitative view of the impact of plastic tags arriving at Macaronesia.

5. Conclusions

The dynamics associated with the Labrador Current and the Gulf Stream have been identified as the driving forces responsible for transporting plastic tags from lobster traps across the North American western coasts to the eastern basin of the North Atlantic Ocean. By combining forward and backward trajectories of virtual particles, we have demonstrated that plastic waste originating from the fishing regions of the USA and Canada is dispersed over a large area in the North Atlantic, with only a small percentage reaching Macaronesia. This suggests that a higher amount of these tags might be still either floating around in the real ocean or reaching other locations in the North Atlantic Ocean coastline.

Notably, the Azores Islands are more susceptible to the arrival of lobster plastic tags that are accidentally released in the fishing regions of the USA and Canada compared to the Canary Islands.

Furthermore, we find that results from the 3-year forward simulation indicate arrival times of virtual particles to Macaronesia in less than a year; in agreement with observational-based estimates following the timeline of plastic tags arriving faster after deployment in the northeastern coasts of the USA and Canada.

We strongly advocate for the involvement of citizen science as a promising tool to enhance the effectiveness of monitoring processes. Citizen participation allows for the regular updating of the database through the input of individuals who encounter plastic tags near the coasts. This collective effort can significantly contribute to tracking plastic pollution and understanding its distribution patterns, supporting further research and initiatives to combat marine pollution.

In summary, this work sheds light on the complex oceanic transport pathways of plastic waste, particularly plastic tags from lobster traps, from the North American coast to the Macaronesia region. Also, the combined use of forward and backward simulations has provided insightful information into the dispersion of plastic waste across the North Atlantic. The results highlight the need for improved waste management practices and underscore the importance of citizen science in monitoring and addressing marine pollution. By advancing the understanding of plastic pollution dynamics, we can support experts and entities to work towards more effective strategies to protect marine ecosystems and promote a sustainable future.

CRediT authorship contribution statement

Marcos Cividanes: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Borja Aguiar-González:** Conceptualization, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing. **May Gómez:** Funding acquisition, Methodology, Writing – review & editing. **Alicia Herrera:** Funding acquisition, Methodology, Writing – review & editing. **Ico Martínez:** Methodology, Writing – review & editing. **Christopher K. Pham:** Funding acquisition, Methodology, Writing – review & editing. **Laura Pérez:** Methodology, Writing – review & editing. **Francisco Machín:** Conceptualization, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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