Marine Pollution Bulletin 209 (2024) 117237

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Towards microplastic hotspots detection: A comparative analysis of *in-situ* sampling and sea surface currents derived by HF radars

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ARTICLE INFO

Keywords:
Microplastics
In-situ monitoring
HF radar
Sea surface current
Remote sensing
Lagrangian simulations

ABSTRACT

Marine plastic pollution is a global issue affecting ecosystems and various aspects of human life. The scientific community is exploring new monitoring and containment approaches. Because *in-situ* sampling campaigns are time and resource demanding, there is a focus on integrating different approaches for marine litter monitoring. Data of two *in-situ* surveys (using a manta net) were compared to sea surface currents data and derived products with the aim to find a proxy variable of the plastic occurrence. Sea surface currents data were provided by the CALYPSO HF network (operating in the Sicily Channel since 2012). Notably, the occurrence of fragment items is inversely correlated with the total kinetic energy ($r^2 \sim 0.85$). This result was confirmed by a Lagrangian tracking model considering the deployment of virtual drifters around each *in-situ* measurement point. The proposed method applied to a wider domain using Copernicus Marine Service (CMS) data revealed that high plastic accumulation areas could be located at the centre of eddies often occurring in the winter period. However, uncertainties arise by the moderate-low correlation found between HF CALYPSO and CMS sea current data.

1. Introduction

Marine litter is a pervasive global pollution issue that negatively impacts various fields including human health and socio-economic sectors (Löhr et al., 2017; Strain et al., 2022). In 2018, the European Union (EU) approved the "Marine Strategy Framework Directive (MSFD, 2008/56/EC) aiming to preserve the quality of the marine ecosystem. Member States interpret the Directive by focusing their actions on eleven descriptors set by the EU to maintain marine biodiversity, reduce eutrophication, manage contamination levels in the sea, etc. One of these descriptors focuses on marine litter, emphasising the importance of considering the "composition, amount and spatial distribution of litter and micro-litter on the coastline, in the water column, and on the seabed" (MSFD, 2008/56/EC). To achieve these goals, several research activities were conducted to investigate the quality of the marine environment, specifically focusing on marine debris.

Marine litter encompasses a wide range of materials with plastics accounting for around 60–80 % of the total (García Rellán et al., 2023). Plastic production has globally increased, reaching 390.7 Million tonnes (Mt) in 2021, with projections suggesting annual production could reach between 850 Mt and 1124 Mt by 2050 (Crawford and Quinn, 2017; PlasticsEurope, 2021).

Plastic pollution affects various geographic areas and aquatic ecosystems (Fu and Wang, 2019; Li et al., 2023; Monteiro et al., 2018; Thiel et al., 2018; Waldschläger et al., 2022). Despite Europe enacting laws to reduce plastic production and define proper disposal practices, millions of tonnes of plastic still end up in the oceans annually, causing environmental, economic, and health problems. Mostly of these plastics are mainly introduced by river runoff and coastline (80%), while about 20 % mainly belong to lost fishing gears and abandoned vessels (Li et al.,

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https://doi.org/10.1016/j.marpolbul.2024.117237
Received 12 July 2024; Received in revised form 30 October 2024; Accepted 31 October 2024

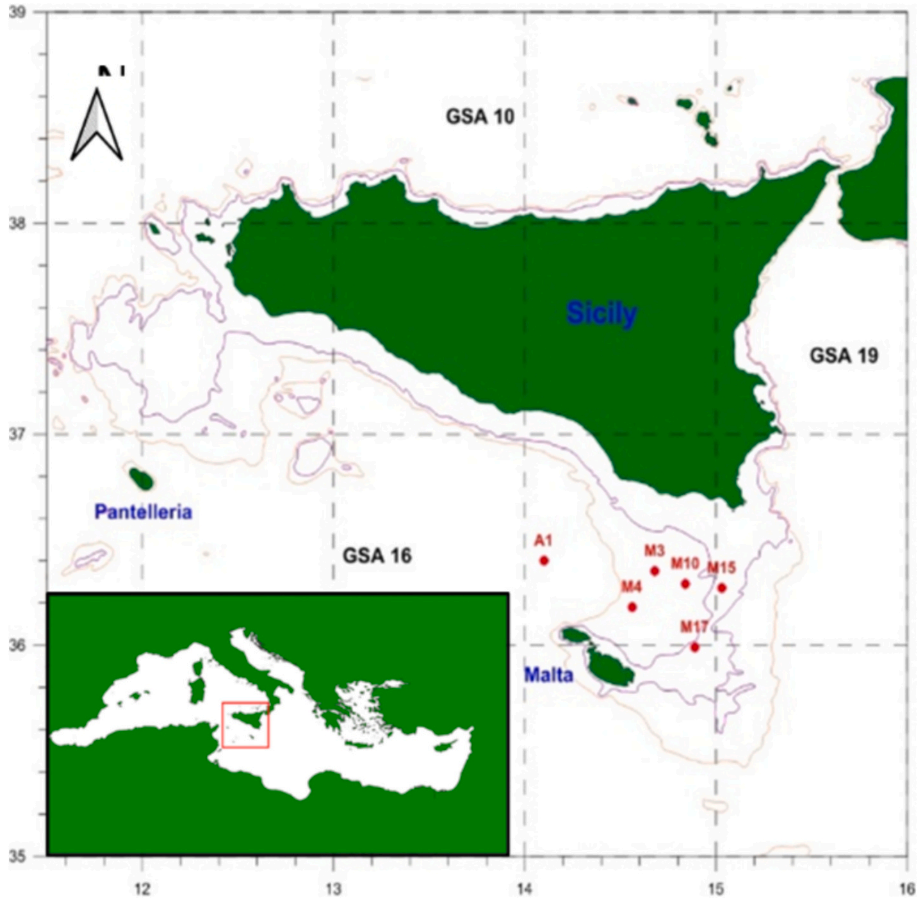

Fig. 1. Study area. The red dots represent the sampling transect realized in GSA 15 and GSA 16. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
In-situ sampling transect details.

Year	Day*	Time (UTC)	SS**	Lon	Lat	
2018	11	21:07	M15	15.03	36.27	***
	12	00:20	M17	14.89	35.99	***
	12	17:11	M10	14.84	36.29	
	12	20:45	M3	14.68	36.35	
	13	00:16	M4	14.56	36.18	
2019	10	04:47	M15	15.03	36.27	***
	10	23:50	M17	14.89	35.99	***
	11	06:21	M10	14.84	36.29	
	11	20:02	M4	14.56	36.18	***
	11	21:20	M3	14.68	36.35	
	12	00:59	A1	14.10	36.40	

* All the samplings were carried out in August.
** Sampling transect (central point of the linear path).
*** Samplings carried out at the CALYPSO domain boundary.

2016; Lebreton et al., 2018).

Plastic items in the sea behave according to the size and density. For instance, particles with density higher than 1.02 g cm^{-3} (Li et al., 2023) may sink and accumulate in the seabed, while others tend to float on the sea surface or be suspended in the water column (Fossi et al., 2012; Li et al., 2023). The position of particles in the water column can change due to several factors, including biofouling, which can increase their density and cause them to sink (Van Cauwenberghe et al., 2015; Wright et al., 2020).

Due to their widespread use, limited biodegradability, and increasing sources, large quantities of plastic items accumulate in marine environments (Narayanan, 2023; United Nations Environment Programme, 2015), raising concerns for marine conservation (Thushari and Senevirathna, 2020).

The scientific community categorises marine plastic items based on their size including mega (> 1 m diameter), macro (between 2.5 cm and < 1 m), *meso* (between 5 mm and < 2.5 cm), micro (between 0.1 μm and < 5 mm) and, nano (<0.1 μm) plastics (Kroon et al., 2018). Each fraction has a different impact on the marine ecosystem. For example, mega and macro plastics cause the entanglement of marine species like turtles, seals, whales, *etc.* (Kühn et al., 2015). On the other hand, microplastics (MPs) are ingested by various species (Lopes et al., 2020; Mak et al., 2019; Sambolino et al., 2023) entering the food chain and posing risks to human health (Gruber et al., 2023). MPs have been found in the digestive system of various fish species in the Mediterranean Sea and other oceans (Neves et al., 2015; Romeo et al., 2015; Sharma et al., 2021).

The effects on marine animals are also worsened by the presence of toxic chemicals in plastics and by the ability of microplastics to attract other harmful substances (Wang et al., 2019). These factors cause an adverse impact on the health of marine species and transfer toxic components to higher trophic levels (Chatterjee and Sharma, 2019). Frequently, floating plastics being transported in the open sea converge and accumulate in areas affected by gyres (Moore, 2008) or eddies (Beron-Vera et al., 2016; Froyland et al., 2014; Haller and Beron-Vera, 2013). Unfortunately, the accumulation of MPs in high sea productivity areas (*e.g.*, nutrients, phytoplankton) increases the plastic pollution impact level.

The Mediterranean Sea is the sixth-highest accumulation hotspot for marine litter and plastics (Cozar Cabañas et al., 2015). Different types of plastic particles are found in various areas, including coastal zones, sea

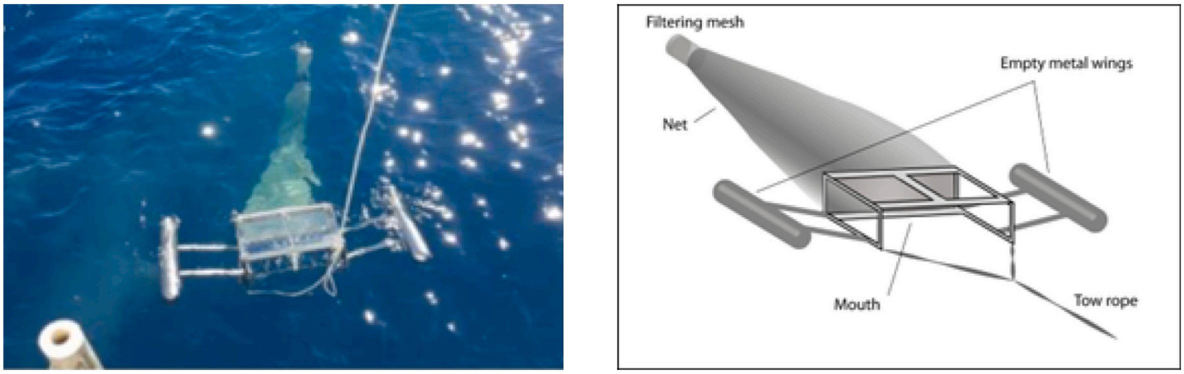

Fig. 2. Manta Net used during the sampling activities: picture of sampler net during survey (a); schematization of sampler net (b).

Table 2
S_d differentiated for the various shapes, sampled during the 2018–2019 monitoring campaign; for each transect values reported on the upper row refer to the 2018 campaign, whereas values reported on the bottom row refer to the 2019 campaign.

S_d (m^{-2})							
Transect	Fragments	Sheets	Filaments	Foams	Granules	Pellets	Total per transect
M3	0.084	0.024	0.004	0	0	0	0.112
	0.055	0.001	0.009	0.007	0	0	0.072
M4	0.147	0.096	0.009	0	0	0	0.252
	0.074	0.016	0.003	0.001	0	0	0.094
M10	0.096	0.029	0.004	0.004	0	0	0.133
	0.018	0.009	0.015	0	0	0	0.042
M15	0.244	0.003	0	0	0	0	0.247
	0.089	0.003	0.021	0	0	0	0.113
M17	0.233	0.073	0.006	0.004	0.021	0.001	0.339
	0.143	0.03	0.001	0	0.001	0	0.175
A1	-	-	-	-	-	-	-
	0.163	0.019	0	0	0	0	0.182
Total per shape	0.804	0.225	0.023	0.008	0.021	0.001	1.082
	0.542	0.078	0.049	0.008	0.001	0	0.678

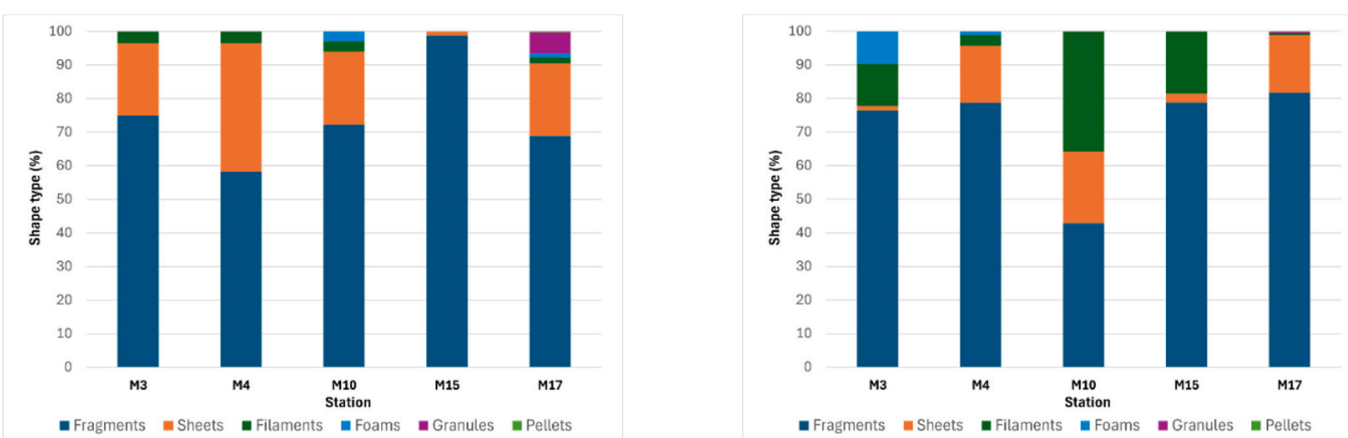

Fig. 3. Shape type (%) sampled for the different transects during the 2018 (panel a) and 2019 (panel b) surveys.

surfaces, and seabed (Sebille et al., 2015). Sea surface currents play a crucial role in defining marine litter accumulation areas, prompting the development of models to describe physical and thermodynamic processes in oceans. This allows the definition of the main circulation patterns which are in continuous evolution and which are also affected by climate change (Bricheno and Wolf, 2018). When available, High Frequency Radar (hereinafter indicated as HFR) data is preferred over numerical model assessments (Lorente et al., 2022; Reyes et al., 2022).

Integrated approaches combining *in-situ* data with remote sensing techniques (Sprovieri et al., 2021) and/or with hydrodynamic models are crucial for reliable marine litter monitoring. In this work, the Sicily Channel (in the Central Area of Mediterranean Sea) was selected as pilot study area due to real-time monitoring of sea surface currents by the CALYPSO HFR network (deployed within the CALYPSO, CALYPSO FO Italy-Malta Interreg projects). The significance of this area in terms of marine biodiversity and socio-economic activities has led to various

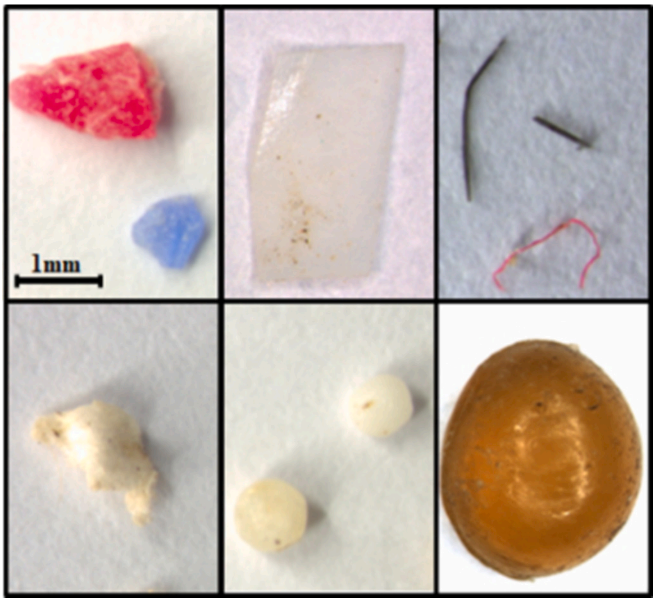

Fig. 4. Sampling views from the stereomicroscope: examples of fragments (top left), sheets (top center), filaments (top right), foam (bottom left), granules (bottom center), and pellets (bottom right).

monitoring campaigns. During the summers of 2018 and 2019, the Consiglio Nazionale delle Ricerche (CNR) with the help of the Agenzia Regionale per la Protezione Ambientale (ARPA) conducted two multidisciplinary surveys aimed at quantifying and characterising microplastics within the CALYPSO HFR network coverage area.

This research presents the outcomes of microplastics laboratory analyses and explores the relationship between the sea surface currents (and derived products) and *in-situ* sampled microplastics. A comparison with the outcomes of Lagrangian particle tracking confirmed that HFR surface currents and derived products can serve as a proxy for identifying microplastic accumulation areas. In contrast, the use of Copernicus Marine Service (CMS) data did not yield satisfactory results.

2. Area of interest

The study area is the Maltese Channel situated between the Maltese archipelago and the Sicily island, connecting the western- and eastern-Mediterranean basins. The surveys were carried out in the Geographical Sub-Area (GSA as defined by the General Fisheries Commission for the Mediterranean - GFCM, 2009) 15 and 16 of the Mediterranean Sea. Meandering currents, mesoscale eddies, filaments, and recurrent wind-driven upwelling events are the main hydrodynamic processes occurring in this region, resulting in intense thermal fronts offshore the southern coasts of Sicily (Capodici et al., 2019). Additionally, the area is characterised by the Atlantic Ionian Stream which serves as the main driver of circulation in the upper layer of the water column (Robinson et al., 1999), inducing a permanent coastal upwelling along the southern coast of Sicily, especially during summer seasons (Bonanno et al., 2014).

The hydrodynamics of the area and the geographical features (characterised by shallow depth and narrow coastal areas) ensure a high level of biodiversity (Béranger et al., 2004; D'Elia et al., 2009; Lermusiaux and Robinson, 2001; Rumolo et al., 2018) thus representing a hotspot for fishing (Eigaard et al., 2017). Furthermore, the study area represent an important spawning and fishery ground for many pelagic species (Basilone et al., 2023; Basilone et al., 2021; Basilone et al., 2013); consequently, mapping the microplastic spatial distribution in the pelagic fish habitat is a fundamental step, particularly those consumed by humans. Several productive activities take place in the area, such as tourism, fisheries, aquaculture, navigation, and energy extraction (Mangano and Sarà, 2017) and other forms of energy

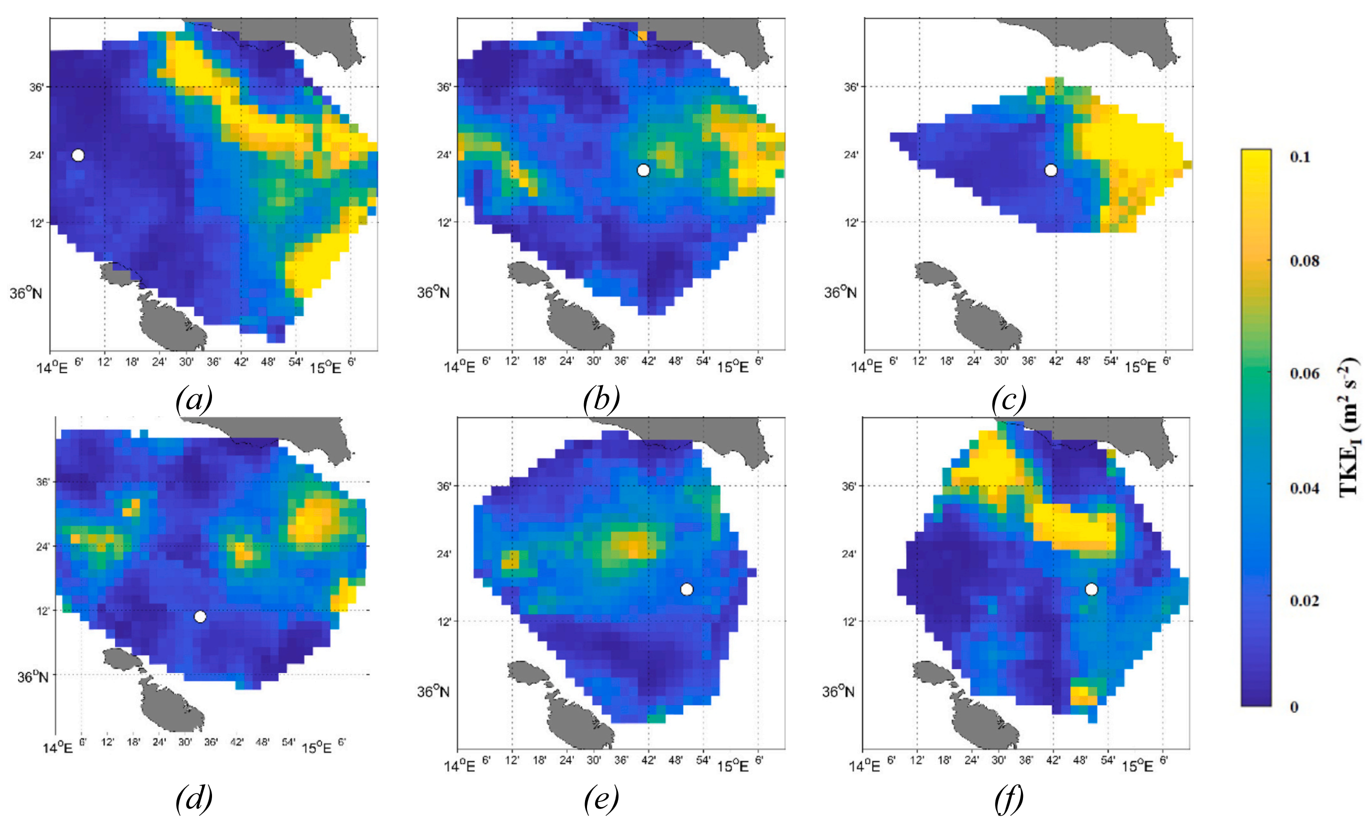

Fig. 5. TKE$_I$ maps related to the SS$_I$: A1–2019 (a), M3–2018 (b), M3–2019 (c), M4–2018 (d), M10–2018 (e), M10–2019 (f); the location of each SS$_I$ is represented by the black/white dot.

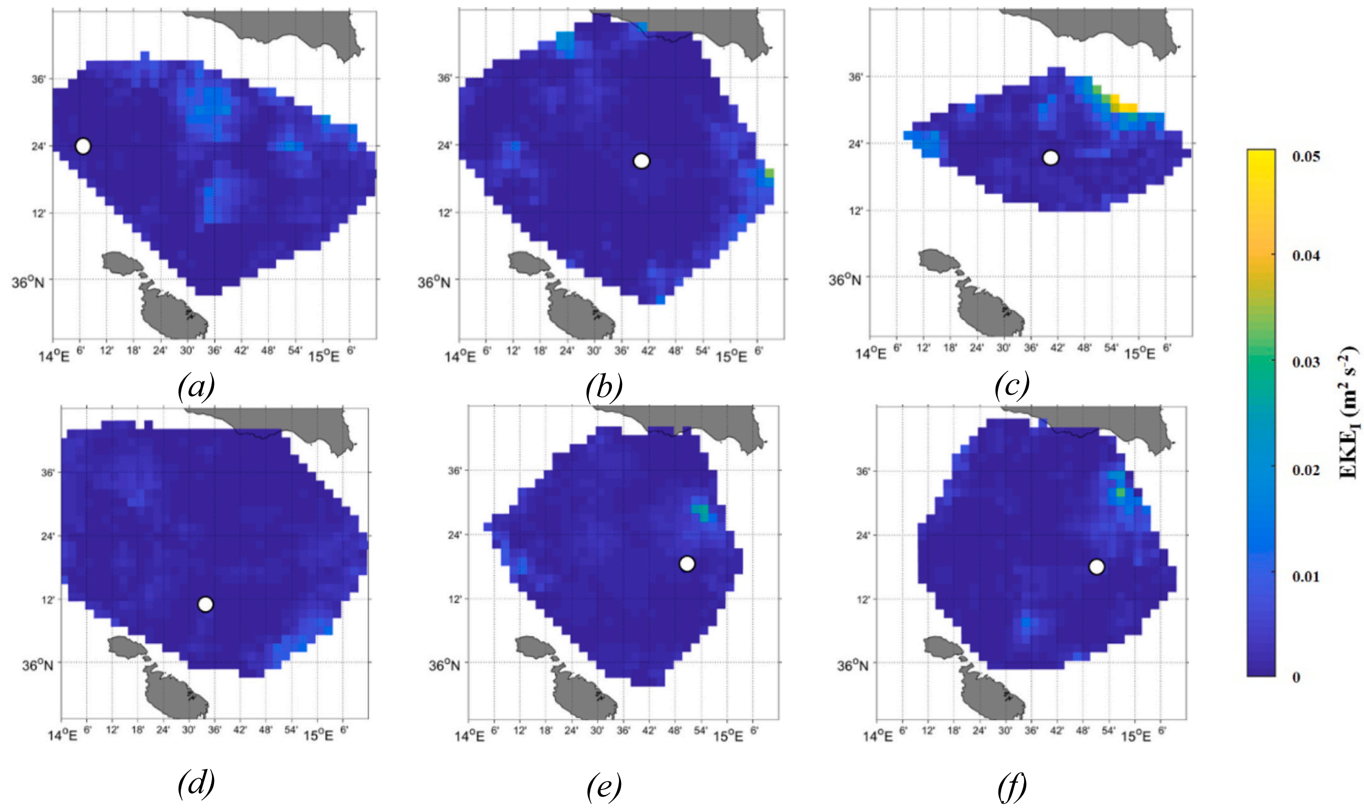

Fig. 6. EKE$_I$ maps related to the SS$_I$: A1–2019 (a), M3–2018 (b), M3–2019 (c), M4–2018 (d), M10–2018 (e), M10–2019 (f); the location of each SS$_I$ is represented by the black/white dot.

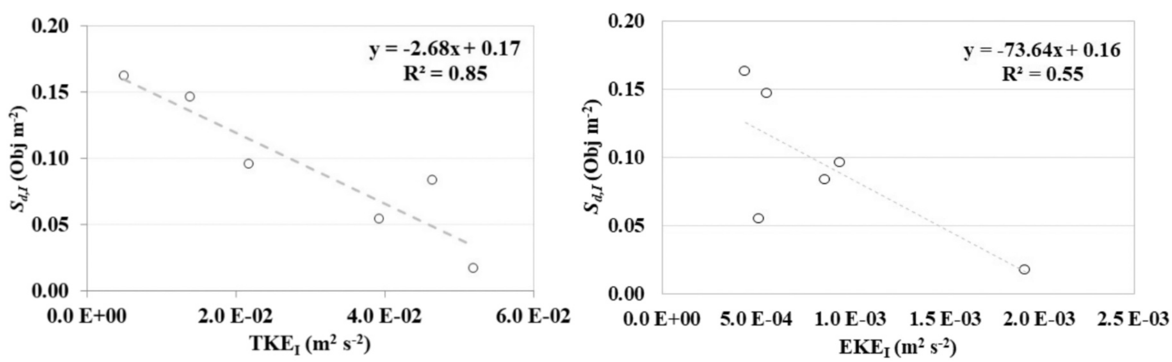

Fig. 7 - TKE$_I$. *vs* S$_{d,I}$ and EKE$_I$ *vs* S$_{d,I}$ for the fragment category.

Table 3
Metrics of the TKE$_I$ *vs* S$_{d,I}$ comparison.

	All	Fragments	Sheets	Filaments
Slope	$-3.4\ 10^{-4}$	$-2.7\ 10^{-4}$	$-9.1\ 10^{-5}$	$1.1\ 10^{-5}$
Intercept	0.23	0.17	0.05	$0.04\ 10^{-1}$
r^2	0.70	0.85	0.25	0.15
t-stat	3.83	3.83	3.83	4.75
p-value	0.036	$8.4\ 10^{-3}$	0.31	0.52

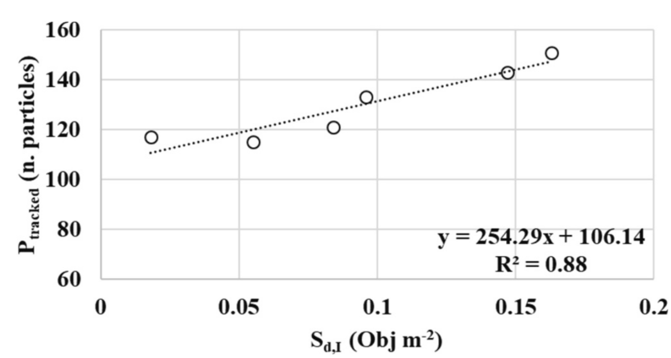

Fig. 8. S$_{d,I}$ *vs* P$_{tracked}$ linear by applying TrackMPD using HFR data as forcings.

production (Bonanno et al., 2018; Werner et al., 2016).

3. Materials and methods

3.1. In-situ sampling survey and data analysis

Two multidisciplinary surveys were carried out onboard the R/V “G.

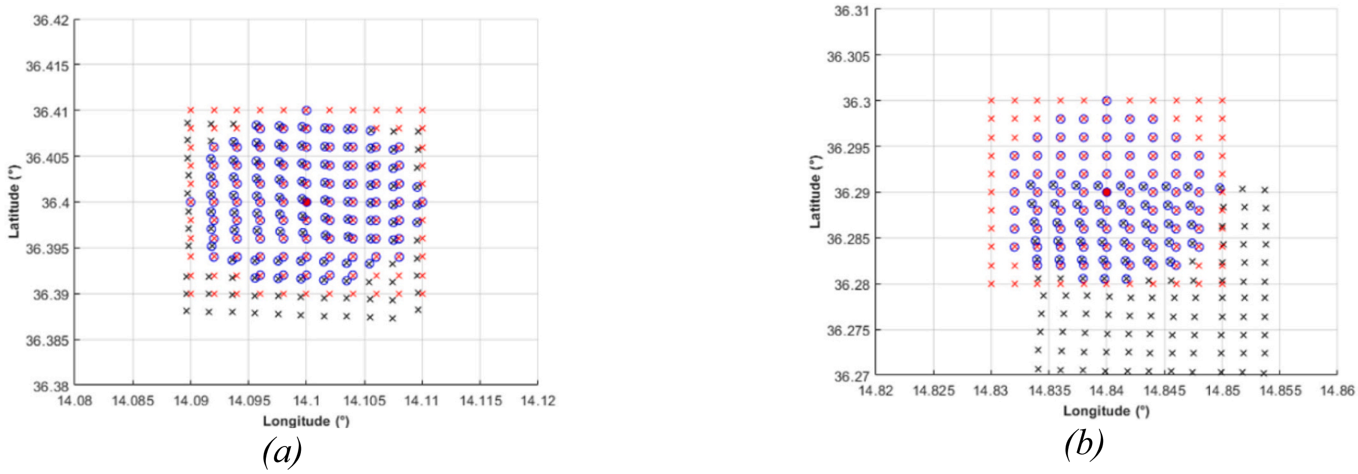

Fig. 9. Detailed results of the TrackMPD experiment applied to A1–2019 and M10–2019 *in-situ* samplings.

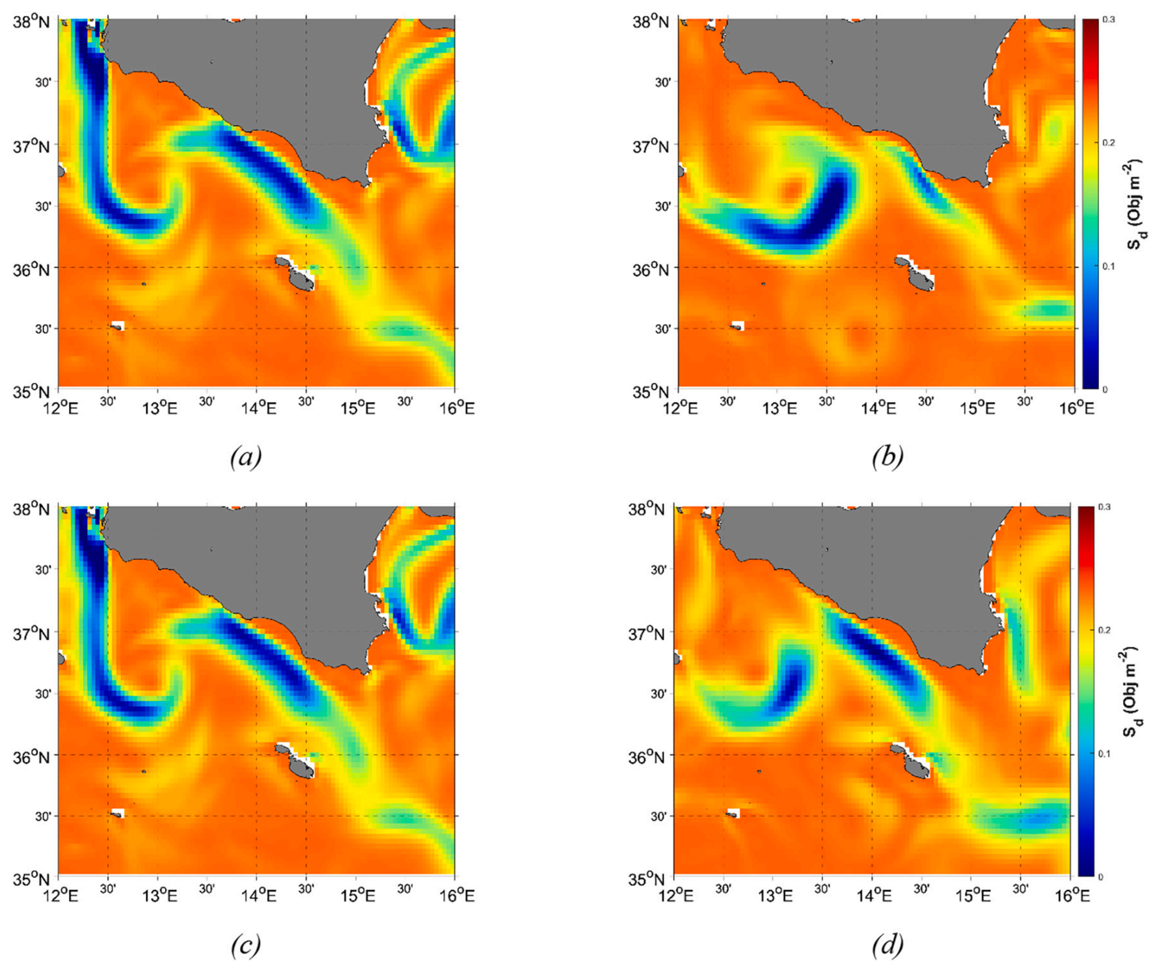

Fig. 10. Fragments of plastic accumulation maps of July and October for the 2018 (a and b panels respectively) and for the 2019 (c and d panels respectively).

Dallaporta" in August 2018 and 2019 in the continental shelf of the Mediterranean Sea, between Sicily and Malta. The sampling activities conducted were an integral part of the MEDIAS (EU Mediterranean International Acoustic Survey - http://www.mediasproject.eu) in the waters of the Strait of Sicily (Ben Abdallah et al., 2018; Bonanno et al., 2021; De Felice et al., 2021; Leonori et al., 2021) and the Calypso South Project. The project was focused on environmental aspects and the correlation between microplastics and hydrological data acquired by an HFR network. Considering that microplastics have small dimensions, do not weigh a lot, and are characterised by low density, they tend to accumulate preferably on the sea surface and in the basal area of the thermocline. Only a small percentage sink to the seafloor. Therefore, the surveys were conducted using a manta-type net that was towed at the surface within the area covered by the coastal HFR network (Fig. 1).

A total of eleven transects were sampled for which the starting and ending coordinates were recorded to calculate the length of the sampling

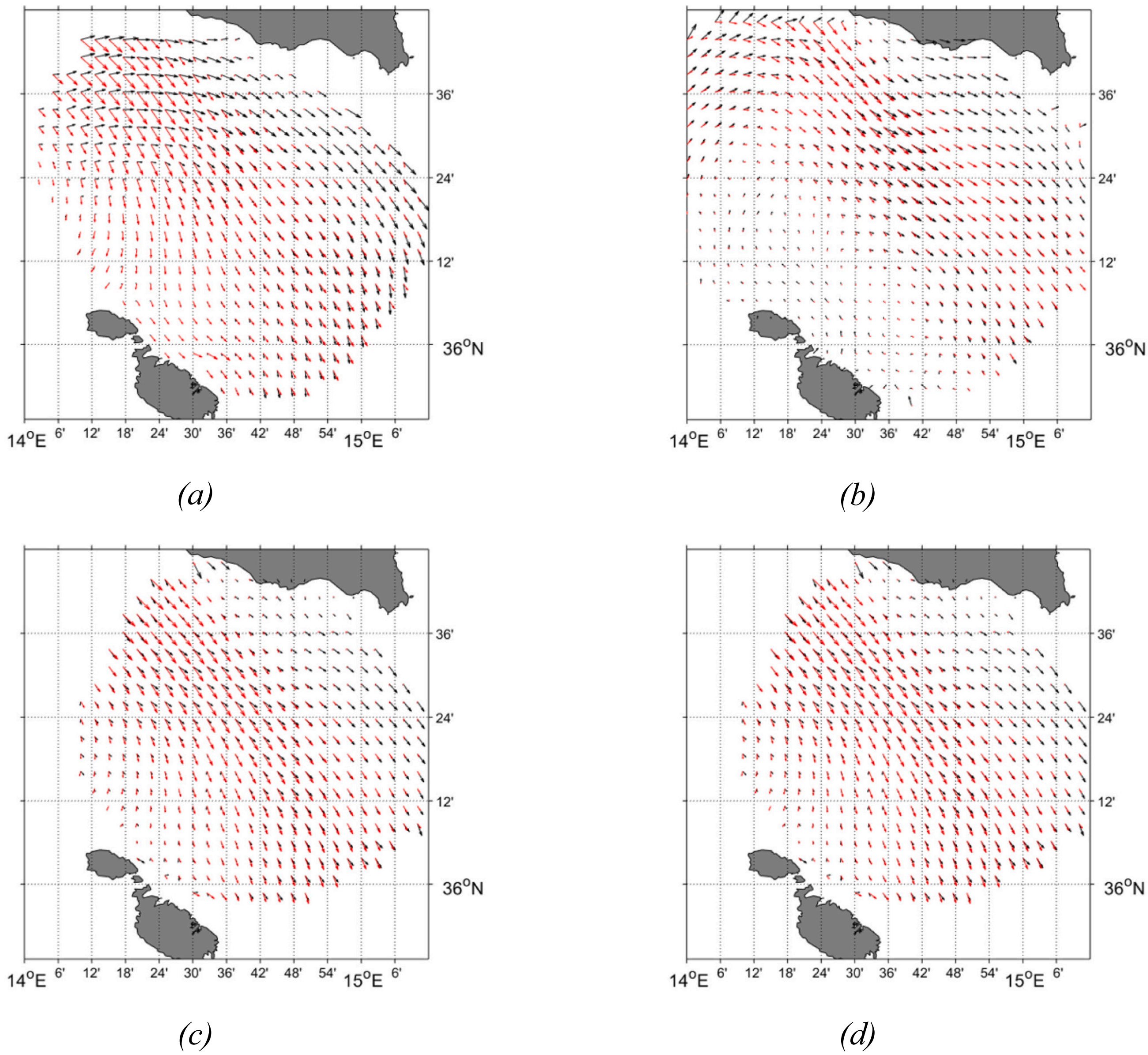

Fig. 11. Sea surface current maps (monthly average) provided by CMS and CALYPSO HFR (red and black arrows respectively) for: a) July 2018; b) October 2018; c) July 2019 and d) October 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

path. In each sampling transect, the net was towed along a linear path for 20 min, with a speed between 1 and 2 knots. This allowed the surface water to be filtered through the mesh to collect any MP samples present. The details concerning *in-situ* sampling for both 2018 and 2019 are reported in Table 1.

The Manta net is made by a conical mesh connected with a rectangular metal mouth and a collection cup with a filter mesh equal to 300 μm at the end. The setup is kept floating by two empty metal wings outside the mouth (Fig. 2).

The concentration of microplastics in each transect can be expressed as the number of objects per m^2 of filtered seawater, S_d (m^{-2}). The surface area of filtered water (S) is calculated using the formula:

$$S = L \, x \, W \quad (1)$$

where:

- L is the length of the sampled linear path.
- W is the width of the manta's mouth.

The observation and analysis of the samples collected during the surveys were carried out in the laboratories of the Arpa Sicilia Area Mare UOC. Prior to carrying out the analyses, samples were filtered through a 5 mm sieve and a 300 μm sieve, to recover the microplastics in a beaker with distilled water. Subsequently each sample was processed under a stereomicroscope (Discovery.V20 Zeiss) identifying and counting all the microplastics. Information on the shape (granule, pellet, foam, filament, fragment, or sheet) and colour, including details on opaqueness or transparency, was collected.

3.2. CALYPSO HF radars network: data and processing

The CALYPSO HF radar network, which measures sea surface currents between Sicily and Malta, has been operational since 2012. This network has continually improved and now consists of seven radars. During the monitoring campaigns, four HFRs were operational: two located in Sicily at the harbours of Pozzallo and Marina di Ragusa, and two in Malta at Barkat (limits of Xghajra) and Tà Sopu (limits of Nadur). These sites are hereinafter referred to as POZZ, MRAG, BARK, and SOPU,

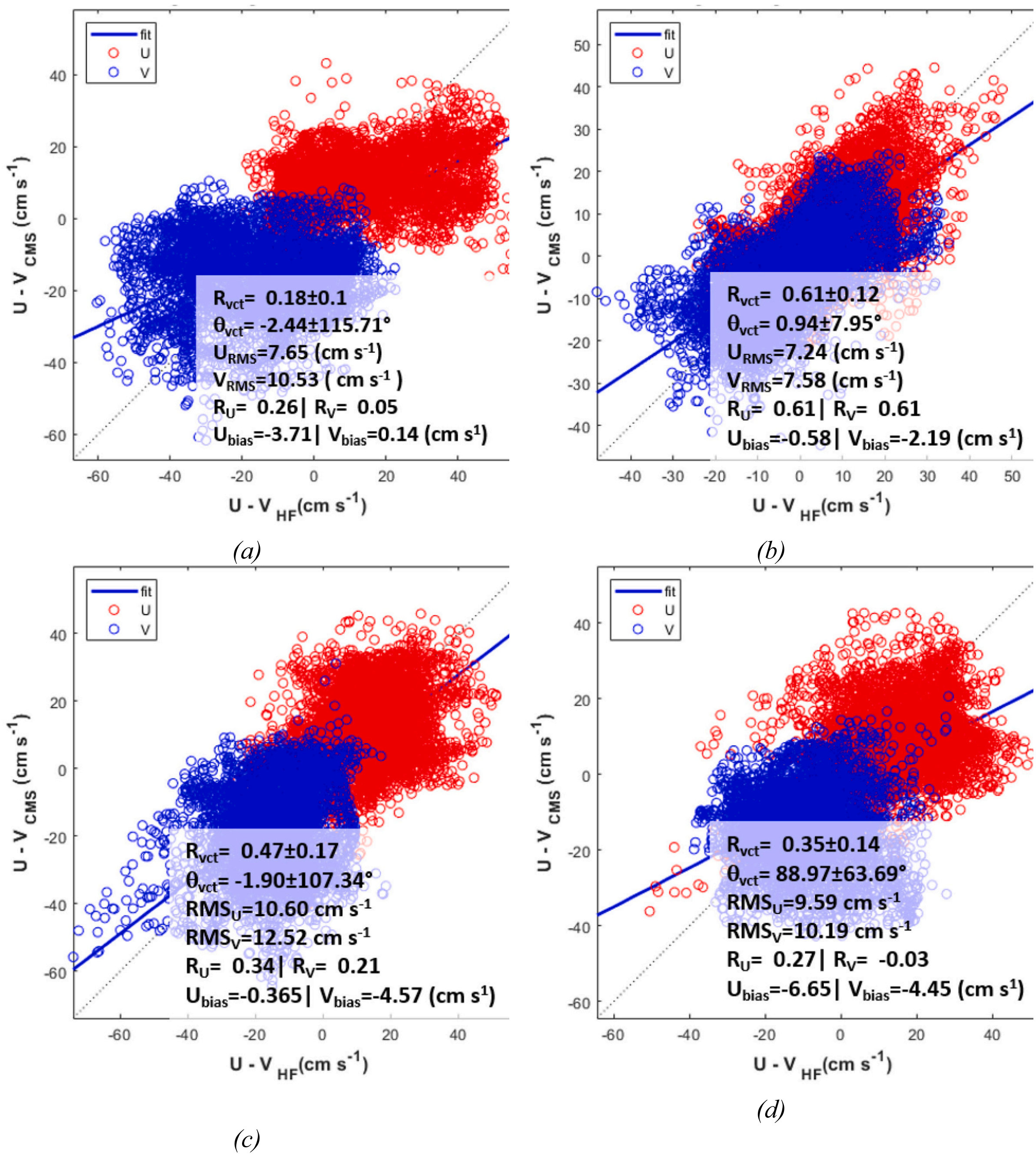

Fig. 12. HFR *vs* CMS scatterplot (U—V components, red and blue dots respectively) for: a) July 2018; b) October 2018; c) July 2019 and d) October 2019; the following metrics are reported inside the text box: U_{RMS} and V_{RMS} (average RMS for U and V components), R_U and R_V (correlation for U and V components) U_{bias} and V_{bias} (average bias for U and V components, *i.e.* HFR minus CMS values). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively. The HFRs covered an area of approximately 11,000 km^2. Each HFR allows hourly measurement of the radial component of sea surface currents between Sicily and Malta (range resolution of 1.5 km, azimuthal resolution of 5°). By combining the radial data (considering radials inside a 6 km radius), the network provides measurements on a grid basis of the time-volume integral near-surface currents (employing an HFR at 13.5 MHz, ~1 m of water column is investigated) at an hourly temporal scale; the final grid spacing is 3 km.

Since microplastics tend to accumulate and disperse by surface currents (Cincinelli et al., 2018), precise knowledge of sea surface current fields are essential. Therefore, data from the CALYPSO HFR network were utilised by selecting HFR maps acquired during the *in-situ* samplings. This was done considering that: *i)* the timestamp of the HFR maps corresponds to the central time of a 75-min temporal window; *ii)* the *in-situ* sampling needs to be referenced to the central time of each *in-situ* transect (hereinafter referred to as the '*in-situ* reference time'). As a result, spatial and temporal matching were performed. Spatial matching was achieved by applying a weighted inverse distance function to the HFR data, while temporal matching was accomplished using linear interpolation. While the CALYPSO HFR network data boasts high accuracy (Capodici et al., 2019), proper filtering is necessary to remove data corrupted by external radio frequency interferences. In this framework, both radial and total sea current data underwent filtering *via* QC/QA (Quality Check/Quality Assessment) analyses to select only the

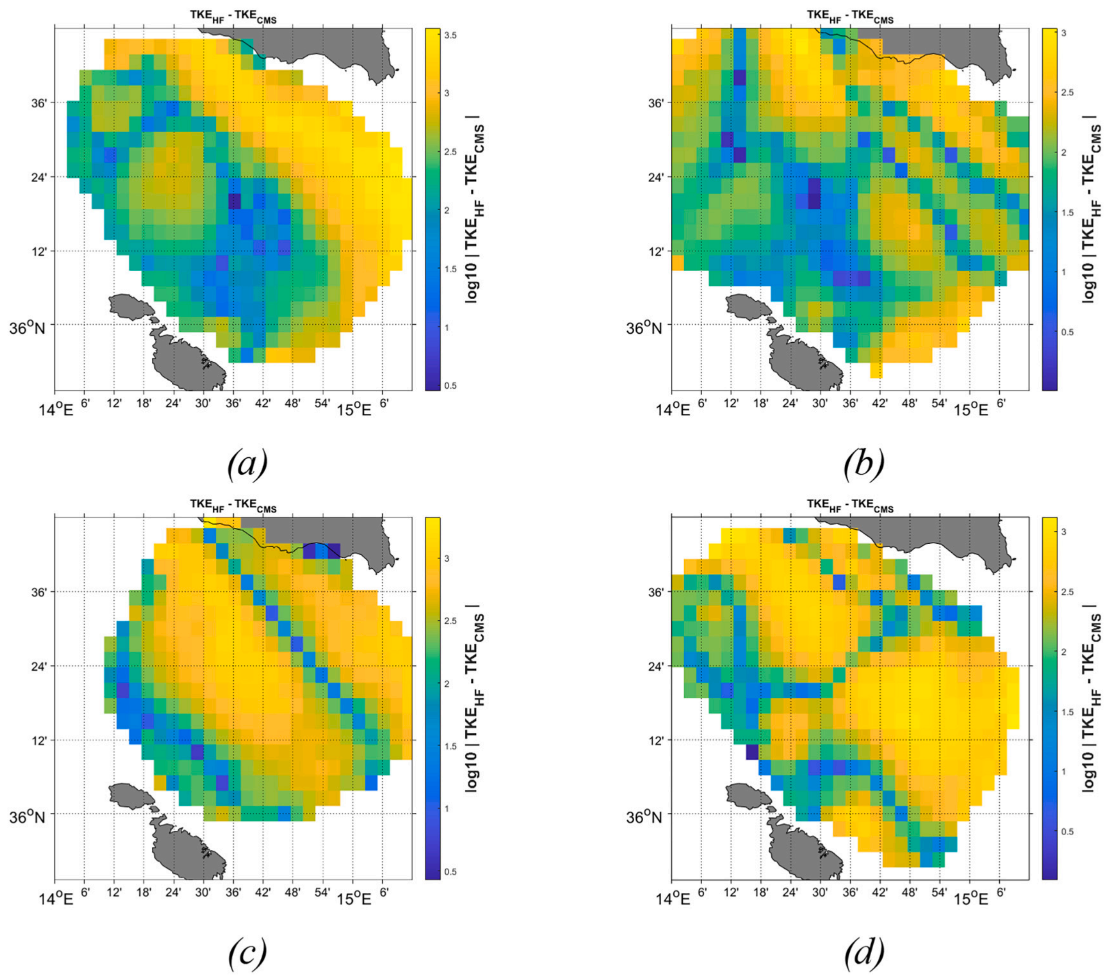

Fig. 13. Absolute TKE differences (HFR - CMS) in log-scale for: a) July 2018; b) October 2018; c) July 2019 and d) October 2019.

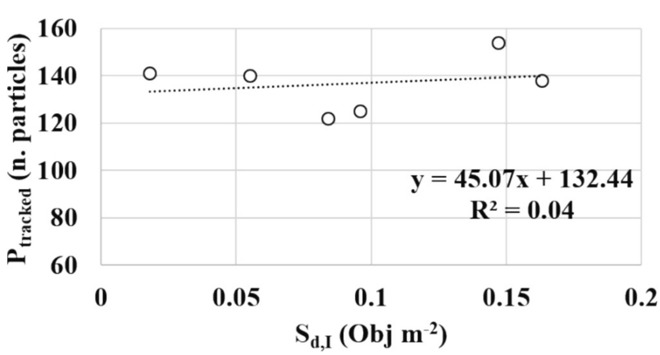

Fig. 14. $S_{d,I}$ *vs* $P_{tracked}$ linear by applying TrackMPD using CMS data as forcings.

best HFR measures for comparison with the *in-situ* microplastic samplings (Table S1, Annex 1). A comparison was carried out among S_d and variables related to HFR currents. Specifically, strong correlations were found between *in-situ* S_d and both the Total Kinetic Energy (*TKE)* units in m^2 s^{-2}, and the Eddy Kinetic Energy (*EKE*) units in m^2 s^{-2}, these latter derived accordingly to Capodici et al. (2018).

The comparisons encompassed both raw (all S_d *vs TKE* and S_d *vs EKE*) and QC/QA filtered data, SS_I, ($S_{d,I}$ *vs TKE* and $S_{d,I}$ *vs EKE*); additionally, the analyses involved the entire *in-situ* dataset and most frequent sub-microplastic classes (i.e, shards, sheets, and filaments). Finally, the TrackMPD particle tracking model (Jalón-Rojas et al., 2019) was forced with HFR QC/QA sea currents to verify the reliability of the above mentioned correlations. Particles were deployed around each *in-situ* sampling point three hours before each *in-situ* sampling (considering a regular grid 0.02° x 0.02° wide with a spacing of 0.002°). The particles were tracked for three hours and those remaining within a search range of 0.01° were counted, $P_{tracked}$, and compared to $S_{d,I}$.

3.3. CMS data: concentration of microplastics in wider areas

Several metrics, including correlation coefficient, bias, slope, t-stats and *p*-value allowed to determine the reliability of the *TKE* (and *EKE*) *vs* S_d regression. With the aim to show maps of potential plastic accumulation for the whole Sicily channel the above mentioned regressions was applied to Copernicus Marine data Service (CMS) at the monthly scale by employing sea surface currents at 0.042° x 0.042° of spatial resolution (doi:10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1). However, CMS sea currents results from numerical simulations. Thus, who intends to apply the proposed method on wider areas (not achievable with HFR networks) needs to validate CMS against independent data, such as HFR and/or ARGO/drifter trajectories to priory assess the CMS data accuracies in the exanimated area. For the present case study, daily CMS and HFR data were compared qualitatively, *i.e.* by overlapping the two current fields; and quantitatively, by computing the differences between *TKE* and *EKE* (at the monthly scale). Finally, by considering deployment scenario previously described in Section 3.1, the TrackMPD particle tracking experiment was repeated but using the CMS data (same deployment scenario employing forcing the model with CMS hourly data).

4. Results and discussion

4.1. In-situ sampling results

The microplastics sampled during the monitoring surveys were quantified and classified, through the stereomicroscope analysis, basing on their shape. The quantities, for each fraction, are reported in Table 2 and represented in Fig. 3. In Fig. 4, the six categories considered are presented.

During both the 2018 and 2019 surveys, and across all transects, 'fragments' were the most abundant shape. However, there were some differences between the two years. In the 2018 campaign, the second most abundant shape was 'sheets'; whereas in 2019, the variety of shapes increased in several transects. A large number of 'filaments' were also collected at M10.

4.2. CALYPSO HFR data results

The *TKE* and the *EKE* maps related to the QC/QA selected *in-situ* samplings (SS_I) are presented in Figs. 5 and 6 respectively.

It is noticeable that the area is characterised by TKE energy values ranging from approximately 0.005 m^2s^{-2} up to about 0.1 m^2s^{-2}. Specifically, TKE_I maps display a narrower range of variability, ranging from around 0.005 to approximately 0.052 m^2s^{-2}. EKE_I, spans between 0.005 m^2s^{-2} and 0.1 m^2s^{-2} even if it is almost constant within the HFR domain ($\sim$ 0.01 m^2s^{-2}) and characterised by small areas with higher values (from 0.02 up to 0.05 m^2 s^{-2}), especially for M3–2019, and M10–2018 and M10–2019. Notably that the SS_I are mostly located within the CALYPSO domain, whereas the excluded ones, SS_{NI}, are situated near the boundary and/or in the peripheral area of the CALYPSO domain (Figs. S1 and S2, Annex 1).

TKE vs $S_{d,I}$ and *EKE vs* $S_{d,I}$ exhibit $r^2 \sim 0.7$ and ~ 0.4 respectively and are characterised by a negative slope meaning that the higher *TKE (*or *EKE)* the lower microplastics occurrences.

Notably, that the highest r^2 were found by restricting the analysis to the fragments subsamples (the most frequent microplastic class) with TKE_I *vs* $S_{d,I}$ characterised by $r^2 \sim 0.85$ (Fig. 7 and Table 3). These results, especially regarding the *TKE vs* $S_{d,I}$ regression open the possibility to consider the *TKE* as a proxy variable of microplastics accumulation. As very low r^2 were characterising the EKE_I *vs* $S_{d,I}$ regression for all the subsamples, only the TKE_I *vs* $S_{d,I}$ will be considered from now on.

The significance of the TKE_I *vs* $S_{d,I}$ regressions evaluated *via* a statistical test (Table 3) highlighted that the regression t-stats are higher than the t-critical (Number of observations = 6, Error degrees of freedom = 4, t-critical = 2.776) whereas the *p*-values are lower than the critical one ($\alpha/2$), with a significance level of α equal to $5\ 10^{-2}$, only for the fragment category.

The Lagrangian model forced with HFR data evidenced a strong $S_{d,I}$ *vs* $P_{tracked}$ linear relation (Fig. 8). As expected, the highest $P_{tracked}$ points were found within the search range around the point characterised by the highest $S_{d,I}$ (A1–2019); *vice versa*, the lowest $P_{tracked}$ value was associated to the M10–2019 where the minimum of $S_{d,I}$ were found *in-situ* (Fig. 9).

4.3. CMS data results

A desirable applicability of the TKE_I *vs* $S_{d,I}$ regression to wider domains requires employing CMS data. As an example of outputs, maps of the possible plastic-fragments accumulation in the whole Sicily channel were derived using CMS monthly data of 2018 and 2019. From the summer (July) and autumn (October) periods maps (Fig. 10) it is noticeably that high plastic accumulations could be verified at the centre of eddy structures (small-scale/gamma-mesoscale) occurring in the area.

Unfortunately, the accuracy of output maps could be compromised when the method is applied to simulated sea surface current fields, such as those provided by CMS. Indeed, comparisons between CMS-derived and HFR-measured sea surface current fields in the study area have shown that the CMS model often exhibits significant inaccuracies (Figs. 11–12). Differences are observed in terms of sea current direction and magnitude resulting in moderate to high *TKE* differences. In particular, absolute *TKE* differences spans between 0 and 0.05 m^2s^{-2}.

Notably that the best agreement was found for October 2018 in which large part of the domain exhibits limited *TKE* differences (of $\pm$0.005 m^2s^{-2}, 0.5–1.5 in the log-scale, Fig. 13). The higher reliability of the CMS current field of October 2018 is underlined by the moderate vectorial correlation value ($R_{vct} \sim 0.6$, average value of the period) and close to zero rotation angle ($\theta_{vec} \sim 0.9^\circ$, average value of the period) computed according to Kundu, 1976. For the other three periods no satisfactory results were achieved.

Finally, the TrackMPD was repeated forcing the model with CMS hourly data resulted in a null $S_{d,I}$ *vs* $P_{tracked}$ relation (Fig. 14).

5. Conclusions

Two multidisciplinary monitoring surveys were performed in 2018 and 2019 in the framework of the MEDIAS and the CALYPSO South Project. These focused on analysing marine plastic pollution in relationship to the surface circulation observed by the HFR network. The quantification and categorisation of sampled microplastics revealed that fragments are the most abundant type. Furthermore, the variety of microplastics sampled, in terms of shape, highlights how pollutant sources are diverse and possibly connected to various activities. Due to the challenges of conducting *in-situ* sampling campaigns and the inability to monitor large areas in reasonable timeframes, the possibility of integrating remote sensing approaches, was evaluated.

This work proposes an innovative approach for monitoring plastic litter. A combined methodology was applied in the Maltese Channel, enabled by the availability of sea surface current data from the CALYPSO HFR network and *in-situ* sampling of microplastics (MPs). An investigation was conducted into whether the total and eddy kinetic energy of sea surface currents correlates with the occurrence of *in-situ* collected MPs, aiming to determine if kinetic energies could serve as proxies for mapping microplastic accumulation and dispersion areas. Both *TKE vs* S_d and *EKE vs* S_d inverse regressions figure out in this study, suggest that the accumulation areas could be those characterised by lower *TKE* and *EKE* values. Of the two, *TKE* exhibit the highest correlation with the *in-situ* S_d ($r^2 \sim 0.85$ for the fragments of plastic fraction). However, it should be noted that this link could be biased due to local effects. For example, an opposite behaviour is expected in cases where high amounts of microplastics are trapped by sea surface currents. This can be evidenced when extreme rainfall occurs during the summer period in the Sicilian Channel, where the Atlantic Ionian Stream is the dominant circulation feature.

The analyses presented here also highlight that occurrence of fragment items are highly correlated with *TKE*, indicating that this type of microplastic primarily drifts by sea surface currents, whereas other types of microplastics are likely influenced not only by marine currents but also by other forcings such as wind actions. A Lagrangian experiment, involving the deployment of virtual drifters on small regular grids around each *in-situ* sampling point, revealed that when the model is forced with HFR data, a larger number of particles remain close to the points where higher microplastic accumulations were actually observed.

The application of the *TKE vs* S_d regression to wider domains through the application of CMS data reveals a widespread distribution of microplastic in a moderate concentration (*i.e.* $S_d \sim 0.2$ obj m^{-2}) throughout the Sicily Channel. Moreover, areas with strong current jets exhibit near-zero concentrations, whereas accumulation peaks are observed at the centres of eddy structures commonly occurring in the area both in summer as well as in autumn-winter periods. However, the accuracy of these outputs could be limited as CMS-derived and HFR-measured sea surface current fields were compared showing that CMS often exhibits significant inaccuracies in the area.

CRediT authorship contribution statement

Fulvio Capodici: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Corbari:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Adam Gauci:** Writing – review & editing, Data curation. **Gualtiero Basilone:** Methodology, Data curation. **Angelo Bonanno:** Methodology, Data curation. **Salvatore Campanella:** Project administration, Formal analysis, Data curation. **Giuseppe Ciraolo:** Writing – review & editing, Supervision, Project administration. **Angela Candela:** Methodology. **Daniela D'Amato:** Formal analysis, Data curation. **Rosalia Ferreri:** Methodology, Data curation. **Ignazio Fontana:** Methodology, Data curation. **Simona Genovese:** Methodology, Data curation. **Giovanni Giacalone:** Methodology, Data curation. **Giuseppina Marino:** Formal analysis, Data curation. **Salvatore Aronica:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Conceptualization.

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.

Acknowledgements

Surveys were cofinanced by the Consiglio Nazionale delle Ricerche and the European Union through the Data Collection Framework (DCF – Reg. Ce. No. 199/2008, No. 665/2008 and Commission Decision No. 949/2008). The surveys were planned as part of a cross-border cooperation project between Italy and Malta (Calypso South – Interreg Italia-Malta COD: C1 3.2 - 79) and we are grateful to the authorities and partners who made this possible. We are also grateful to all the captains and the crew of R/V "G. Dallaporta" for their help in collecting data in 2018-2019.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117237.

Data availability

All data used during this study are available from the corresponding authors upon request.

References

Basilone, G., Bonanno, A., Patti, B., Mazzola, S., Barra, M., Cuttitta, A., McBride, R., 2013. Spawning site selection by European anchovy (*Engraulis encrasicolus*) in relation to oceanographic conditions in the Strait of Sicily. Fish. Oceanogr. 22, 309–323. https://doi.org/10.1111/fog.12024.

Basilone, G., Ferreri, R., Aronica, S., Mazzola, S., Bonanno, A., Gargano, A., Pulizzi, M., Fontana, I., Giacalone, G., Calandrino, P., Genovese, S., Barra, M., 2021. Reproduction and sexual maturity of European sardine (Sardina pilchardus) in the Central Mediterranean Sea. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.715846.

Basilone, G., Ferreri, R., Aronica, S., Bonanno, A., Genovese, S., Rumolo, P., Carbonara, P., Barra, M., 2023. Growth variability in Atlantic horse mackerel Trachurus trachurus (Linneus, 1758) across the central Mediterranean Sea: contrasting latitudinal gradient and different ecosystems. Front. Mar. Sci. 10. https://doi.org/10.3389/fmars.2023.1161552.

Ben Abdallah, L., Barra, M., Gaamour, A., Khemiri, S., Genovese, S., Mifsud, R., Basilone, G., Fontana, I., Giacalone, G., Aronica, S., Mazzola, S., Jarboui, O., Bonanno, A., 2018. Small pelagic fish assemblages in relation to environmental regimes in the Central Mediterranean. Hydrobiologia 821, 113–134. https://doi.org/10.1007/s10750-018-3540-0.

Béranger, K., Mortier, L., Gasparini, G.-P., Gervasio, L., Astraldi, M., Crépon, M., 2004. The dynamics of the Sicily Strait: a comprehensive study from observations and models. Deep Sea Research Part II: Topical Studies in Oceanography, The Physical Oceanography of Sea Straits 51, 411–440. https://doi.org/10.1016/j.dsr2.2003.08.004.

Beron-Vera, F.J., Olascoaga, M.J., Lumpkin, R., 2016. Inertia-induced accumulation of flotsam in the subtropical gyres. Geophys. Res. Lett. 43, 12,228–12,233. https://doi.org/10.1002/2016GL071443.

Bonanno, A., Barra, M., Mifsud, R., Basilone, G., Genovese, S., Di Bitetto, M., Aronica, S., Giacalone, G., Fontana, I., Mangano, S., Ferreri, R., Pulizzi, M., Rumolo, P., Gargano, A., Buscaino, G., Calandrino, P., Di Maria, A., Mazzola, S., 2018. Space utilization by key species of the pelagic fish community in an upwelling ecosystem of the Mediterranean Sea. Hydrobiologia 821, 173–190. https://doi.org/10.1007/s10750-017-3350-9.

Bonanno, A., Placenti, F., Basilone, G., Mifsud, R., Genovese, S., Patti, B., Di Bitetto, M., Aronica, S., Barra, M., Giacalone, G., Ferreri, R., Fontana, I., Buscaino, G., Tranchida, G., Quinci, E., Mazzola, S., 2014. Variability of water mass properties in the Strait of Sicily in summer period of 1998–2013. Ocean Sci. 10, 759–770. https://doi.org/10.5194/os-10-759-2014.

Bonanno, A., Barra, M., De Felice, A., Giannoulaki, M., Iglesias, M., Leonori, I., Ventero, A., Aronica, S., Biagiotti, I., Ticina, V., Genovese, S., 2021. Acoustic Correction Factor Estimate for Compensating the Vertical Diel Migration of Small Pelagic Species. https://doi.org/10.12681/mms.25120.

Bricheno, L.M., Wolf, J., 2018. Future wave conditions of Europe, in response to high-end climate change scenarios. J. Geophys. Res. Oceans 123, 8762–8791. https://doi.org/10.1029/2018JC013866.

Capodici, F., Ciraolo, G., Cosoli, S., Maltese, A., Mangano, M.C., Sarà, G., 2018. Downscaling hydrodynamics features to depict causes of major productivity of Sicilian-Maltese area and implications for resource management. Sci. Total Environ. 628–629, 815–825. https://doi.org/10.1016/j.scitotenv.2018.02.106.

Capodici, F., Cosoli, S., Ciraolo, G., Nasello, C., Maltese, A., Poulain, P.-M., Drago, A., Azzopardi, J., Gauci, A., 2019. Validation of HF radar sea surface currents in the Malta-Sicily Channel. Remote Sens. Environ. 225, 65–76. https://doi.org/10.1016/j.rse.2019.02.026.

Chatterjee, S., Sharma, S., 2019. Microplastics in our oceans and marine health. Field Actions Science Reports. J. Field Actions 54–61.

Cincinelli, A., Martellini, T., Guerranti, C., Scopetani, C., Chelazzi, D., Giarrizzo, T., 2018. A potpourri of microplastics in the sea surface and water column of the Mediterranean Sea. TrAC Trends Anal. Chem. 110. https://doi.org/10.1016/j.trac.2018.10.026.

Cozar Cabañas, A., Sanz-Martín, M., Martí, E., Ignacio González-Gordillo, J., Ubeda, B., Gálvez, J.Á., Irigoien, X., Duarte, C.M., 2015. Concentrations of Floating Plastic Debris in the Mediterranean Sea Measured during MedSeA-2013 Cruise. https://doi.org/10.1594/PANGAEA.842054.

Crawford, C.B., Quinn, B., 2017. Plastic production, waste and legislation. In: Microplastic Pollutants. Elsevier, pp. 39–56. https://doi.org/10.1016/B978-0-12-809406-8.00003-7.

De Felice, A., Iglesias, M., Saraux, C., Bonanno, A., Ticina, V., Leonori, I., Ventero, A., Hattab, T., Barra, M., Gasparevic, D., Biagiotti, I., Bourdeix, J.-H., Genovese, S., Juretic, T., Aronica, S., Malavolti, S., Saraux, C., Bonanno, A., Ticina, V., Leonori, I., Ventero, A., Hattab, T., Barra, M., Gasparevic, D., Biagiotti, I., Bourdeix, J.-H., Genovese, S., Juretic, T., Aronica, S., Malavolti, S., 2021. Environmental drivers influencing the abundance of round sardinella (Sardinella aurita) and European sprat (Sprattus sprattus) in different areas of the Mediterranean Sea. Mediterr. Mar. Sci. 22, 812–826. https://doi.org/10.12681/mms.25933.

D'Elia, M., Patti, B., Sulli, A., Tranchida, G., Bonanno, A., Basilone, G., Giacalone, G., Fontana, I., Genovese, S., Guisande, C., Mazzola, S., 2009. Distribution and spatial structure of pelagic fish schools in relation to the nature of the seabed in the Sicily Straits (Central Mediterranean). Mar. Ecol. 30, 151–160. https://doi.org/10.1111/j.1439-0485.2009.00328.x.

Eigaard, O.R., Bastardie, F., Hintzen, N.T., Buhl-Mortensen, L., Buhl-Mortensen, P., Catarino, R., Dinesen, G.E., Egekvist, J., Fock, H.O., Geitner, K., Gerritsen, H.D., González, M.M., Jonsson, P., Kavadas, S., Laffargue, P., Lundy, M., Gonzalez-Mirelis, G., Nielsen, J.R., Papadopoulou, N., Posen, P.E., Pulcinella, J., Russo, T., Sala, A., Silva, C., Smith, C.J., Vanelslander, B., Rijnsdorp, A.D., 2017. The footprint of bottom trawling in European waters: distribution, intensity, and seabed integrity. ICES J. Mar. Sci. 74, 847–865. https://doi.org/10.1093/icesjms/fsw194.

Fossi, M.C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., Minutoli, R., 2012. Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera physalus). Mar. Pollut. Bull. 64, 2374–2379. https://doi.org/10.1016/j.marpolbul.2012.08.013.

Froyland, G., Stuart, R.M., van Sebille, E., 2014. How well-connected is the surface of the global ocean? Chaos: An Interdisciplinary Journal of Nonlinear Science 24, 033126. https://doi.org/10.1063/1.4892530.

Fu, Z., Wang, J., 2019. Current practices and future perspectives of microplastic pollution in freshwater ecosystems in China. Sci. Total Environ. 691, 697–712. https://doi.org/10.1016/j.scitotenv.2019.07.167.

García Rellán, A., Vázquez Ares, D., Vázquez Brea, C., Francisco López, A., Bello Bugallo, P.M., 2023. Sources, sinks and transformations of plastics in our oceans: review, management strategies and modelling. Sci. Total Environ. 854, 158745. https://doi.org/10.1016/j.scitotenv.2022.158745.

Gruber, E.S., Stadlbauer, V., Pichler, V., Resch-Fauster, K., Todorovic, A., Meisel, T.C., Trawoeger, S., Hollóczki, O., Turner, S.D., Wadsak, W., Vethaak, A.D., Kenner, L., 2023. To waste or not to waste: questioning potential health risks of micro- and nanoplastics with a focus on their ingestion and potential carcinogenicity. Expo. Health 15, 33–51. https://doi.org/10.1007/s12403-022-00470-8.

Haller, G., Beron-Vera, F.J., 2013. Coherent Lagrangian vortices: the black holes of turbulence. J. Fluid Mech. 731, R4. https://doi.org/10.1017/jfm.2013.391.
Jalón-Rojas, I., Wang, X.H., Fredj, E., 2019. A 3D numerical model to track marine plastic debris (TrackMPD): sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes. Mar. Pollut. Bull. 141, 256–272. https://doi.org/10.1016/j.marpolbul.2019.02.052.
Kroon, F.J., Motti, C.E., Jensen, L.H., Berry, K.L.E., 2018. Classification of marine microdebris: a review and case study on fish from the Great Barrier Reef, Australia. Sci. Rep. 8, 16422. https://doi.org/10.1038/s41598-018-34590-6.
Kühn, S., Bravo Rebolledo, E.L., van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 75–116. https://doi.org/10.1007/978-3-319-16510-3_4.
Kundu, P.K., 1976. Ekman veering observed near the ocean bottom. J. Phys. Oceanogr. 6, 238–242.
Lebreton, L., Slat, B., Ferrari, F., et al., 2018. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Sci. Rep. 8, 4666. https://doi.org/10.1038/s41598-018-22939-w.
Leonori, I., Tičina, V., Giannoulaki, M., Hattab, T., Iglesias, M., Bonanno, A., Costantini, I., Canduci, G., Machias, A., Ventero, A., Somarakis, S., Tsagarakis, K., Bogner, D., Barra, M., Basilone, G., Genovese, S., Juretić, T., Gašparević, D., Felice, A.D., 2021. History of hydroacoustic surveys of small pelagic fish species in the European Mediterranean Sea. Mediterr. Mar. Sci. 22, 751–768. https://doi.org/10.12681/mms.26001.
Lermusiaux, P.F.J., Robinson, A.R., 2001. Features of dominant mesoscale variability, circulation patterns and dynamics in the Strait of Sicily. Deep-Sea Res. I Oceanogr. Res. Pap. 48, 1953–1997. https://doi.org/10.1016/S0967-0637(00)00114-X.
Li, W.C., Tse, H.F., Fok, L., 2016. Plastic waste in the marine environment: A review of sources, occurrence and effects. Sci. Total Environ. 566–567, 333–349. https://doi.org/10.1016/j.scitotenv.2016.05.084.
Li, J., Shan, E., Zhao, J., Teng, J., Wang, Q., 2023. The factors influencing the vertical transport of microplastics in marine environment: a review. Sci. Total Environ. 870, 161893. https://doi.org/10.1016/j.scitotenv.2023.161893.
Löhr, A., Savelli, H., Beunen, R., Kalz, M., Ragas, A., Van Belleghem, F., 2017. Solutions for global marine litter pollution. Current Opinion in Environmental Sustainability, Sustainability governance 28, 90–99. https://doi.org/10.1016/j.cosust.2017.08.009.
Lopes, C., Raimundo, J., Caetano, M., Garrido, S., 2020. Microplastic ingestion and diet composition of planktivorous fish. Limnology and Oceanography Letters 5, 103–112. https://doi.org/10.1002/lol2.10144.
Lorente, P., Aguiar, E., Bendoni, M., Berta, M., Brandini, C., Cáceres-Euse, A., Capodici, F., Cianelli, D., Ciraolo, G., Corgnati, L., Dadić, V., Doronzo, B., Drago, A., Dumas, D., Falco, P., Fattorini, M., Gauci, A., Gómez, R., Griffa, A., Guérin, C.-A., Hernández-Carrasco, I., Hernández-Lasheras, J., Ličer, M., Magaldi, M.G., Mantovani, C., Mihanović, H., Molcard, A., Mourre, B., Orfila, A., Révelard, A., Reyes, E., Sánchez, J., Saviano, S., Sciascia, R., Taddei, S., Tintoré, J., Toledo, Y., Ursella, L., Uttieri, M., Vilibić, I., Zambianchi, E., Cardin, V., 2022. Coastal high-frequency radars in the Mediterranean – part 1: status of operations and a framework for future development. Ocean Sci. 18, 761–795. https://doi.org/10.5194/os-18-761-2022.
Mak, C.W., Ching-Fong Yeung, K., Chan, K.M., 2019. Acute toxic effects of polyethylene microplastic on adult zebrafish. Ecotoxicol. Environ. Saf. 182, 109442. https://doi.org/10.1016/j.ecoenv.2019.109442.
Mangano, M.C., Sarà, G., 2017. Collating science-based evidence to inform public opinion on the environmental effects of marine drilling platforms in the Mediterranean Sea. J. Environ. Manage. 188, 195–202. https://doi.org/10.1016/j.jenvman.2016.12.013.
Monteiro, R.C.P., Ivar do Sul, J.A., Costa, M.F., 2018. Plastic pollution in islands of the Atlantic Ocean. Environ. Pollut. 238, 103–110. https://doi.org/10.1016/j.envpol.2018.01.096.
Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108, 131–139. https://doi.org/10.1016/j.envres.2008.07.025.
Narayanan, M., 2023. Origination, fate, accumulation, and impact, of microplastics in a marine ecosystem and bio/technological approach for remediation: A review. Proc. Safe. Environ. Protect. 177, 472–485. https://doi.org/10.1016/j.psep.2023.07.013.
Neves, D., Sobral, P., Ferreira, J.L., Pereira, T., 2015. Ingestion of microplastics by commercial fish off the Portuguese coast. Mar. Pollut. Bull. 101, 119–126. https://doi.org/10.1016/j.marpolbul.2015.11.008.
PlasticsEurope, 2021. Plastics - the Facts 2021 - An Analysis of European Plastics Production, Demand and Waste Data.
Reyes, E., Aguiar, E., Bendoni, M., Berta, M., Brandini, C., Cáceres-Euse, A., Capodici, F., Cardin, V., Cianelli, D., Ciraolo, G., Corgnati, L., Dadić, V., Doronzo, B., Drago, A., Dumas, D., Falco, P., Fattorini, M., Fernandes, M.J., Gauci, A., Gómez, R., Griffa, A., Guérin, C.-A., Hernández-Carrasco, I., Hernández-Lasheras, J., Ličer, M., Lorente, P., Magaldi, M.G., Mantovani, C., Mihanović, H., Molcard, A., Mourre, B., Révelard, A., Reyes-Suárez, C., Saviano, S., Sciascia, R., Taddei, S., Tintoré, J., Toledo, Y., Uttieri, M., Vilibić, I., Zambianchi, E., Orfila, A., 2022. Coastal high-frequency radars in the Mediterranean – part 2: applications in support of science priorities and societal needs. Ocean Sci. 18, 797–837. https://doi.org/10.5194/os-18-797-2022.
Robinson, A.R., Sellschopp, J., Warn-Varnas, A., Leslie, W.G., Lozano, C.J., Haley, P.J., Anderson, L.A., Lermusiaux, P.F.J., 1999. The Atlantic Ionian stream. J. Mar. Syst. 20, 129–156. https://doi.org/10.1016/S0924-7963(98)00079-7.
Romeo, T., Pietro, B., Pedà, C., Consoli, P., Andaloro, F., Fossi, M.C., 2015. First evidence of presence of plastic debris in stomach of large pelagic fish in the Mediterranean Sea. Mar. Pollut. Bull. 95, 358–361. https://doi.org/10.1016/j.marpolbul.2015.04.048.
Rumolo, P., Fanelli, E., Barra, M., Basilone, G., Genovese, S., Gherardi, S., Ferreri, R., Gargano, A., Mazzola, S., Bonanno, A., 2018. Trophic relationships between anchovy (Engraulis encrasicolus) and zooplankton in the Strait of Sicily (Central Mediterranean sea): a stable isotope approach. Hydrobiologia 821. https://doi.org/10.1007/s10750-017-3334-9.
Sambolino, A., Iniguez, E., Herrera, I., Kaufmann, M., Dinis, A., Cordeiro, N., 2023. Microplastic ingestion and plastic additive detection in pelagic squid and fish: implications for bioindicators and plastic tracers in open oceanic food webs. Sci. Total Environ. 894, 164952. https://doi.org/10.1016/j.scitotenv.2023.164952.
Sebille, E. van, Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Franeker, J.A. van, Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. Environ. Res. Lett. 10, 124006. https://doi.org/10.1088/1748-9326/10/12/124006.
Sharma, S., Sharma, V., Chatterjee, S., 2021. Microplastics in the Mediterranean Sea: sources, pollution intensity, sea health, and regulatory policies. Front. Mar. Sci. 8.
Sprovieri, M., Ribera d'Alcalà, M., Roose, P., Drago, A., De Cauwer, K., Falcini, F., Lips, I., Maggi, C., Mauffret, A., Tronczynski, J., Zeri, C., Moretti, P.F., 2021. Science for good environmental status: a European joint action to support marine policy. Sustainability 13, 8664. https://doi.org/10.3390/su13158664.
Strain, E.M.A., Lai, R.W.S., White, C.A., Piarulli, S., Leung, K.M.Y., Airoldi, L., O'Brien, A., 2022. Editorial: marine pollution - emerging issues and challenges. Front. Mar. Sci. 9.
Thiel, M., Luna-Jorquera, G., Álvarez-Varas, R., Gallardo, C., Hinojosa, I.A., Luna, N., Miranda-Urbina, D., Morales, N., Ory, N., Pacheco, A.S., Portflitt-Toro, M., Zavalaga, C., 2018. Impacts of marine plastic pollution from continental coasts to subtropical gyres—fish, seabirds, and other vertebrates in the SE Pacific. Front. Mar. Sci. 5.
Thushari, G.G.N., Senevirathna, J.D.M., 2020. Plastic pollution in the marine environment. Heliyon 6, e04709. https://doi.org/10.1016/j.heliyon.2020.e04709.
United Nations Environment Programme, 2015. UNEP 2014 Annual Report.
Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M.B., Janssen, C.R., 2015. Microplastics are taken up by mussels (Mytilus edulis) and lugworms (Arenicola marina) living in natural habitats. Environ. Pollut. 199, 10–17. https://doi.org/10.1016/j.envpol.2015.01.008.
Waldschläger, K., Miao, L., Adyel, T.M., 2022. Editorial: plastics in aquatic systems: from transport and fate to impacts and management perspectives. Frontiers in Environmental Science 10.
Wang, J., Liu, X., Liu, G., Zhang, Z., Wu, H., Cui, B., Bai, J., Zhang, W., 2019. Size effect of polystyrene microplastics on sorption of phenanthrene and nitrobenzene. Ecotoxicol. Environ. Safe. 173, 331–338. https://doi.org/10.1016/j.ecoenv.2019.02.037.
Werner, S., Budziak, A., van Franeker, J., Galgani, F., Hanke, G., Maes, T., Matiddi, M., Nilsson, P., Oosterbaan, L., Priestland, E., Thompson, R., Veiga, J., Vlachogianni, T., 2016. Harm caused by Marine Litter: MSFD GES TG Marine Litter - thematic report. Publications Office of the European Union, Luxembourg.
Wright, R.J., Erni-Cassola, G., Zadjelovic, V., Latva, M., Christie-Oleza, J.A., 2020. Marine plastic debris: A new surface for microbial colonization. Environ. Sci. Technol. 54, 11657–11672. https://doi.org/10.1021/acs.est.0c02305.