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Distribution and transport of microplastics in the upper 1150 m of the water column at the Eastern North Atlantic Subtropical Gyre, Canary Islands, Spain

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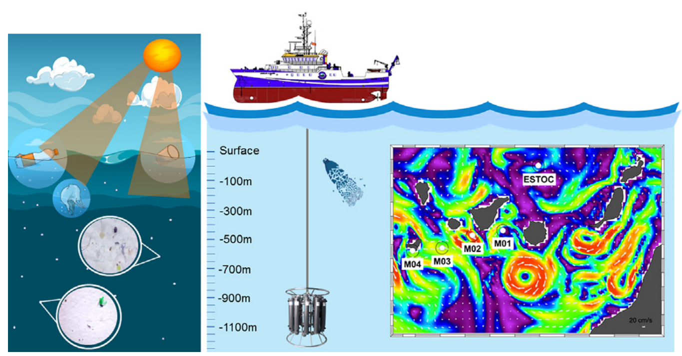
HIGHLIGHTS

- Microplastic (MP) present at the water column until at least 1150 m depth
- MP transported by oceanic dynamic as passive drifters horizontally and vertically
- MP distribution related with convergence areas and mesoscale convective flows
- Differences at MP vertical distribution according to season and latitude

GRAPHICAL ABSTRACT



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ABSTRACT

Nowadays it is widely known that pollution by microplastics (MP) at the open ocean covers immense areas. Buoyant plastics tend to accumulate in areas of convergence at the sea surface such as subtropical gyres, while non-buoyant plastics accumulate at the seafloor. However, previous studies have revealed that the total amount of plastic in the different oceans is not well correlated with the concentrations measured at the sea surface and the sea floor, evidencing a significant amount of missing plastic in the oceans. This deviation could be related to an underestimation of the role played by small fragments of plastic and fibers in the oceans. Furthermore, microplastic fragments with a density lower than the density of seawater have been gathered hundreds of meters below the sea surface in the Pacific Ocean due to their size and shape.

The main objective of this study is to carry out, for the first time, an equivalent analysis along the water column for the Atlantic Ocean. In that sense, a total number of 51 samples were collected during four different oceanographic cruises between February and December 2019, from the sea surface down to 1150 m depth at the open ocean waters of the Canary Islands region (Spain). For each sample, 72 l of seawater were filtered on board with a mesh size of 100 μm, where the presence of microplastics has been clearly observed. Our results reveal the presence of microplastics at least up to 1150 m depth, at the Northeastern Atlantic Subtropical Gyre with noticeable seasonal differences. The spatial distribution of these small fragments and fibers at the water column is mainly related to the oceanic dynamics and mesoscale convective flows, overcoming the MP motion induced by their own buoyancy. Moreover, these microplastics have being transported by the ocean dynamics as passive drifters.

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1. Introduction

Marine pollution by plastic is a world-wide concern (European Commission, 2019; Law, 2017). Microplastic (MP) covers vast areas of the open ocean, and buoyant plastic tends to accumulate at surface convergence areas like subtropical gyres (Eriksen et al., 2013, 2014; Law et al., 2010; Lebreton et al., 2018; Sebille et al., 2015).

MP has been defined as plastic smaller than 5 mm (Baztan et al., 2017; Bergmann et al., 2017; Masura et al., 2015; Reisser et al., 2015), which are divided into primary MP, i.e. those manufactured directly of this size such as virgin pellets, and secondary MP, those formed due to fragmentation processes (Hidalgo-Ruz et al., 2013; Ivar Do Sul and Costa, 2014; ter Halle et al., 2016).

Outputs from models focused on evaluating the plastic intake from land to the ocean present a misfit with respect to experimental data collected at the different oceans, unveiling an important unaccounted amount of MP in the oceans (Jambeck et al., 2015; Koelmans et al., 2017). At 2004, when Thompson highlighted the marine MP concern, he already suggested that small plastic fragments and fibers may have been underestimated (Thompson et al., 2004). This fraction of small MP could be the answer to the deviations detected between models and in situ observations.

Small MP (SMP, 1–1000 μm) is the fraction less studied, so its abundance presents a large uncertainty between 2 and 4 orders of magnitude higher than large MP (LMP,1–5 mm) (Poulain et al., 2018). Most MP sampling at the open ocean is usually performed with 0.33 mm mesh size (Cole et al., 2011), so the fraction below this value has been frequently excluded from the MP monitoring (Andrady, 2017), despite the abundance of MP increases exponentially when particle size decreases (Song et al., 2014).

The buoyancy of MP is determined by the initial density of the plastic and can vary according to the plastic type (Chubarenko et al., 2016; Nerland et al., 2014); later on, physical-chemical degradation processes and biofouling on their surface may alter their density and consequently produce a variation in their buoyancy (Kooi et al., 2017; Kowalski et al., 2016).

The most abundant buoyant MP in the ocean are high and low-density polyethylene (PE) and polypropylene (PP) (Chubarenko et al., 2016), which tend to float at seawater according to their density. They are transported by surface currents and waves into coastal regions, mainly beaches, as it is the case of virgin pellets (Herrera et al., 2018; Miller et al., 2017). However, SMP may be observed at the water column due to their gradual sinking velocity that can be lower than 1 mm s^{-1} (Bagaev et al., 2017; Kaiser et al., 2019), and remain suspended or with slow sinking rate due to the effect of the ocean dynamics and turbulence (Poulain et al., 2018).

Most field studies have focused their sampling at the sea surface (up to a maximum depth of 20 m) (Kanhai et al., 2017; Poulain et al., 2018) or near the bottom (Bagaev et al., 2018). Below 20 m depth, the presence of MP along the water column has been reported by only few studies. Doyle et al. (2011) reported the presence of MP by sampling between 0 and 212 m depth with bongo nets, a sampling system that cannot provide the depth where the MP was collected. Conversely, two recent studies at the Pacific Ocean apply a rather different strategy and show that MP, mainly of the buoyant plastic type (density lower than seawater density), is spread over the water column until at least 2000 m depth (Egger et al., 2020), with a MP concentration that can be even higher than that at the sea surface (between 200 and 600 m depth) (Choy et al., 2019).

There is still a considerable uncertainty about the processes involved in the distribution of MP all the way down to the deep sea sediments from the sea surface (Egger et al., 2020; Galgani et al., 2015). The lack of studies providing MP concentrations at the water column is preventing a comprehensive global assessment of the final fate of plastic debris into the oceans. SMP concentration at the water column is not addressed in forecasting models, thus underestimating the total amount of plastic found in the marine environment (Kooi et al., 2016).

Several studies relate plastic debris transport and accumulation with the ocean dynamics (Ballent et al., 2013; Onink et al., 2019). On the one hand, it is highlighted the MP accumulation at the subtropical gyres, as they mainly act as convergence areas in the upper ocean (Barnes et al., 2009; Cózar et al., 2014; Eriksen et al., 2014; Maximenko et al., 2012; Sebille et al., 2015). On the other hand, recent studies relate thermohaline currents with MP accumulation at benthos (Kane et al., 2020). Finally, in addition to the effect of global accumulation areas, it could be remarkable the relevance of mesoscale activity in the MP distribution. This is particularly significant in the Canary Islands area, a place where it has been observed a long-lived eddies pathway named as the Canary Eddy Corridor (Sangrà et al., 2009). This pathway is located south of the Canary Islands and it would be formed by long-lived eddies that last for periods longer that 3 months. The impact of these long-lived eddies in the accumulation of MP is an issue still to be address. In the Atlantic ocean, MP concentration at anticyclonic mesoscale structures could be up to 9 times larger than in cyclonic gyres (Brach et al., 2018).

This manuscript aims at assessing the MP concentration along the water column at the Northeastern Atlantic Subtropical Gyre, by sampling MP fragments and fibers from the sea surface down to 1150 m depth at 5 different oceanographic stations during four different cruises carried out in 2019.

2. Materials and methods

2.1. Study area

Four different oceanographic cruises were carried out at the Canary Islands region for MP collection in 2019: PLOCAN0219, VULCANA-II-0319, VULCANA-II-1119 and PLOCAN1219. During these cruises five different stations were defined, all of them sampled twice in the same year: winter and fall (Fig. 1). The northeasternmost one was the open ocean site “European Station for Timeseries in the Ocean Canary Islands (ESTOC)” located at 29°10′N and 15°30′W (sampled in February and December'19). The 4 additional open ocean stations (M01, M02, M03 & M04) were sampled south of the westernmost Canary Islands (in March and November'19).

2.2. Microplastic sampling and oceanographic variables

51 oceanic MP samples between 0 and 1150 m depth were collected at these five different stations between February and December 2019. Conductivity, temperature and pressure data were collected using a SeaBird 911-plus CTD equipped with dual temperature and conductivity sensors, with accuracies of 0.001 °C and 0.0003 S/m respectively, continuously recording data with a sampling rate of 24 Hz. CTD sensors were calibrated at the SeaBird laboratory before and after the cruises.

Discrete water samples for MP in the water column were collected using a rosette of 24–12-L Niskin bottles (Bagaev et al., 2017).

Six Niskin bottles were closed at every sampling depth (4 different depths per station). A total of 44 water samples were gathered at different depths. Seawater collected was then filtered through 100 μm filters of mesh size (72 l of seawater per MP sample). This filter was washed with Milli-Q water and concentrated in a 47 mm Whatmann GF/F filter for MP evaluation. Samples were kept at −80 °C for later visual assessment and counting. A blank filter was installed on the lab next to the filtration site to discard on board contamination by similar fibers.

Moreover, 7 additional samples were taken from the deepest point of each station up to the surface by filtering 237,6 l of seawater per 100 m depth of the water column with a net of 100 μm of mesh size installed inside one Niskin bottle. The total volume filtered per sample varied according to the station maximum depth (ranging from 222 m and 1152 m depth according to the station).

A VWR® stereo-microscope (model SZB250) was used for MP visual identification, counting and classification.

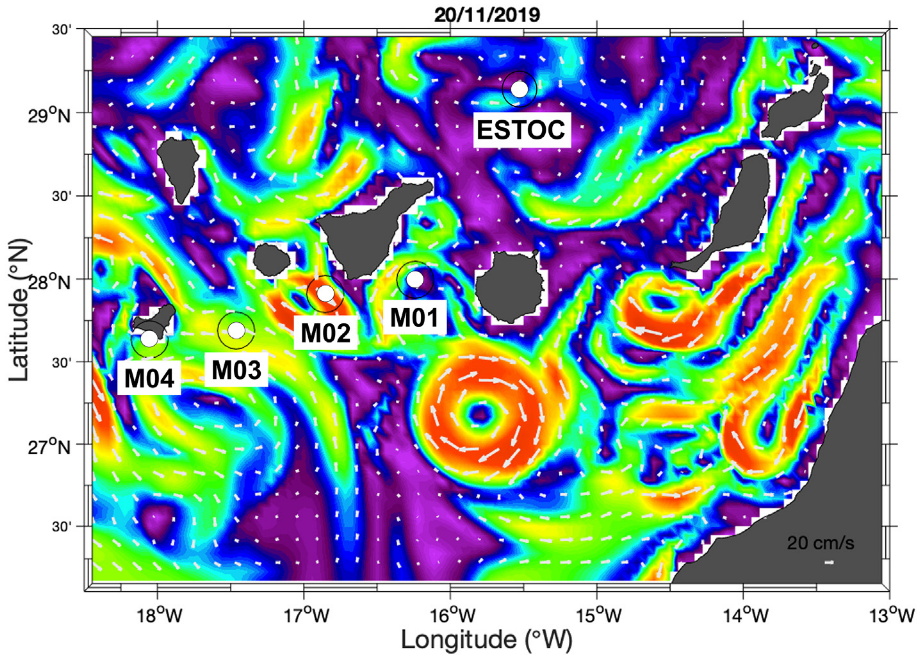

Fig. 1. Map of the studied region with the stations sampled (ESTOC, M01, M02, M03 & M04) between February and December'19. Stations are represented over the sea surface current field modelled for the 20th November 2019.

2.3. Velocity data

Daily velocity data from 2019 at the whole water column were extracted from the operational Atlantic – Iberian Biscay Irish (IBI) Ocean Analysis and Forecasting dataset (https://marine.copernicus.eu). The model is daily run by Nologin in coordination with Puertos del Estado and with the support, in terms of supercomputing resources, of CESGA. The dataset provides a 5-day hydrodynamic forecast including high frequency processes of paramount importance to characterize regional scale marine processes (i.e. tidal forcing, surges and high frequency atmospheric forcing, fresh water river discharge, etc.). A weekly update of IBI downscaled analysis is also delivered as historic IBI best estimates (Sotillo et al., 2015). The system is based on an eddy-resolving NEMO model application run at 1/36° (≈2–3 km) horizontal resolution (Madec, 2008). The velocity data are vertically distributed into a 50 z-levels with a resolution decreasing from approximately 1 m in the upper 10 m to more than 400 m in the deep ocean. In this study the first 32 z-levels were used, covering the depth range from 0.5 to 1500 m depth.

Divergence fields where derived from IBI velocity dataset for each z-level for the first 1500 m of the water column. Divergence and velocity horizontal contours where generated using Matlab R2019b.

3. Results and discussion

3.1. Ocean dynamic and convergence areas

As passive drifters, the MP spatial distribution is largely related to the underlying velocity field. In the ideal case of a laminar flow, the MP would just be transported by the flow and exhibit a spatial distribution mainly related to the variability in the source of MP. However, such a laminar flow is seldom observed in a real ocean, so the final spatial distribution is mostly related to the velocity field acting on the MP. The flow observed north of the Canary Islands is basically featured by a meandering southwestward flow, while the pattern is much more complex south of the islands due to the presence of mesoscale structures. The accumulation of MP might respond to the existence of long-lived mesoscale convergent structures, which is the case of wakes and eddies.

Fig. 2a & b present the velocity field distribution at several depths during winter and fall 2019, as provided by the numerical model IBI. Those velocity fields are built after averaging the daily fields obtained during the 15 days previous to the cruises. The first obvious feature is that the velocities decrease with depth, being much higher at 1 m depth that at 250 m. A remarkable similarity is observed at both seasons for the velocity field patterns at the first 500 m, i.e., within the Canary Current; that pattern is slightly different at the deepest level selected at 1150 m. The divergence of the velocity field exhibits alternating areas of divergence/convergence, revealing areas of MP potential accumulation. Overall, divergence seems to be related to clockwise circulation patterns, while convergence is mostly related to anti-clockwise circulation areas. Those divergence/convergence areas might be related to coherent mesoscale cyclonic or anticyclonic eddies, that would be part of the eddy corridors reported in this domain.

The flow below 250 m north of the islands is largely affected during winter and fall by the presence of a meddy just north of Gran Canaria island, which highly conditions the circulation and the convergent/divergent areas. On the other hand, south of the islands we may observe alternative patterns of convergent/divergent areas, likely related to the presence of mesoscale eddies, which can generate mesoscale and submesoscale variability (Maes et al., 2018), not related with seasonal patterns.

3.2. Microplastic vertical distribution

MP were identified in all samples analyzed between surface and 1150 m depth, with the presence of fibers (Bagaev et al., 2017) and small fragments. MP can also be found down to the maximum sample depth (1150 m) (Fig. 3_F). Fibers that could be similar in appearance and number to those identified in the blank run on board were discarded.

Fig. 3 presents the MP content filtered at nine different samplings along the water column. These pictures clearly evidence a significant presence of MP below the sea surface. Samples show a constant presence of fibers; some of them, according to their size, could originate from the fishing gear fragmentation (see Fig. 3B & C) (Prata et al., 2020; Xue et al., 2020). The presence of MP fragments with a size bigger

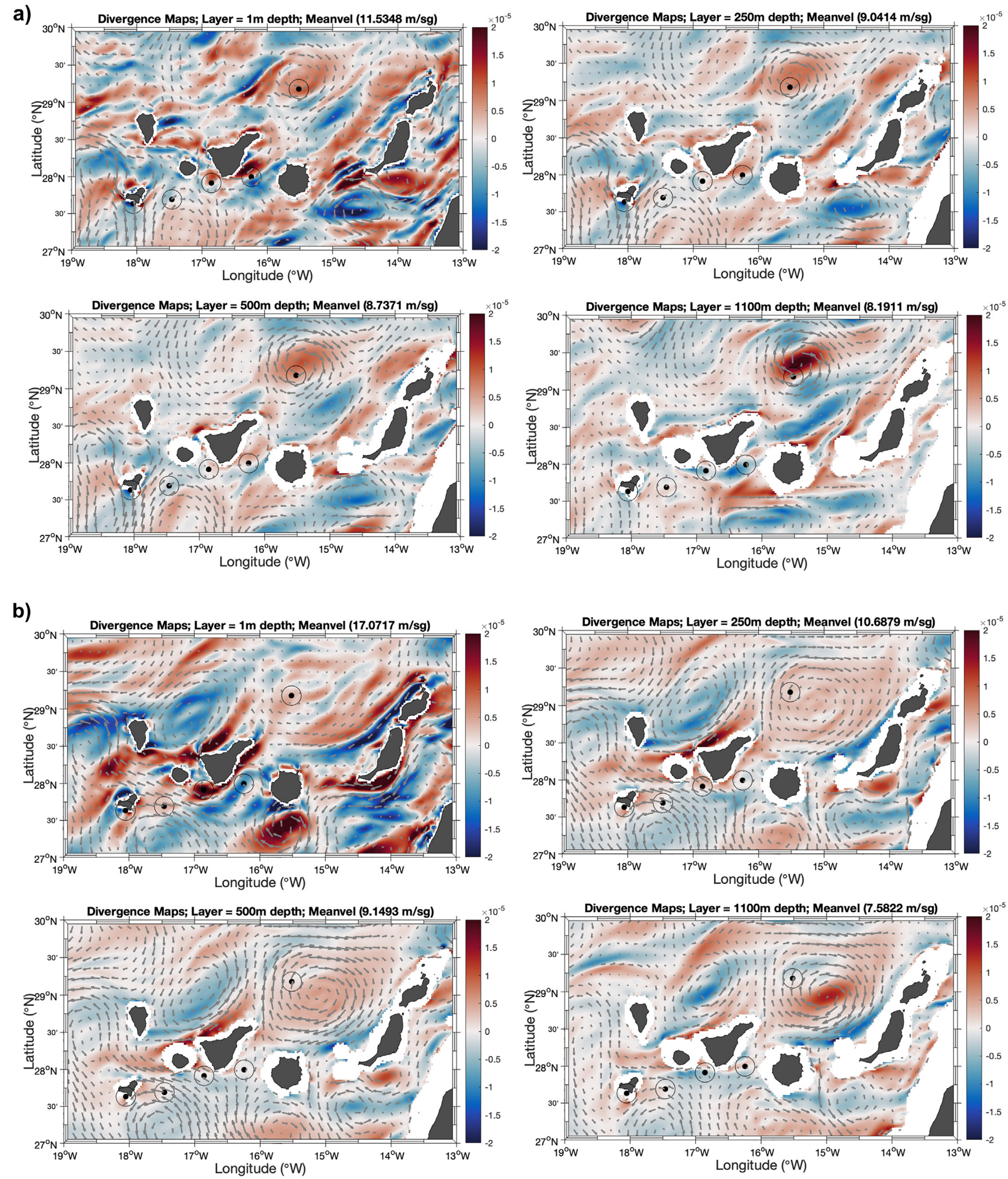

Fig. 2. Divergence of the velocity field during winter'19 (2a) and fall'19 (2b) at 4 different depths: surface, 250 m, 500 m and 1100 m. Velocity fields are averaged during the 15 days previous to the samplings.

than 500 μm is reported in some samples (Fig. 3A, C, H & I). All fragments and fibers visible under the stereo zoom microscope were counted regardless of their size.

Fig. 4a & b present the vertical distribution of fibers and fragments at the different stations considered (units per liter). ESTOC is located north of the Canary Islands, and it was the site with the lowest concentrations

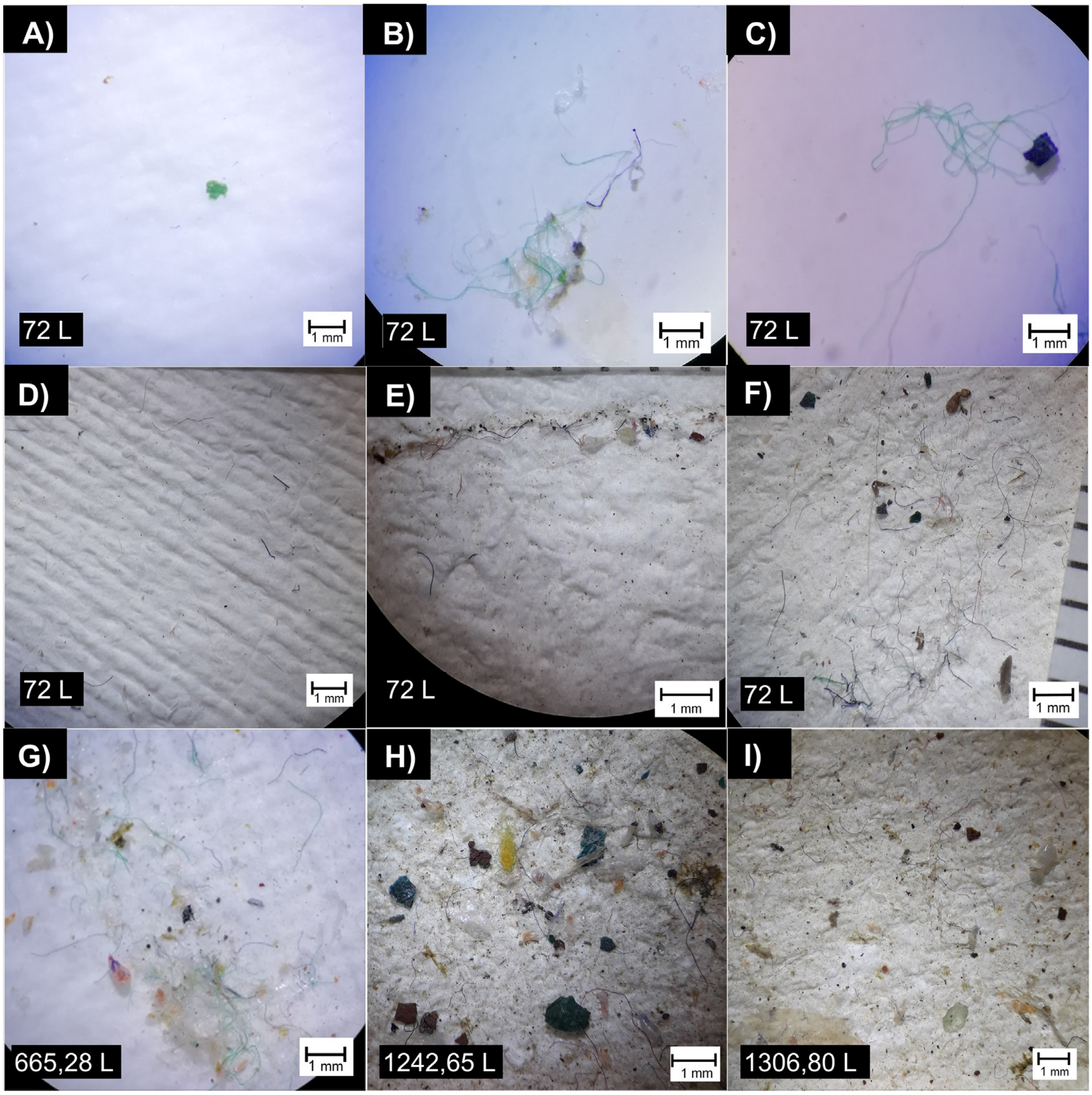

Fig. 3. Pictures showing a selection of MP samples filtered. Box on the left bottom of each subfigure refers to the seawater volume filtered (at 100 μm of mesh size). A) ESTOC at 258 m depth (Feb'19), B) M03 at 98 m (March'19), C) M04 at 280 m (March'19), D) ESTOC at 150 m (Dec'19), E) M02 at 485 m (Nov'19), F) M04 at 1152 m (Nov'19), G) M04 between 0 & 280 m (March'19), H) M03 between 0 & 523 m (Nov'19), I) M04 between 0 & 550 m (Nov'19).

for fibers and for fragments in fall, providing moreover a quite constant distribution with depth. Seasonal differences on fragment and fibers concentrations between winter and fall are remarkable, being much higher in fall than in winter: fibers are 4-fold higher in fall while fragments increase up to 2 orders of magnitude. In all cases the vertical distribution at M01-M04 is much variable than at ESTOC, with MP concentration below the surface in most cases at least equal to or greater than those observed at surface samples.

MP vertical distribution might be indicating that the long-term velocity field north of the Canary Islands is not inducing a large variability in the MP spatial distribution, as revealed by the rather constant vertical distributions at ESTOC. However, for stations M1 to M4, located south of the islands, the concentrations are notably higher and variable with depth, likely as a consequence of the mesoscale variability (Cózar et al., 2021; Maes et al., 2018), as eddies might be contributing to MP accumulation (Brach et al., 2018) and vertical transfer along the water column. It is not observed a seasonal pattern that would explain the variability of MP between winter and fall'19, as it might be the different stratification of the water column. Previous studies at the Canary region report similar results (Rapp et al., 2020; Reinold et al., 2020), supporting the hypothesis that MP variability is mainly driven by mesoscale structures.

The average of MP sampled in these four cruises is equivalent to $50 \cdot 10^6$ MP pieces/km^2, a value in good agreement with data reported for the North Atlantic Subtropical Gyre (10^6 MP pieces/km^2) (Eriksen et al., 2014).

3.3. MP colour classification

Fragment and fiber colours were evaluated on samples collected at fall'19 (Table 1).

The predominant colour for fibers and fragments sampled was blue. These results are similar to previous studies at the Atlantic area for MP sampled at the sea surface (Herrera et al., 2019; Lusher et al., 2014).

The predominance is quite different between fibers and fragments. At fibers, red and white colour have higher percentage than for fragments. Fragments higher than 500 μm (at least one) are present in most samples.

3.4. Relation between MP predominance and zooplankton abundance

At several stations, zooplankton with size lower than 1 mm was observed together with MP samples (see Fig. 5). Their distribution is quite similar, with a high zooplankton abundance related to samples with high MP concentration.

Despite zooplankton move cyclically with the diel vertical migration (DVM), the transport of small zooplankton due to physical processes and ocean dynamic could be more efficient than their own mobility (Carr et al., 2008; Wiafe et al., 1996). According to this fact and taking into account our results, zooplankton and MP could be both acting as 'passive drifters' of ocean dynamic along the water column, not only at surface but also in depths at least down until 1150 m.

Considering MP colours, previous studies show a prevalence of blue fibers and fragments, as indicated in Section 3.2, even in those MP ingested by planktivorous species (Ory et al., 2017). These authors suggest that it could be due to the zooplankton mistakenly-ingested MP when its prey was some species of blue copepods.

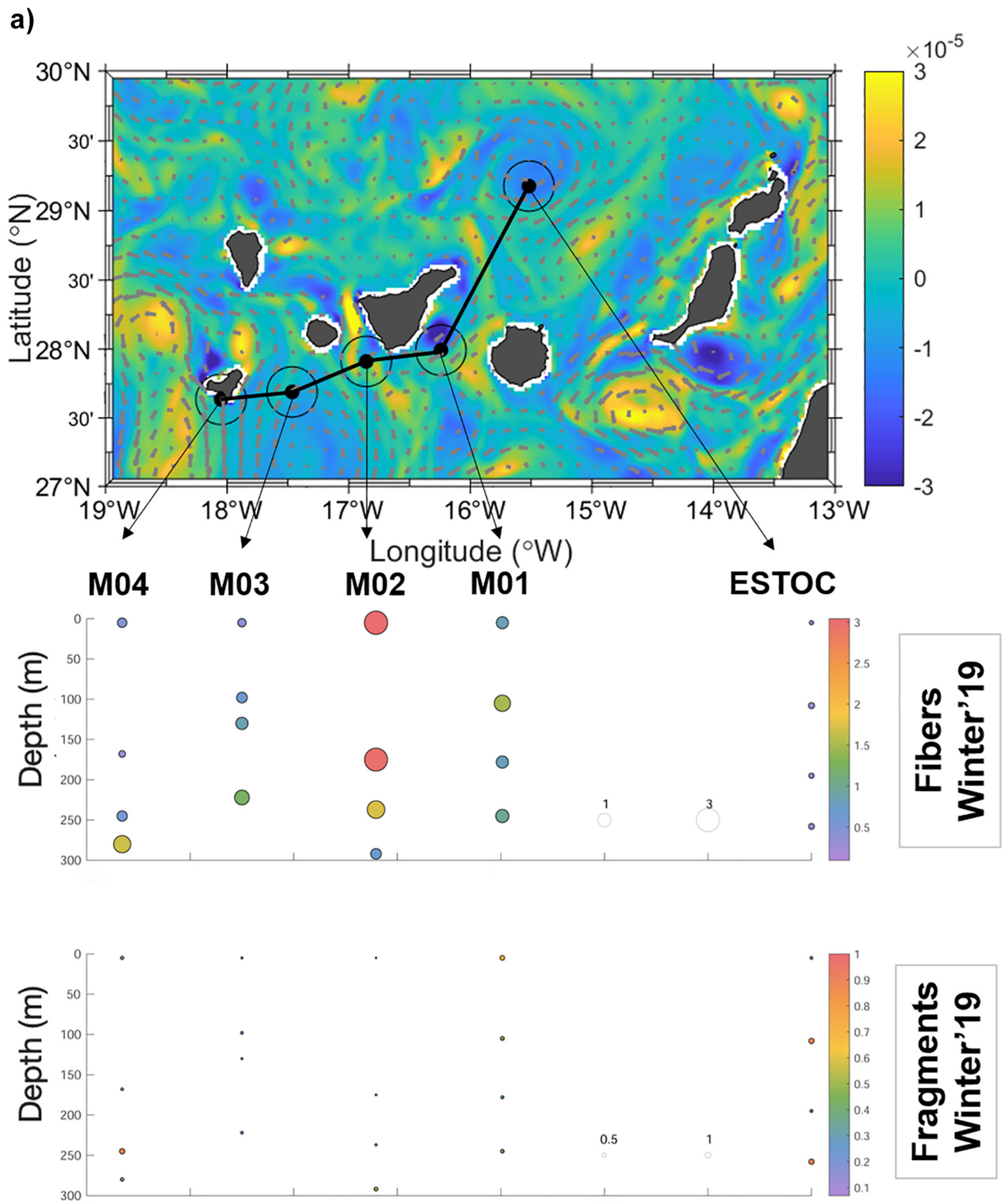

Fig. 4. Microplastic vertical distribution of fibers and fragments per station in winter'19 (24th February & 12-15th March'19, Fig. 4a) and fall'19 (19-20th November & 4th December'19, Fig. 4b), given as the number of MP per seawater liter filtered. The upper panel presents the vorticity at surface estimated with the velocity field averaged during the 15 days previous to the cruise. In the lower two panels, dot size and colour are given according to their concentration.

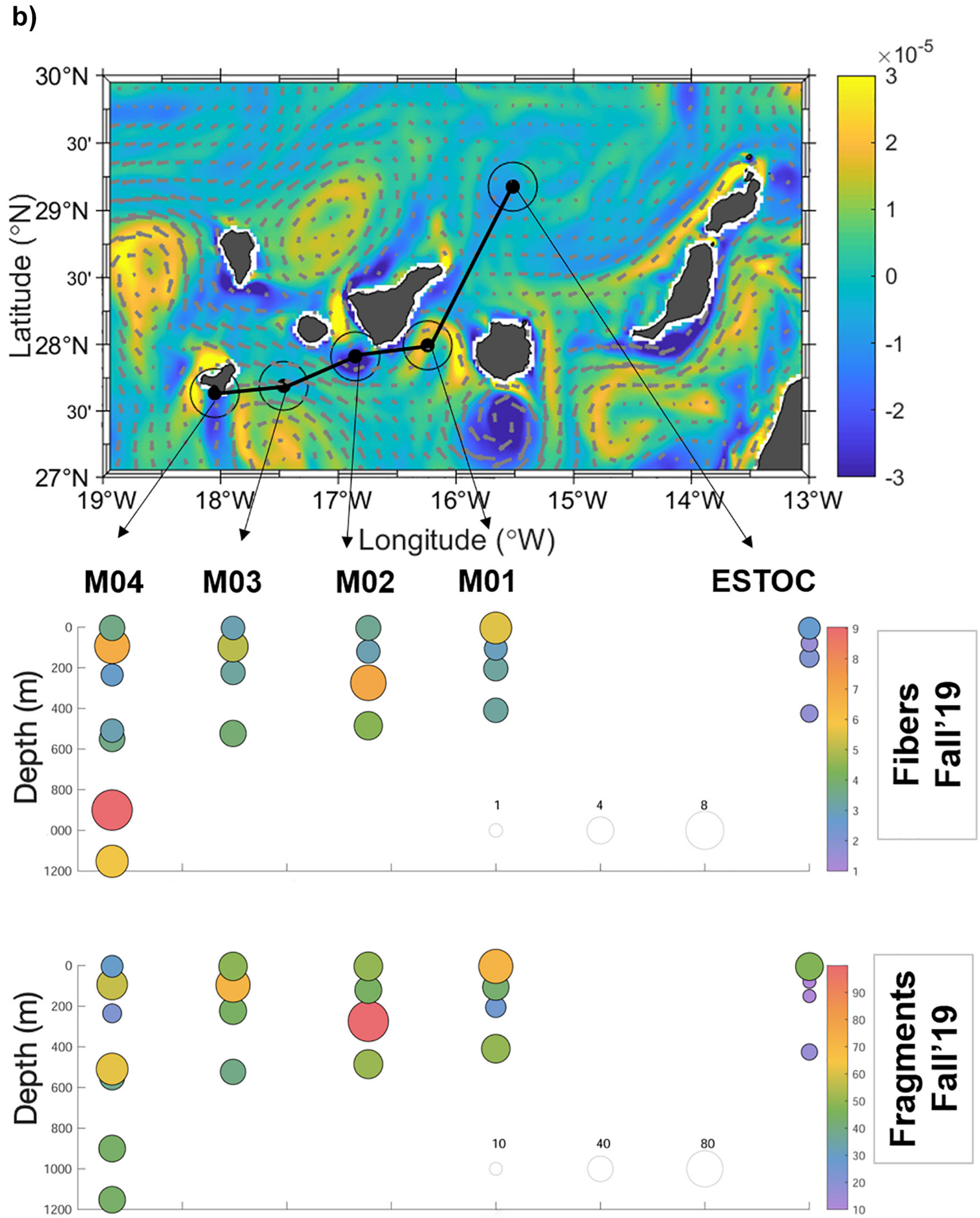

Fig. 4 (*continued*).

At the Canary region, some authors have analyzed the presence of MP particles in the digestive tract of Atlantic chub mackerel (*Scomber colias*), and it was reported the presence of some copepods (*Labidocera sp*) with MP fragments and fibers (Herrera et al., 2019). These authors report a proportion of blue colour at MP fragments and fibers at a similar percentage than our results in the same area. This finding might indicate, in contrast with previous studies, that zooplankton could not select their preys by colour, taking into account that the MP colour fraction within organisms and at the water column were similar.

The scarcity of MP historical observations and the large water volume needed to produce a reliable dataset recommends that alternative paths are also explored to fully address the MP spatio-temporal variability. On the one hand, MP relationship with zooplankton would provide a priori locations with large potential for MP samplings, as it could be their distribution within mesoscale structures. On the other hand, numerical modelling would also produce a framework to develop the relationship of MP with mesoscale structures, a main factor that seems to be largely driving the MP spatio-temporal variability.

Table 1
Microplastic colour distribution (%) of fragments and fibers sampled.

Station	November–December'19									
	Fragment Colours (%)					Fiber Colours (%)				
	B&P	BK	R	G&Y	W&T	B&P	BK	R	G&Y	W&T
ESTOC	89,14	0,58	5,97	3,26*	1,04	42,91	1,58	6,13	4,73	44,66
M01	89,65	1,10*	6,95	2,07	0,23*	54,70	2,95	11,35	13,84	17,16
M02	88,14	0,45*	9,27	1,87	0,28	43	1,58	20,24	11,54	23,64
M03	80,73	0,70*	15,35	2,67*	0,56	51,61	2,15	17,11	6,27	22,85
M04	87,85	0,98*	7,66	2,81	0,70*	39,71	0,44	10,35	4,79	43,95

Colours:

- B&P: Blue & Purple
- BK: Black
- R: Red
- G&Y: Green & Yellow
- W&T: White & Transparent

* Presence of fragments > 500 μm

4. Conclusions

Several studies assess the presence of MP in the ocean, but just a few does so in the water column below 20 m depth. In this manuscript, samples have been collected from different depths down to 1150 m, evidencing the widespread presence of MP in all oceanographic cruises conducted. The spatial distribution of these small plastics (fragments and fibers) at the water column is mainly related to the oceanic dynamics and mesoscale convective flows, overcoming the MP motion induced by their own buoyancy. This implies that there could be a large amount of flat irregularly-shaped MP pieces in the layers below the thermocline that still needs to be fully quantified.

A remarkable difference has been observed in the MP abundance distribution when comparing the station north of the Canary Islands at ESTOC with the stations south of the Islands. The abundance at ESTOC is usually lower and with a nearly constant vertical distribution; however, south of the islands the abundance presents much random vertical distributions likely related to the mesoscale activity in this southern side of the archipelago. Moreover, notable seasonal differences in the MP abundance are observed, having in fall MP concentrations even 100 times higher than in winter.

Future work in this research area should comprise a number of additional approaches to develop a comprehensive knowledge about the MP distribution in the water column. On the one hand, the number of deep samplings along the water column should be increased, as measurements performed so far point out that these plastics might also be extensively present below 1150 m depth. On the other hand, sampling should be performed at stations located closer within some 30–50 km, to estimate the spatial scales in MP distribution, both north and south of the Canary Islands, where the MP are driven by different forcings. Finally, regular samplings should be performed at the same stations, in order to produce a pattern about the temporal evolution in the abundance of MP.

Canary Islands is an archipelago largely affected by plastic residue from other regions, as revealed by the MP found at remote beaches on the less populated islands (Baztan et al., 2014, 2015; Herrera et al., 2018). Our results, together with previous studies, evidence that MP pollution near to Canary region is not a coastal phenomenon, and these observations can be used as a proxy for ubiquitous MP pollution at the North Atlantic Subtropical gyre.

CRediT authorship contribution statement

Daura Vega-Moreno Conceptualization, Investigation, Methodology, Writing- Original draft preparation, Editing**, Bárbara Abaroa-Pérez** Experimental Data (Laboratory work)**, Paula Domínguez Rein-Loring** Experimental Data (Laboratory work)**, Carmen Presas-Navarro** Experimental Data (Laboratory work – oceanographic cruises)**, Eugenio Fraile-Nuez** Investigation, Methodology, Data Processing**, Francisco Machín** Investigation, Data Processing, Writing- Reviewing, 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.

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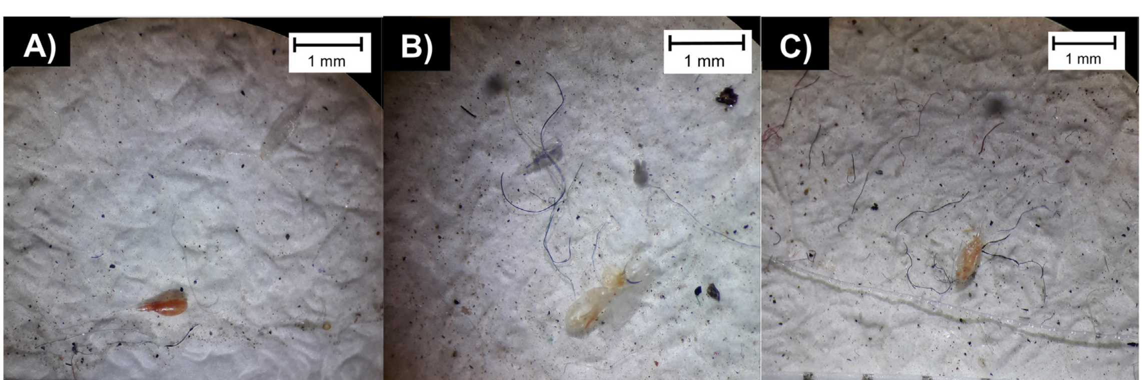

Fig. 5. MP samples filtered in November'19 (72 l of seawater through a net 100 μm of mesh size). A) M01 at 106 m depth, B) M01 at 205 m, C) M03 at 96 m.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147802.

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