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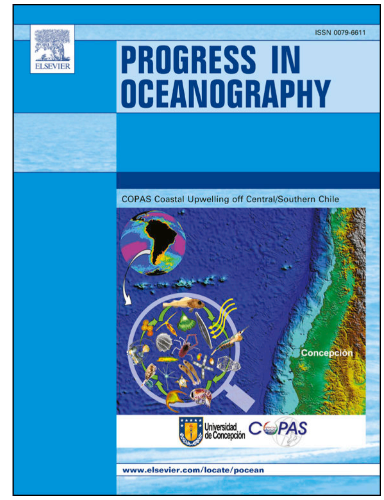

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Predicting marine litter accumulation patterns in the Mediterranean basin: spatio-temporal variability and comparison with empirical data

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Abstract

The Mediterranean Sea is now acknowledged to be a hot spot for marine litter. However, little is known about Floating Macro Litter (FML) concentration at the scale of the entire basin; predictions regarding this would greatly help guide policymaking to fight this scourge. While previous studies have shown high spatio-temporal variability in FML distribution, the aim of this study was to accurately identify seasonal debris accumulation patterns on regional and local spatial scales across the Mediterranean basin. The objective was then to quantitatively compare this distribution model to other simulations and empirical data. We first studied FML distribution with a 2-D Lagrangian model coupled to an oceanic general circulation model (OGCM) at a horizontal resolution of $1/12^o$. From an initial homogeneous deployment, we deployed a set of $> 10^8$ virtual particles across the whole basin and tracked each particle during 3-month journeys. Then we described the FML distribution model outputs and compared them both to empirical observations at the scale of the whole basin (gathered from a review of scientific papers on surface debris distribution), and to other numerical FML simulations from previous studies. The results of our offshore modeled distribution of FML fully agreed with characteristic debris accumulation patterns analyzed in our review of other studies. This indicates that our model could allow the prediction of monthly litter accumulation patterns at the scale of the entire Mediterranean Sea.

Keywords:
Floating debris, Mediterranean, Empirical data, Modeling, Literature review, Accumulation patterns

1. Introduction

Plastic pollution has become a very sensitive issue, from both an ecological and socio-economic point of view, in many places around the world. As a semi-closed and highly urbanized area, the Mediterranean Sea is particularly affected, and litter inputs and distribution have been increasingly investigated by the scientific community over the last decade (Galgani, 2014; Suaria and Aliani, 2014; Mansui et al., 2015; Zambianchi et al., 2017).

Recent studies based on floating marine litter distribution models have estimated that the total surface plastic load in the Mediterranean basin ranges from a few thousand tons (Cózar et al., 2015) to 23,150 tons (Eriksen et al., 2014) or 30,000 tons (van Sebille et al., 2015). Visual observations have confirmed the predominance of plastic items in the Mediterranean (e.g. Arcangeli et al., 2018; Fossi et al., 2017; Suaria and Aliani, 2014). Suaria and Aliani (2014) estimated that at least 62 million macro litter items was floating on the surface of the entire sea in 2013, with plastic accounting for 82% of all manmade floating items encountered. Such a surface load of plastic, evaluated either by simulations or by visual observation, seems worse than the so-called 'garbage patches' encountered in the five subtropical gyres, making the Mediterranean one of the world's most plastic-polluted sea (Lebreton et al., 2012). This pollution may have a high impact on the marine environment and biodiversity (Compa et al., 2019), e.g. related to marine fauna ingestion or entanglement (Deudero and Alomar, 2015). As light plastics passively concentrate in the Mediterranean, with few possibilities of escaping the area naturally, the identification and anticipation of accumulation patterns is crucial in order to target efficient management measures for limiting the environmental risks.

The accumulation of floating plastic debris in the Mediterranean Sea likely results from large input related to high human pressure, combined with the hydrodynamics of this semi-enclosed basin. The latter is greatly constrained by a net inflow of surface water from the Atlantic through the Strait of Gibraltar, and a limited outflow that mainly occurs through a deep water layer, resulting in a lack of outflow possibility for items that are less dense than seawater. Consequently, the Mediterranean Sea has an overall water residence time (considering the entire depth of the water column) as long as a century (Lacombe et al., 1981), and thus acts as a sink for plastic pollution.

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The motion of floating macro-litter (i.e. here considered as floating items > 2 cm, and hereafter FML in abbreviated form) is usually described in terms of the passive displacement of conservative particles since their presence does not affect the dynamics of the water mass and does not undergo any transformation (time scales of plastic degradation are generally much longer than those of their transport, Barnes et al., 2009; Andrady, 2011). The spatio-temporal distribution of FML depends on various hydrodynamic factors as well as wind; these redistribute debris from their initial input in the ocean until they eventually wash ashore or sink. Debris input locations and the varying intensity of these sources over time are other key issues. In this way, the transport of FML is inherently a Lagrangian problem that can be resolved with, for example, numerical circulation models coupled with Lagrangian particle-tracking algorithms. This method has proved successful in estimating the relationships between particle distribution and the physical processes leading to FML accumulation at sea (Martinez et al., 2009; Lebreton et al., 2012; Maes and Blanke, 2015).

Modeling research on the transport and distribution of floating marine debris in the Mediterranean basin was initialy triggered by studies targeting the accumulation patterns in the oceanic gyres (e.g. Kubota, 1994; Martinez et al., 2009; Maximenko et al., 2012). Using global scale simulations, Lebreton et al. (2012) were the first to model FML distribution in the Mediterranean Sea and to describe the basin as a potential high-density marine debris region. Using alternative global scale simulations, Eriksen et al. (2014), Cózar et al. (2015) and van Sebille et al. (2015) confirmed that the concentration of floating marine litter in the Mediterranean Sea is in the same order of magnitude as in the oceanic gyres. However, none of these three studies identified the structure of local accumulation, as global scale simulations are not suitable for resolving regional ocean dynamics. Likewise, while field observations have shown high spatial and temporal variability in FML distribution, with local peak densities higher than 50 items/km^2 (Suaria and Aliani, 2014; Di-Méglio and Campana, 2017; Campana et al., 2018), they have not identified any stable FML accumulation structure.

In recent years, several studies have aimed to simulate floating marine litter drift in order to identify permanent accumulation patterns (Mansui et al., 2015; Zambianchi et al., 2017; Liubartseva et al., 2018). Given the lack of a standard global dataset on FML input, Mansui et al. (2015) used a simulation model with an initial homogeneous deployment of virtual particles in order to evaluate litter accumulation patterns over the entire Mediterranean basin. That study was the first to show that spatio-temporal variability in Mediterranean circulation hampers the formation of stable retention areas at the basin scale. It identified three temporary potential accumulation patterns, two in the northwestern sub-basin and one in the central sub-basin. It also underlined relevant coastal features such as the most polluted coastline, where a majority of debris was stranded (located in the southeastern Levantine sub-basin, but also between Tunisia and Syria) and, in contrast, a rather low coastal impact in the western Mediterranean.

In a more recent paper, Zambianchi et al. (2017) used the largest available set of historical Lagrangian data gathered in the Mediterranean basin, together with two different initial deployments of virtual particles (homogeneous and coastal distributions) in order to construct a Markov chain model. That study found a long-term accumulation pattern in the southern and southeastern Levantine sub-basin that was similar to that encountered in the global ocean. In contrast to Mansui et al. (2015), the study did not consider stranding, but only surface circulation, which might explain the discrepancy between the two studies on the existence of long-term accumulation patterns.

Finally, Liubartseva et al. (2018) carried out more sophisticated modeling to investigate the distribution of plastic debris in all marine compartments: at the sea surface, on the coastlines and on the seafloor. They considered an initial particle distribution based on plastic inputs from the urban population within a 10-km coastal strip, the main rivers and the congested shipping lanes. A Lagrangian module calculated the transport of floating plastic debris, while algorithms using a Monte Carlo technique determined stranding and sedimentation on the seabed. That study concluded that long-term accumulation patterns could not be found in the Mediterranean Sea due to an overall dissipative behavior over the basin. In contrast, they identified several temporary accumulation patterns, namely the Cilician sub-basin (northeastern Levantine), the Catalan Sea, and the region of the Po River delta and the Venice lagoon, which were all associated with high stranding rates.

Despite the few studies mentioned above, modeling plastic litter transport at sea is still in its relative infancy, resulting in insufficient knowledge on the issue. Moreover, different tracking schemes, resolutions or model set-ups can sometimes lead to contrasting results. Until now, no comparison of models and data had been made to get a picture of the spatial and temporal distribution of floating marine litter at sea at the basin scale - a key issue identified in the UNEP/MAP (2015) report - although a large set of visual observations (from aerial surveys and commercial or oceanographic cruises) is starting to develop.

To address this gap, this study aimed to investigate spatio-temporal variability in potential FML accumulation and stranding areas at the scale of the entire Mediterranean Sea, when Mansui et al. (2015) only focused on locating FML accumulation patterns considering an average picture of the FML distribution throughout the year. For this purpose, we performed multi-annual simulations, based on the model designed by Mansui et al. (2015), and calculated binning density index to study FML distribution according to season. We focused on three topics: a description of the modeled offshore accumulation patterns at various spatial and temporal levels, the identification of the origin of these FML accumulation patterns, and a description of preferential stranding areas. Concurrently, we conducted a literature review of the scientific papers on marine litter distribution in the Mediterranean basin, based on at-sea and aerial surveys and on numerical simulations. We then compared our outputs with empirical/simulated data found in this literature review in order to test our model accuracy.

2. Material and methods

2.1. Models

The FML distribution model was built using Lagrangian simulations, as described in Mansui et al. (2015). In this method, virtual particles acted as Lagrangian tracers and mimed the marine debris transport at the sea surface. The particle-drift simulation process had two stages. First, we computed the ocean state and velocity fields by selecting an oceanic general circulation model (OGCM) suitable at our scale. Then we simulated the drift of virtual particles with an advection model using velocity fields provided by the OGCM.

We used the NEMO OGCM (Madec et al., 1998; Madec, 2008) configured for the whole Mediterranean basin (MED12 configuration, Beuvier et al., 2012; Lebeaupin Brossier et al., 2012a,b) on a 1/12° 'ORCA' grid (Madec, 2008). This configuration has been validated and used in numerous studies, guaranteeing the required level of confidence for our numerical study. Currents computed from the MED12 model configuration included Ekman drift, baroclinic motion, and inertial currents, as well as Stokes drift induced by waves. We chose daily average velocity field outputs from January 2001 to December 2010 to obtain a long-term description of the general and mesoscale surface circulations.

General transport pathways were computed using the Lagrangian off-line tool ARIANE (Blanke and Raynaud, 1997) to track virtual particles. The ARIANE code (available at http://www.univ-brest.fr/lpo/ariane) has been validated for both circulation (Iudicone et al., 2008; Koch-Larrouy et al., 2008; Lique et al., 2010) and biological studies (e.g. Bonhommeau et al. (2009) and Berline et al. (2013) respectively studied European eel larvae migration in the Atlantic Ocean, and jellyfish stranding along the French Riviera coast). Recently, it has also been successfully applied to marine litter transport studies (Maes and Blanke, 2015; Mansui et al., 2015). In our study, we banned vertical movements since little is known about degradation rates and buoyancy changes of plastic items at sea. Consequently, we forced particles to stay just below the surface (at a depth of 50 cm) at the first OGCM level of velocity and did not consider any windage. All these phenomena (vertical movements (Hardesty et al., 2017), buoyancy (Yoon et al., 2010; Carlson et al., 2017), windage (Neumann et al., 2014)) need to be better understood and taken into account in further modeling.

Particular attention was given to the modeling assumptions of trapped coastal particles. Because of model boundary conditions, particles reaching the last ocean grid cell did not really stop, but could stagnate for long periods (i.e. from weeks to months) and/or eventually recirculate offshore when surface currents became more intense. In order to ensure that nearshore particles can still contribute to offshore concentration, we have decided not to remove particles that experienced such long stagnations. Finally, particles that will remain stuck in a coastal bin for at less one week will be considered as stranded. For additional information on the MED12 parametrization and forcing, as well as the Ariane configuration, refer to Mansui et al. (2015).

2.2. Lagrangian simulations and diagnostics

Particle input and time of advection are two key parameters in the numerical modeling of FML distribution at sea. In our study, the same initial homogeneous particle distribution characterized all simulations, with a spatial step of 10 km in the zonal and meridional directions (25,500 particles scattered in the basin for each simulation). The choice of a suitable advection time is critical in the sense that an integration time that is too short would not allow particles to concentrate or disperse at a mesoscale, whereas if it is too long it is unnecessarily time-consuming. We assumed that integration times from 3 months to 1 year were adequate regarding the basin size. While physical processes with complete annual variability were included in 1-year runs, a 3-month advection time was long enough to allow the particles to cross the Mediterranean sub-basins and agglomerate in specific patterns. Liubartseva et al. (2018) reached similar conclusions on integration time and defined the Mediterranean basin as a dissipative system with a mean particle half-life of 7-80 days. Finally, we performed 1-year runs every day from 1 January 2001 to 31 December 2009, saving daily particle positions in order to extract shorter advection times.

To quantify particle agglomeration patterns and determine their spatio-temporal variability, we defined a 'mean binning density' index σ in the same way as Mansui et al. (2015):

$$\sigma(t) = \frac{1}{n}\sum_{s=1}^{n}\left(\frac{b^s_{i,j}(t)}{b^s_{i,j}(0)}\right) - 1$$

where $b^s_{i,j}(t)$ is the number of particles in the bin located in (i, j) at time t and for the s^{th} simulation, and n is the total number of simulations (n =3287). This allows particle accumulation or scattering to be easily distinguished by, respectively, the positive/negative sign of σ (initial particle density is obtained for $\sigma = 0$).

Mansui et al. (2015) essentially used the σ index to determine major FML accumulation patterns, but bin size prevented the investigation of some major hydrodynamic regions in the Mediterranean such as the Corsica Channel. Recently, FML has nevertheless been observed in this region with high variability in density levels (Suaria and Aliani, 2014; Fossi et al., 2017). To overcome this problem, we adopted 20 km x 20 km bins to allow a better spatial description of both local and regional particle accumulation patterns, as well as to avoid oversmoothing of the mean σ field. Care was taken to ensure bins included a sufficient number of particle trajectories, thereby ensuring robust statistical analyses. Binning density σ was calculated with advection times of 3, 6, 9 and 12 months. We only present results for the shorter advection time (3 months) because they showed more pronounced accumulation areas. We did not remove virtual particles when they reached a land bin, so all particles were free to move at any time in the basin. Consequently, nearshore bins can host a large number of particles for a long period, resulting in very high values of σ, but may also contribute to offshore concentration.

The origin of particles trapped in accumulation patterns was also determined in order to complement the information about

potential FML accumulation patterns. To do this, we first visually defined the geographical domain of each accumulation pattern. Then, particles located inside each domain were identified when the accumulation process was effective (only the runs with an appropriate time window were considered). Finally, we recorded and saved the initial position of each of the particles, and, since the same homogeneous particle distribution was used for all the runs, we presented results in terms of occurrence frequency. This method is equivalent to backward integration, but is less time-consuming.

2.3. *Comparison of the model with empirical and simulated data*

2.3.1. *Aerial surveys of the northwestern Mediterranean sub-basin*

We used the data on surface meso- to mega-litter abundance collected by Pettex et al. (2012a,b) in the framework of the SAMM (Suivi Aérien de la Mégafaune Marine: Aerial Survey of Marine Megafauna) campaign in winter 2011-12 and in the summer of 2012 to validate one subset of our model results in the northwestern Mediterranean sub-basin. The aerial survey period was not covered by our simulations (daily runs from 2001 to 2009), but data from the SAMM campaign are the only data available in the area with such a spatio-temporal coverage. Combined with a climatological analysis of our numerical simulations (9-year seasonal averages of binning densities), they allowed a quantitative analysis of our results in this region. Therefore, we defined a new diagnostic test to compare our model results with this dataset: first the FML abundances observed in the SAMM campaign were split into three categories: low abundance (density < 5 debris/observation), medium abundance ($5 \leq$ density < 10 debris/observation), and high abundance (density ≥ 10 debris/observation). We then calculated the shortest distance D_S between a medium or high abundance observation and a cell with a positive value of seasonally averaged σ. No analysis based on statistical correlations between instantaneous observations and binning density was conducted. Fossi et al. (2017) recently showed in the Ligurian Sea that such an analysis must consider time average values of FML density to avoid any correlation decrease with increasing simulation time (3 to 15 days in the Fossi et al. (2017) study). However, as mentioned above, the SAMM dataset was composed of only two series of aerial observations, which prevented us from coomparing our model to smaller time scales. Additional information on the SAMM protocol can be found in Darmon et al. (2017).

2.3.2. *Empirical and simulated data from studies across the entire Mediterranean basin*

Literature that compares numerical simulations of floating marine litter distribution with *in situ* observations is currently limited for the Mediterranean basin. Some regional evaluations have recently been undertaken (e.g. Fossi et al., 2017; Zambianchi et al., 2017), but modeled data have not yet been qualitatively compared with observational data at the basin scale. One study by Cózar et al. (2015) revealed some inconsistencies between modeled surface concentrations of floating micro-litter and net tow samplings. The sporadic character of empirical data and large gaps in coverage were indeed the main limitation for making comparisons (Zambianchi et al., 2017; Liubartseva et al., 2018). However, a significant body of scientific papers about marine litter observations (micro, macro, surface, seafloor and stranded) now exists on the Mediterranean basin and can be used to improve the spatio-temporal coverage of each study.

Consequently, we conducted a review of scientific papers to obtain the most exhaustive and up-to-date qualitative description of marine litter distribution in the Mediterranean Sea. A search was performed in three scientific databases (Google Scholar, BibCnrs and ScienceDirect), using a list of key terms to identify relevant research papers. We exclusively searched for studies concerning the Mediterranean basin, with no date limitation. The search terms used were: floating debris/litter/plastic, marine litter, beach litter/debris, benthic litter/debris, plastic debris/occurrence, plastic and Mediterranean. The references in the selected documents were also used to find possible additional studies. Finally, oceanic surface, seafloor and 'beach' compartments, as well as litter of all size class from micro-class (< 5 mm) to mega-class, were considered.

The resulting relevant articles were then split into five categories: 1) surface observations of meso-litter (5 mm $\leq$ meso- $<$ 2 cm) to mega-litter (> 1 m); 2) surface micro-plastics; 3) observations of plastic debris on beaches; 4) observations of deep seafloor litter; 5) modeling studies on floating marine litter distribution. For the comparison with our simulated FML distribution, we selected three of these categories: the results from surface observations of meso- to mega-litter (1), stranded litter (3) and other floating marine litter modeling studies (5). In the 'Discussion' section, we also discuss our results in light of outcomes from studies of surface micro-plastics (2) and deep seafloor litter (4).

Since any metrics-based validation of the modeled FML surface density cannot yet be conducted on the whole Mediterranean basin due to the relative heterogeneity of experimental protocols used for obtaining data from *in situ* observations, we focused only on qualitative comparisons with our model outputs. All notable events that were mentioned in the collected bibliographic corpus, such as peaks of FML density or low FML abundance in different time windows, were recorded to this end.

3. Description of surface circulation from model outputs

The spatial and temporal resolution of the MED12 configuration allowed the simulation of mesoscale circulation, in particular the ocean eddies that may be responsible for FML transport and accumulation. Understanding the structure of these currents (their position, temporality and variability) is a critical issue in the study of FML distribution, particularly in a basin as energetic as the Mediterranean Sea. As the Mansui et al. (2015) study previously described the major features of MED12's general circulation, here we aimed to provide an additional descrip-

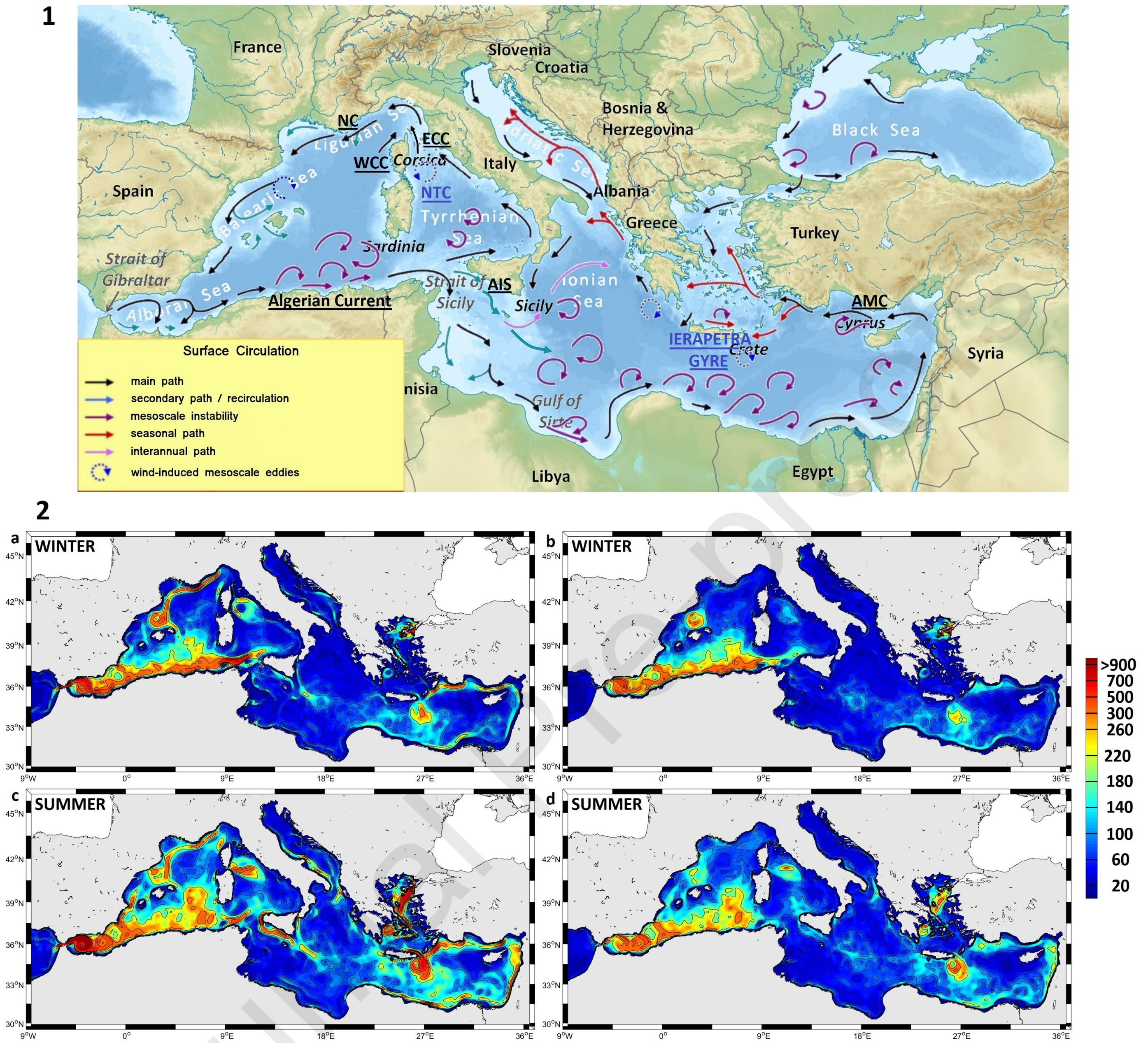

Figure 1: Map of the Mediterranean Sea. (1) Schematic representation of the general Mediterranean Sea upper circulation, modified after Millot and Taupier-Letage (2005). (2) Kinetic Energy ($cm^2 s^{-2}$) from MED12: extended winter MKE (a) and EKE (b); extended summer MKE (c) and EKE (d). Some structures of the surface circulation used in the text are given: the Algerian Current, Asia Minor Current (AMC), Atlantic Ionian Stream (AIS), Eastern Corsican Current (ECC), Ierapetra Gyre, Northern Current (NC), Northern Tyrrhenian Cyclone (NTC), and Western Corsican Current (WCC).

tion of the variability in surface circulation, in order to better compare our model outputs with the *in situ* observations described above. The variability in surface circulation was based on an analysis of the Mean Kinetic Energy (MKE) and Eddy Kinetic Energy (EKE) fields (Fig. 1), which were considered proxies for the velocity field. The hydrodynamic model velocity fields from 2001 to 2010 were then calculated as follows:

$$MKE_{i,j} = \frac{1}{2}\, mean_t[u^2_{i,j}(t) + v^2_{i,j}(t)]$$

$$EKE_{i,j} = \frac{1}{2}\, mean_t[(u_{i,j}(t) - \overline{u})^2 + (v_{i,j}(t) - \overline{v})^2]$$

where $mean_t$ is the time average, $u_{i,j}(t)$ and $v_{i,j}(t)$ the zonal and meridional components of the velocity field at (i,j) grid point, and $\overline{u}$ and $\overline{v}$ their time average, respectively (for a formal definition of MKE and EKE, see Trani et al. (2014)).

In order to characterize the main seasonal variability in surface circulation, we defined extended seasons: 'extended winter', from November to April, and 'extended summer' from May to October. These are generally accepted as the most ap-

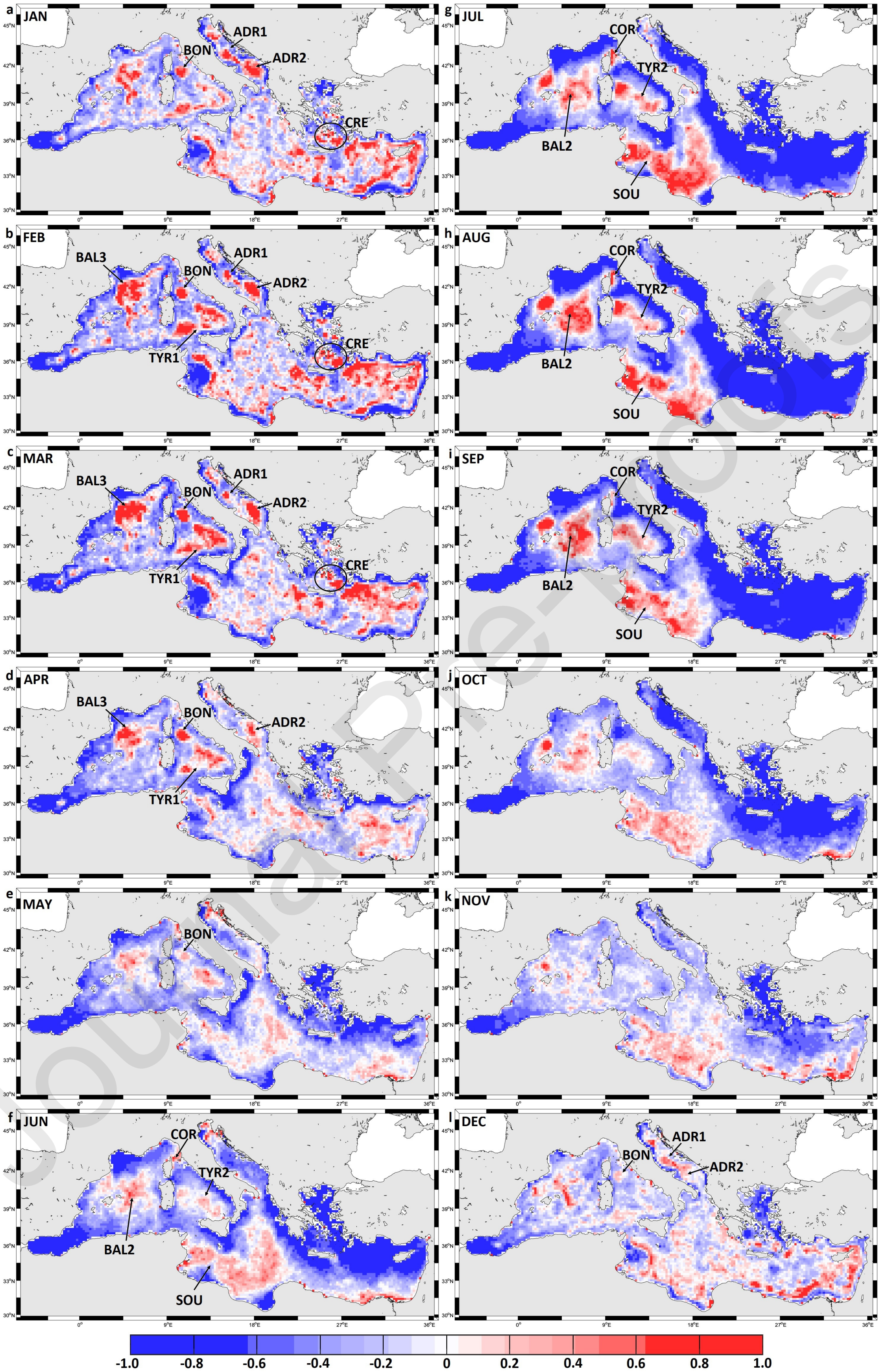

Figure 2: Monthly mean binning densities. Red shades (positive values) show particle accumulation. Gray and blue shades (negative values) show emptying areas.

propriate periods to investigate variability in sea surface circulation in the Mediterranean basin (Marullo et al., 1994; Poulain and Zambianchi, 2007; Rinaldi et al., 2010).

The MED12 circulation mainly agrees with well-known currents and semi-permanent eddy structures already reported in the literature. The most evident feature of the modeled surface circulation in the Mediterranean basin was the Algerian Current, which the model showed to be well-formed all year long and characterized by strong mesoscale activity (Fig. 1b and 1d), with meanders or eddies detaching from the coastal jet in a northward course toward the central western basin (Pessini et al., 2018). Several more or less organized gyres could be seen in the Alboran Sea - these are mainly the result of the geometry and orientation of the strait (Millot, 1999; Sayol et al., 2013).

At the Sicily Channel, the Algerian Current split into two different veins (Fig. 1a and 1c), one entering the Tyrrhenian Sea, and the other the eastern Mediterranean basin. The first created a complex surface circulation in the southeastern part of the sub-basin, where higher energy was observed. Rinaldi et al. (2010) have demonstrated how eddies along the Sicilian and Italian coasts shift the Atlantic Water from the Algerian Current offshore rather than flow cyclonically. In the northern part of the sub-basin, a well-marked cyclonic gyre, the North Tyrrhenian Cyclone (NTC), was present in accordance with observations (Astraldi and Gasparini, 1994; Rinaldi et al., 2010). It is induced by strong northwesterly winds (channeled by the Strait of Bonifacio), and is associated with an upwelling phenomenon. MED12 simulations showed high seasonal variability in the size and dimension of the NTC (Fig. 1), affecting the coastal current flowing along the northeastern part of the Tyrrhenian Sea. During the summer, the NTC clearly stretched along the zonal direction (Fig. 1c), as mentioned by Artale et al. (1994) and Astraldi and Gasparini (1994), but no meridional stretching of the gyre was displayed during the winter season (Fig. 1a).

In the Ligurian Sea, the model showed the Northern Current (NC) flowing westward along the shelf up to the Spanish coast, as part of the general cyclonic circulation in the western Mediterranean basin. This coastal current results from the merging of the Eastern Corsican Current (ECC) and the Western Corsican Current (WCC). It was characterized by high seasonal variability, with a quite steady though weak flow in summer and a more energetic flow in winter (Fig. 1c) caused by a stronger ECC (not shown in Fig. 1).

MED12 simulations showed a quasi-permanent anticyclonic structure in the Balearic Sea, northwest of Menorca Island. Its position remained almost stationary (for a period longer than six months), with a spatial dimension about 100 km in diameter and velocities up to 70 cm/s. Several studies have already documented this wind-induced mesoscale structure in terms of position, magnitude and spatio-temporal variability (Larnicol et al., 2002; Pascual et al., 2002; Rubio et al., 2005, 2009). Tintoré et al. (1990) also discussed the local generation of smaller structures in the Balearic Sea.

The second part of the Algerian Current entering the Sicily Channel split into two separate branches around Pantelleria Island: a meandering Atlantic Ionian Stream (AIS) along the Sicilian coast and a second vein heading toward the Tunisian coast. Clear seasonality in the AIS was shown in the MED12 10-year simulations (Fig. 1), reaching a maximum in summer, as mentioned by Poulain et al. (2012). East of Malta, the AIS flow split once again into one branch moving northward and forming a basin-wide anticyclonic circulation in the northern Ionian Sea, and a southeastward outflow in the central Ionian toward the Levantine sub-basin (stronger during the extended summer, see Fig. 1c).

MED12 simulations revealed some noteworthy features regarding the surface dynamics in the Levantine sub-basin. For example, it showed a very thin, strong coastal jet flowing eastward along the Egyptian, Israeli and Syrian coasts, with the Asia Minor Current (AMC), located south of the Turkish coast, flowing westward. A strong anticyclonic wind-induced structure was also shown southeast of Crete; this is generally known as the Ierapetra Gyre. These dynamic features were more intense in summer (Fig. 1c) and associated with strong mesoscale activity (Fig. 1d).

Aegean Sea circulation is very complex due to the numerous islands; the resolution of MED12 does not allow adequate detail of the dynamics of such a narrow region. For similarl reasons, the Adriatic Sea was not considered in the FML density distribution analysis conducted in Mansui et al. (2015). In this study, binning density cells of 20 km by 20 km allow a better description of modeled FML accumulation areas. Comparisons between the results of our model and other models or *in situ* observations were still considered, keeping in mind the model limitations in these Mediterranean regions.

4. Results

The variability in the mesoscale circulation showed by our model in some Mediterranean sub-regions is expected to strongly influence FML distribution. For example, the difference in EKE shown in Fig. 1b and 1d, north of Balearic islands, tends to indicate that the retention mechanisms in this area could be significantly different between the summer and winter seasons. The seasonal weakening of some coastal/offshore currents could also slow down FML surface transport. This may be the case in the Liguro-Provencal sub-basin, where the Northern Current is known as a potential FML carrier (Ourmieres et al., 2018), but is at the same time subject to significant seasonal variability, with minimum surface velocities during the summer season. In the same way, the Atlantic Ionian Stream (central Mediterranean), and the coastal jet found along the southeastern Levantine coastline are generally assumed to be FML carriers. Both are less energetic during the winter season (Fig. 1a and 1c), which is probably linked to weak FML transport in these areas. The absence of a seasonal signal in other Mediterranean sub-regions (e.g. the Alboran Sea, Fig. 1b and 1d) also suggests that FML distribution might not show seasonal variation. It is, however, possible that sub-seasonal variation could modulate the final results in such cases.

4.1. Modeled FML accumulation patterns

Monthly binning density maps (Fig. 2) obtained after an advection time of 3 months revealed high spatial and temporal variability in offshore FML distribution, resulting from the spatio-temporal variability in the surface circulation of the Mediterranean. Several accumulation patterns can be identified across the Mediterranean basin at different times of the year.

4.1.1. Offshore patterns

The formation of large and temporary accumulation patterns in summer only occurred in the western and southern parts of the Mediterranean Sea. Between June and September, simulations showed that the surface circulation concentrated the majority of the FML in only three main patterns (BAL2, TYR2 and SOU, respectively located between the Balearic and Sardinian islands, in the center of the Tyrrhenian Sea and offshore the Tunisian and Libyan coasts). However, apart from these large patterns, many other local or regional FML accumulation patterns occurred during winter and spring. It appears that all sub-basins located in the western Mediterranean Sea are interconnected, sharing FML throughout the year. Such trading synergy was not observed in the eastern Mediterranean, where virtual particles entering the Levantine sub-basin could not escape.

In the northwestern Mediterranean, a clear pattern of FML accumulation (noted BAL3) appeared from February to April in the south of the Gulf of Lions (Fig. 2b-d). High σ values were found at the same time in the Northern Current path, showing that the FML attracted by the BAL3 pattern was mainly advected by this coastal current. The variability in Mediterranean surface currents gradually scattered the pattern in May and June, in a more or less southerly direction, leading to the emergence of two new well-formed accumulation patterns from July to September/October (Fig. 2g-j). One of these patterns (BAL2) filled the center of the western sub-basin, stretching from the Balearic archipelago to the islands of Sardinia and Corsica. With a diameter of around 400 km, this was the second largest accumulation pattern modeled in the Mediterranean basin by our numerical simulations. Some expansion occurred in the northwesterly part of the structure, exporting FML toward Corsica, where the West Corsican Current could advect it toward the Ligurian Sea. In November and December, FML was totally scattered throughout the sub-basin.

Several distinct accumulation patterns were also found in the Tyrrhenian Sea, with two interconnected patterns (TYR1) from February to April (Fig. 2b-d): one in the southeastern part of the sub-basin, and another between the Sicilian and Italian coasts. A third major accumulation pattern (TYR2) occurred in summer (July to September) and was more or less oriented in a northwest to southeast direction (Fig. 2g-i). High σ values were found off Sicilian coasts during this period, when circulation features are stronger (Rinaldi et al., 2010). The Northern Tyrrhenian Gyre, east of the Strait of Bonifacio, was a more local accumulation pattern (BON), and attracted FML during the winter season (December/January to April/May). Finally, the variability of surface circulation in the sub-basin prevented any FML accumulation structure the rest of the year.

The Corsica Channel was the only other sub-region in the western Mediterranean where a local accumulation pattern (COR) appears. Numerical simulations showed high σ values during the summer season (from June to September), when the Eastern Corsican Current is less intense than in winter.

In the southern Mediterranean, the largest FML accumulation pattern (hereafter, SOU) occurred off the Tunisian and Libyan coasts. The SOU was about 700 km long in the zonal direction, and 200 km long in the meridional direction. Fig. 2 also shows a local accumulation structure found in winter (from December to February), south of the Sicily Channel.

We did not find any main accumulation areas in the Levantine sub-basin. From December to April, binning densities showed patchy FML distribution, with local accumulation patterns scattered throughout the sub-basin. These accumulations then quickly moved to the coastal strips during the summer season (from May to September, Fig. 2e-i). As illustrated by the simulations, such a phenomenon occurs only in the Levantine sub-basin, and to some extent in the Adriatic sub-basin.

Other accumulation patterns also occurred in narrow seas such as the Adriatic and Aegean. Three local accumulation patterns formed, for example, in the Adriatic Sea from December to April, related to cyclonic circulation. From north to south, we found a circulation pattern that deflected FML from the Po delta and Venice lagoon to the Gulf of Trieste, the Middle Adriatic Gyre (ADR1), and the South Adriatic Gyre (ADR2). This suggests that cyclonic gyres could probably also favor the retention of floating debris, as already suggested by Suaria and Aliani (2014). High σ values were still displayed in the northern part of the sub-basin in May and June. In the Sea of Crete, numerical simulations mainly showed another patchy FML distribution (CRE) in winter (from January to March).

4.1.2. Origin of offshore litter accumulation patterns

The initial position and recurrence of the particles trapped in all the identified accumulation patterns (Fig. 3) show that debris items may sometimes be transported far away from their source before accumulating, even after only a 3-month advection time. The largest patterns, located in the southern Mediterranean (SOU), east of the Balearic archipelago (BAL2), and in the Tyrrhenian Sea (TYR1 and TYR2), all shared great spatial variety in terms of FML origin. For example, SOU could attract FML coming from several remote sub-regions of the Mediterranean basin, particularly the Algerian and Tyrrhenian sub-basins, the Ionian and Aegean Seas, and, to some extent, the northwestern sub-basin, the Adriatic sub-basin, as well as the western part of the Levantine sub-basin (Fig. 3j). The results indicate that SOU is the main 'sink region' for Mediterranean FML. The three other large patterns (BAL2 and TYR1/2) trapped debris from almost the whole western Mediterranean sub-basin, although a more local origin (respectively, the Northern Current for BAL2, Fig. 3b, and the Tyrrhenian sub-basin for TYR1 and TYR2, Fig. 3i and 3d) can also be observed.

Local accumulation patterns identified in the Balearic Sea

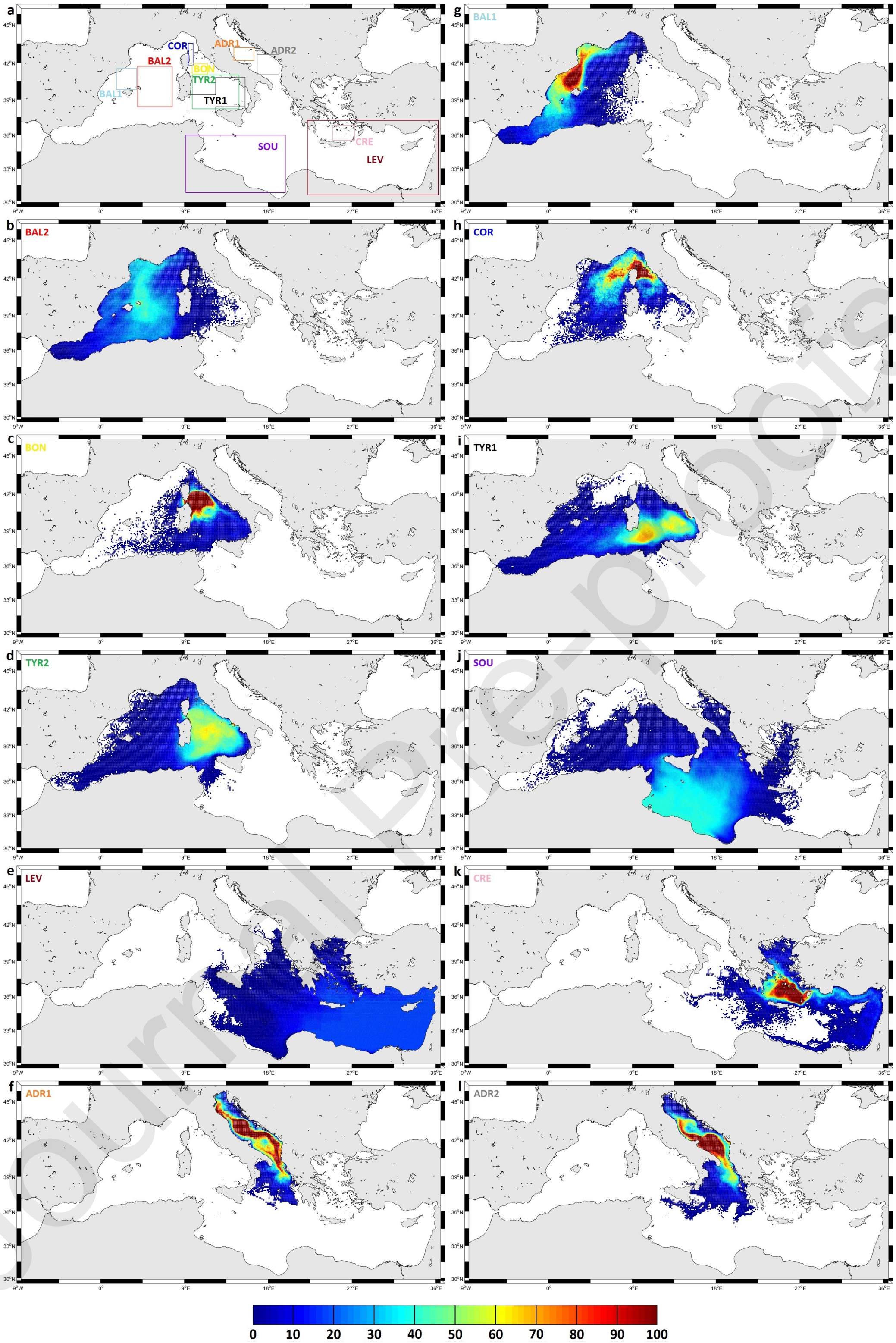

Figure 3: Source of FML for some of the offshore accumulation patterns identified in Fig. 2. Colors represent the recurrence of a particle's initial position (in %) as a source of particles trapped by accumulation patterns. Ten distinct patterns and one region are investigated. All patterns are referenced by a name code in the paper (e.g. BON refers to the local accumulation pattern formed by the Northern Tyrrhenian Gyre during the winter season; LEV refers to the Levantine sub-basin). Each panel only includes simulations ending when offshore FML accumulation occurs in the suitable region.

(BAL1, Fig. 3g) and the Corsica Channel (COR, Fig. 3h), off the Strait of Bonifacio (BON, Fig. 3c), and in the Adriatic Sea (ADR1 and ADR2, respectively Fig. 3f and 3l), had nearer sources, often confined to the sub-basin where the FML

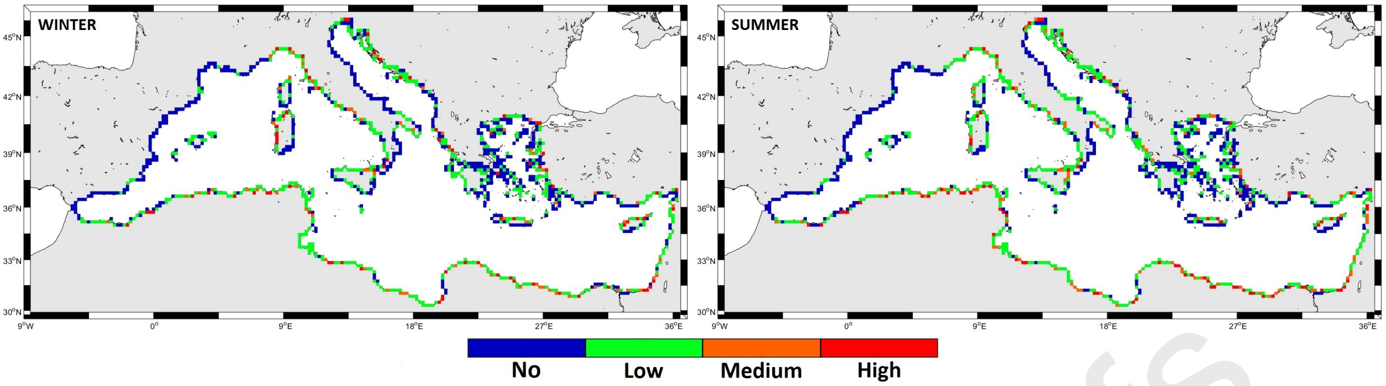

Figure 4: Stranding from numerical simulations (3-month advection time): extended winter (left) and extended summer (right). Binning densities for coastal cells were split into 4 classes: No ($\sigma < 0$), Low ($0 \leq \sigma < 8$), Medium ($8 \leq \sigma < 16$) and High ($\sigma \geq 16$).

accumulation pattern was located and/or to upstream flows. The Tyrrhenian Sea was, for example, the major source region for the FML accumulation pattern related to the Northern Tyrrhenian Gyre (BON). For its part, the Corsica Channel drained FML from the Tyrrhenian Sea, but also debris items advected by the Western Corsican Current and coming from the northwestern sub-basin, and, to some extent, the Algerian sub-basin.

In the eastern Mediterranean, simulations found only one patchy offshore accumulation of FML, mainly from December to April (Fig. 2). The origin of FML trapped by these small patterns was mostly restricted to the sub-basin and the Ionian Sea (Fig. 3e). We could not identify any preferential offshore source when considering the whole area (LEV). However, that was not the case for distinct patterns, such as the accumulation pattern identified in the Sea of Crete in winter (CRE, Fig. 3k), where a local origin prevailed, but was not exclusive.

4.1.3. Main stranding areas

Debris floating in the Mediterranean Sea can travel far away from its release point due to the interconnectedness of the sea's sub-basins. Depending on the season, the surface circulation created accumulation patterns of different sizes and locations. While spatio-temporal variability in circulation prevents any static long-term accumulation of FML in the Mediterranean basin, this is not the only dissipative process. Stranded FML can also remove, for short or longer time periods, significant quantities of debris from the sea, potentially reducing offshore FML accumulation. Energetic coastal jets associated with high stranding rates can lead to an effective cleansing of some Mediterranean sub-basins. Binning densities for coastal cells (Fig. 4) revealed several interesting points regarding this.

First, the Levantine sub-basin was a local potential source of FML for its coast, its southern part forming the most affected coastline. The accumulation rates of FML on beaches were greater during the summer season (Fig. 4), when more energetic surface currents prevented the formation of offshore accumulation patterns. However, some stranding hot spots could still be identified in the winter along the western Egyptian and southern Israeli coastlines.

In addition, numerical simulations highlighted other stranding areas along the southern Mediterranean coastline: namely the eastern Algerian sub-basin and the Tunisian and western Libyan coasts. Mansui et al. (2015) only found the latter. We also found some local hot spots throughout the northern part of the Mediterranean basin: in the Ligurian Sea, along the western Sardinian coastline, and in the Adriatic Sea (Fig. 4). Nevertheless, our model did not show any marine debris stranding along the western coastlines (Spanish coasts, Sardinian/Corsican coasts or the Italian Tyrrhenian or Adriatic coasts).

4.2. Validation from aerial surveys in the northwestern Mediterranean

	All datasets		Excluding GL	
	High FML abundance	Medium FML abundance	High FML abundance	Medium FML abundance
winter 2011/2012	27.74	22.93	19.87	19.71
summer 2012	49.93	52.71	28.40	33.77
mean	38.84	37.82	24.14	26.74

Table 1: Distances D_s values between the simulated accumulations and the two SAMM aerial survey campaigns that observed FML in the northwestern Mediterranean. Observations recorded in the Gulf of Lions were removed from the dataset (right column: 'Excluding GL') in order to overcome a FML transport dynamic that was not properly resolved in this subregion.

Aerial surveys conducted during the SAMM campaign (Pettex et al., 2012a,b) allowed us to confirm the validity of our model outputs in the northwestern Mediterranean. The mean shortest distance (D_S) between an aerial observation of a medium or high abundance of debris (detailed in 'Material and methods') and a bin of σ positive value (seasonal average) was evaluated for winter 2011/2012 and summer 2012. An average of 38.33 km (high and medium FML abundances) was found for the whole SAMM dataset (Table 1), decreasing to 25.44 km when the SAMM observations conducted in the Gulf of Lions restricted zone were excluded. This distance is on the order of

magnitude of the bin cells used for binning densities (20 km). A shorter value of D_S was recorded during the winter 2011/2012, with mean D_S below 20 km for the dataset that excludes the Gulf of Lions area. Consequently, for every SAMM observation of medium or high debris abundance not conducted in the Gulf of Lions, modeled binning densities directly showed accumulation behavior in the cell where the observation was made or in one of the adjacent cells.

4.3. Literature review

We reviewed a total of 99 scientific papers and reports broken down into the following categories (three papers simultaneously falls into two categories) : 1) 14 surface observations of FML (Appendix 1); 2) 22 micro-plastic surface samplings (Appendix 2); 3) 24 observations of plastic debris on beaches; 4) 32 litter observations on deep-water seafloor; and 5) 10 modeling studies (Appendix 3). As previously mentioned, we used references from categories 1, 2 and 5 to qualitatively compare to our FML distribution model at the scale of the entire Mediterranean basin.

4.4. Comparison with in situ litter observations

A large dataset of FML observations is available in the western Mediterranean region. Several studies have reported FML accumulation patterns in the Sardinian-Balearic sub-basin. Arcangeli et al. (2018) and Campana et al. (2018) observed significant seasonal patterns, with levels of FML increasing from autumn/winter to the maximum values recorded in spring/summer. These results are in line with the outcomes of our analysis: we found large accumulation patterns (BAL2 and BAL3) between February and September, and more scattered FML distribution during the autumn/winter seasons. Suaria and Aliani (2014) also reported observations of high debris density in 2013 along a straight line linking the Balearics to Sardinia, and in the northern part of the Algerian sub-basin, where we identified the BAL2 accumulation pattern. Campana et al. (2018) observed another high-density debris area in spring and summer, northwest of Menorca Island, which corresponds to the wind-induced anticyclonic structure (BAL1) pointed out by our numerical simulation as a retention area for marine pollution.

In the Liguro-Provencal sub-basin (NW Mediterranean Sea), Di-Méglio and Campana (2017) and Ourmieres et al. (2018) reported a clear FML accumulation pattern, with peaks of FML density in May/June and October, and a distinct decrease between July and September (2006, 2007 and 2008). This behavior was also shown by our simulations in 2007 (Fig. 5) and in 2006 and 2008 (not included in the figures). However, we cannot consider this a seasonal pattern since it did not happen again in our simulations between 2001 and 2009. Indeed, our simulated monthly binning densities (Fig. 2) showed low FML density along the French Riviera coast between July and September, but no seasonal accumulation patterns before or after this period.

In the Tyrrhenian Sea, visual observations were generally more scattered than in the northwestern Mediterranean and less suitable for comparison with our model results. However, some were valuable and lent support to our findings. For example, Suaria and Aliani (2014) carried out a dozen visual observations in the center of the sub-basin during summer and recorded medium debris densities that could be related to the TYR2 FML accumulation pattern. Arcangeli et al. (2018) also recorded a significant seasonal accumulation pattern at the same location. Other observations made during the summer months east of the Strait of Bonifacio, in the Sardinia Channel, and in the Strait of Sicily, noted low FML densities that were very similar to our results (Suaria and Aliani, 2014). In the Bonifacio sector, Arcangeli et al. (2018) and Campana et al. (2018) found a litter accumulation pattern in proximity to the land, mainly during spring. Our simulations also showed such an accumulation pattern (BON), especially between January and May, but in a location further offshore (60 km east of the pattern identified by Campana et al. (2018)).

Finally, our review of the literature highlighted high variability in FML abundance in the center of the Ligurian Sea, mainly caused by the impact of different meteorological conditions and litter inputs (Aliani and Molcard, 2003a; Aliani et al., 2003b). Ourmieres et al. (2018) have recently shown that FML distribution along the French Riviera is highly constrained by the position of the Northern Current and the presence/absence of onshore/offshore winds. Our simulations mainly found high σ values inside the Northern Current during winter (Fig. 2), when the current is at maximum intensity. In the Corsica Channel (the southern part of the Ligurian Sea), Arcangeli et al. (2018) did not observe any FML accumulation pattern between October 2013 and September 2016, but rather a decrease in litter density from spring to summer. This was not the case in the studies of Suaria and Aliani (2014) and Fossi et al. (2017), who reported the presence of a local pattern of high FML density during summer (Fossi et al. found an average value of 175.24 macro-plastics/km^2 in September 2014). Fossi et al. (2017) also accurately modeled this local accumulation pattern. Their outcomes agree with our results showing high debris densities in the Corsica Channel between July and September (Fig. 2).

As pointed out by Zambianchi et al. (2017), the comparison of model outputs on FML distribution with *in situ* observations is not straightforward for the central and eastern Mediterranean Sea, since a complete standardized observational dataset is still lacking. We found only five offshore surveys reporting FML density in this part of the Mediterranean Sea in the literature. These surveys were mainly confined to the Ionian Sea and off the Gulf of Sirte - only one was conducted in the Leventine sub-basin. Morris (1980a) was the first (August 1979) to report FML sightings and to estimate debris density in the central Mediterranean Sea, 40 miles southwest of Malta. He observed values up to 2,000 items/km^2: at least one or two orders of magnitude higher than other FML sightings that have been conducted in the Mediterranean basin. Yet although the Morris observations date from 38 years ago, this sighting location matches very well with the northern edge of the larger FML accumulation pattern (SOU) identified by our simulations. The Morris (1980a) study was conducted in August, when our

modeled offshore accumulation was high (between July and September, see Fig. 2). Other studies carried out by Suaria and Aliani (2014) and Arcangeli et al. (2018) made coastal sightings in the Sicilian and the northern Ionian seas. They recorded FML densities ranging from 1.9 to 21.6 items/km^2, which also fits with the low binning densities we found in these sub-regions throughout the year. In July/August 1986, Mc Coy (1988) also observed very low FML densities (< 2.5 items/km^2) east of the seasonal SOU accumulation pattern. Finally, in June and July 2017, Constantino et al. (2019) found a very high mean FML density (232 ± 325 items/km^2) south of Cyprus Island (with an extreme peak estimated at 1593 items/km^2). Such high FML densities contradict our simulations, which showed an effective cleansing of the Levantine sub-basin in summer, and high stranding rates on the southern and eastern coastlines.

Concerning litter sightings in the narrow Adriatic sub-basin, we found a rather close qualitative agreement with Arcangeli et al. (2018) and Zeri et al. (2018), who respectively recorded a peak of litter abundance in winter, and high debris densities in the Gulfs of Venice and Trieste (only from January to June). Some clear inconsistencies might also be noted with the first large-scale survey conducted by Suaria and Aliani (2014). In that survey, in the central Adriatic Sea, the highest litter densities (with an average value of 54.6 ± 11.1 items/km^2) were recorded during the summer months, whereas our simulations showed an effective cleansing of the debris from an offshore location to the eastern coastline of the sub-basin.

4.4.1. *Comparison with other modeling studies*

Other modeling studies in the Mediterranean basin have provided further indications of high debris density areas and appear clearly compatible with our FML distribution results. First, Liubartseva et al. (2018) modeled a large medium-to-high plastic debris density pattern in the center of the Balearic-Sardinian sub-basin. The pattern appears on a map of multi-year averaged plastic debris concentrations despite obvious smoothing due to the averaging process. Zambianchi et al. (2017) found a large accumulation pattern of floating marine litter in the same geographical area (during the summer season), assuming a homogeneous initial distribution of virtual particles. Both studies also indicated high debris concentration during the extended winter season (Zambianchi et al. (2017) adopted a coastal initial distribution). The wind-induced anticyclonic structure of the Balearic Sea resulted in this floating marine litter accumulation pattern. Moreover, the Liubartseva et al. (2018) study is the only that suggests potential floating marine litter accumulation in the Tyrrhenian Sea, even if the modeled plastic debris concentrations are rather low and do not allow a clear or large pattern to be identified, as our model does.

Results of modeling studies in the central Mediterranean Sea had more contrasting results. Zambianchi et al. (2017) did not find any floating marine litter accumulation patterns in this sub-region, either with a coastal (CID) or with a homogeneous initial distribution (HID) hypothesis on the initial position of virtual particles. On the other hand, Liubartseva et al. (2018) modeled a large pattern of medium plastic debris concentrations in the center of the Ionian sub-basin, while one of the lowest debris concentrations was found in the Gulf of Sirte. However, Poulain and Zambianchi (2007), using Lagrangian drifter data to study surface circulation in the central Mediterranean Sea, clearly showed that the Gulf of Sirte is a likely retention area. Shchekinova and Kumkar (2018) recently confirmed this, identifying temporary local patterns off the Tunisian and Libyan coasts.

Zambianchi et al. (2017) and Liubartseva et al. (2018) modeled high long-term accumulation of litter in the Levantine sub-basin, but identified different sub-regions as the main floating marine litter retention area: respectively, the southern part of the sub-basin, or the area located between the island of Cyprus and the Turkish coastline (Cilician Sea). In our simulations, these sub-regions stand out as temporary FML retention areas since accumulation patterns can only be found during relatively limited time windows (in May, June and from October to December for the southern sub-region, and from December to March for the Cilician sub-region).

Some results can also be highlighted in narrower sub-basins such as the Adriatic and Aegean Seas. For example, other numerical simulations (Liubartseva et al., 2016, 2018; Carlson et al., 2017) did not show any long-term debris accumulation in the Adriatic Sea, which is in agreement with the results of our simulation model and can also be inferred from Mansui et al. (2015). All these studies identified local and temporary floating marine litter accumulation patterns in these sub-basins. Liubartseva et al. (2016) identified an elongated band along the Italian coastline, narrowing from the northwest to the southeast, and extending during the winter season in the middle and southern Adriatic. This suggests that the central and southern Adriatic gyres can act as retention patterns, as shown by Carlson et al. (2017) and our study (see Fig. 2 for binning densities from January to March). Liubartseva et al. (2016) also described a shift of high plastic concentrations toward the northern Adriatic in spring, and an effective cleansing of the debris from the central and southern parts of the sub-basin during summer. We can infer such a phenomenon from our simulations, although FML accumulation in the northern Adriatic was less obvious in our case.

Finally, Politikos et al. (2017), who used a higher resolution than we did to study FML distribution in the very complex sub-region of the Aegean Sea, partly described the patchy FML distribution we identified in this sub-region (CRE). Their model analysis showed a clear tendency of litter particles to concentrate in the North Aegean Sea, whereas the eastern part of the archipelago was the least affected. The relative absence of litter along the Aegean Turkish coastline appears clearly compatible with our model outcomes, as does the litter survey carried out by Topçu et al. (2010) in August 2008.

5. Discussion

5.1. *Evidence of FML seasonal accumulation patterns across the Mediterranean*

Our study modeled seasonal FML transport and accumulation across the whole Mediterranean basin, and is the first to

compare simulation outcomes with all published meso- and macro-litter sightings, as well as with other simulation studies carried out in the basin. As other studies have found (Mansui et al., 2015; Liubartseva et al., 2018), our simulations do not demonstrate any permanent large or local FML patterns, in contrast to oceanic gyres (Lebreton et al., 2012; Maximenko et al., 2012). Indeed, the seasonal and inter-annual variability of surface currents that we brought to light shows sufficient anomalies to define the Mediterranean basin as a dissipative system (Liubartseva et al., 2018), which steers the litter distribution at sea. Nevertheless, our model outputs highlight several seasonal FML patterns, the three largest located east of the Balearic Islands (BAL2), in the central Tyrrhenian Sea (TYR1), and off the Tunisian and Libyan coasts (SOU, Fig. 2). While these locations have already been defined as main retention areas (Mansui et al., 2015), our analysis based on binning densities allows the description of their seasonal behavior, showing that all retention areas are exclusively formed during summer/autumn (from June to September/October). In this context, we can note that heterogeneous σ values inside the SOU pattern suggest that it results from the merging of three smaller patterns, mainly between July and September (Fig. 2g-i). However, FML accumulation can still be seen in June, October and November in a more homogeneous pattern (Fig. 2f, j and k), with lower σ values indicating the gradual formation/disintegration of the pattern.

As we built the model with a constant input of virtual particles, main retention areas are not related to the FML peak input due to the tourist season. Our simulations rahter demonstrate the interconnection between source regions. They show that FML trapped in these main accumulations can originate from the whole western Mediterranean sub-basin (BAL2 and TYR1) or from the main part of the Mediterranean Sea, but never from the Levantine sub-basin (SOU). The exchange of FML between different Mediterranean sub-basins is the result of a complex process that is strongly affected by spatio-temporal variability in surface circulation. Localizing the origin of FML trapped by accumulation patterns of different sizes is of significant importance, particularly in the objective of designing management measures to reduce this pollution. The ability of our study to describe the origin of FML related to the main accumulation patterns is a significant step in this challenge.

Our analysis identified several other FML accumulation patterns throughout the basin, but its key contribution is the description of local accumulation throughout the year, such as the BAL1 pattern (northwest of Menorca Island, in summer) related to the wind-induced mesoscale anticyclonic structure (see the description of surface circulation), the BON pattern (Strait of Bonifacio, in winter), or the transit area associated to the Corsica Channel (COR, in summer). From autumn to spring, our simulations point to patchy FML distribution in different subregions of the Mediterranean Sea, such as the Levantine subbasin and the Ionian Sea. Finally, our results show that most FML accumulation patterns occur in the western and central Mediterranean Sea and are mainly associated with regions of high kinetic energy favoring litter concentration or scattering. One example is one of the two interconnected patterns located in the Tyrrhenian Sea (TYR1) and centered on a strong and recurrent anticyclonic circulation, the South Tyrrhenian Anticyclone, which is more intense in winter than in summer (Rinaldi et al., 2010).

5.2. Model limitations

It should be noted that we made certain assumptions in order to model the transport and accumulation of FML. For example, the resolution of the oceanic general circulation model used to advect virtual particles did not allow the capture of all sub-grid processes. Another important issue is the vertical displacement of FML, which we did not take into account, together with any biochemical transformation or windage. All these phenomena could play a significant role in the particle fate, but as a comprehensive knowledge about this type of displacement is still lacking, we thus considered that virtual particles confined to the sea surface could adequately model FML behavior. However, this can lead to a potential overestimation of the abundance of FML. The definition of correct model set-up is another critical point, as well as stranding process management. In general, the boundary conditions used in Lagrangian particle-tracking models poorly represent the interactions of FML with the shoreline. Our Eulerian model could not resolve coastline shape under 6-8 km, but nearshore dynamics are usually not properly resolved by most models in any case. The stranding process is complex and results from a combination of interacting factors, such as coastline type (rocky or sandy beaches), bathymetry, presence/absence of sea and land breezes, waves, and other factors that cannot be resolved at a suitable resolution. Consequently, the numerical values for FML stranding, as well as for re-floating, are unrealistically represented. It is, however, important to consider that coastal accumulation is by definition linked to a preferential stranding area, even though the model cannot simulate the complete process. Our simulations were able to predict the possible stranding of floating debris items, considering their stagnation along the coastline. In this sense, the simulation outputs showed in Fig. 4 should be considered as a risk of contamination/stranding more than actual stranding. It is nevertheless essential not to overlook this process as dissipative in order to avoid any artificial long-term FML accumulation, as in Zambianchi et al. (2017). The results we found clearly indicate the southern and southeastern coastlines as the main stranding areas of the Mediterranean basin.

Particular care must be taken when comparing model outputs with large-scale floating marine litter sightings. One way to do this is to conduct metrics-based validation. However, despite the number of existing studies on FML sightings in the Mediterranean basin that we reviewed (4 on meso-, 14 on macro-litter), existing empirical observations still remain too scattered in space and time to conduct a validation at the scale of the entire basin. Our approach was thus to compare FML abundance and characteristic seasonal behaviors (e.g. accumulation patterns, floating, stranding) described in the reviewed studies with our modeled FML binning densities. The only exception regards the northwestern Mediterranean Sea, where aerial observations give a synoptic picture of FML abundance at sea for two distinct seasons. The advantage provided by our

model concerning seasonal Mediterranean FML distribution is closely linked to the fact that FML surveys generally relate only to one season, since they tend to be carried out over short periods and rarely over a complete year.

5.3. Strong congruence with empirical observations

Generally, all characteristic FML accumulation behavior patterns that we noted in our literature review fit very well with our offshore modeled FML abundance, even in narrow sub-basins such as the Adriatic Sea. In some parts of the Mediterranean, Lagrangian measurements clearly confirmed our modeled FML abundance. For example, Rinaldi et al. (2010) analyzed surface drifter advection in the Tyrrhenian Sea and showed the presence of particle retention areas in this sub-basin. However, a comparison of the modeled FML abundance with aerial sightings shows some discrepancies in the Gulf of Lions. While high FML abundance was reported in this sub-region in aerial surveys, our mean binning densities are negative (although higher D_s values are observed when considering the Gulf of Lions). The main reason for such a discrepancy might arise from a FML transport dynamic not properly resolved (the NC could be located further offshore than it can actually be observed). This may also be caused by a predominance of litter from local origin (i.e. mainly from land-based sources located all along the semi-enclosed Gulf of Lions), which was not simulated by our model. Consequently, the results of our simulation cannot be considered a local realistic picture of the FML distribution for this distinctive region of the Mediterranean Sea. This is not the case for the rest of the northwestern sub-basin, where very low shortest distance values D_s qualitatively confirmed the modeled FML distribution at sea, at least for winter and summer.

Unfortunately, gathering *in situ* data in the Levantine sub-basin and along the southern coast of the Mediterranean Sea is very difficult. Such data is still lacking and is urgently needed to complement a basin-scale comparison of FML sightings with results from numerical simulations. Conveyor currents and recirculation features have been previously demonstrated by Lagrangian measurements (Gerin et al., 2009; Menna et al., 2012; Poulain et al., 2012), and could potentially influence FML aggregation. However, the only FML sighting study conducted in the region recently shows high debris densities in the eastern part of the sub-basin during the summer (Constantino et al., 2019), while our model did not show any offshore FML accumulation during the same period and favored a high stranding process on the southeastern coastline. A pattern of accumulation was also clearly demonstrated in the models of Zambianchi et al. (2017) in summer, a study which considered climatological patterns for both coastal and homogeneous initial distribution of virtual particles (however, seasonal reconstructions of floating marine litter distribution did not show any offshore accumulation). The absence of any stranding in the Zambianchi et al. (2017) study appears to be the main reason why this floating marine litter accumulation pattern occurs in the region. This suggests that our simulations may overestimate the stranding process in the Levantine sub-basin, but only during the summer (see the discussion about stranding surveys below). On the other hand, as in our study, Liubartseva et al. (2018) also modeled high stranding rates on the eastern Levantine coastline, as a medium plastic concentration south of the Cyprus Island. The multi-annual character of their analysis does not yet provide enough information to maintain whether this offshore accumulation occurs during summer. Finally, the comparison with global models of floating marine litter distribution (Lebreton et al., 2012; Maximenko et al., 2012; van Sebille et al., 2012) provides no additional information since these models strongly differ in the eastern Mediterranean Sea (van Sebille et al., 2015).

5.4. Mediterranean coastline as FML receptor

The stranding results from our simulations were compared to results from other modeling studies. We deliberately excluded the reviewed stranding surveys from this comparison since the origin of litter on beaches remains ambiguous. Litter related to tourist traffic or normal beach use cannot in fact be distinguished from stranded items due to inshore currents. Stranding can only be differentiated when exceptional events occur, such as the June 2010 event reported by Ourmieres et al. (2018) on the French Riviera, related to a river run-off peak combined with an onshore wind event. In the Levantine sub-basin, some studies demonstrate that the southeastern coasts are a main receptor of FML (Golik and Gertner, 1992; Bowman et al., 1998; Pasternak et al., 2017; Portman and Brennan, 2017), as highlighted by our findings and by Liubartseva et al. (2018). Pasternak et al. (2018) recently revealed that the Israeli coast is not only a sink for Mediterranean marine debris, but also a source, since debris originated in Israel can travel to the northern part of the sub-basin.

5.5. Macro- and micro-litter accumulation patterns, but also surface and seafloor litter distribution, are not necessarily correlated

Another interesting point is to compare FML distribution at the sea surface with the observed marine debris distribution on the seabed. Previous studies have found similarities between the quantities of these two types of litter. For example, during deep seafloor and surface surveys, Ramirez-Llodra et al. (2013) and Suaria and Aliani (2014) respectively found the presence of plastics in 92.8% and 82% of samples. At the basin scale, high seafloor litter quantities can indeed be associated with the main FML accumulation patterns (Fig. 6a): east of the Balearic archipelago, under the Northern Current path, in the northwestern Adriatic Sea, and, to some extent, in the northeastern Levantine sub-basin. The highest quantities were recorded in coastal locations, that is to say, near land-based sources. The proximity to land-based sources, the level of proper solid waste management, but also the vertical detail of Mediterranean circulation and seabed topography are factors that influence seafloor litter distribution (Pierdomenico et al., 2019). Further standardized samplings of marine litter are nevertheless needed to allow a quantitative comparison since no observations are available in a common unit of measurement, especially in key sub-regions such as the central Tyrrhenian Sea, off the Tunisian and Libyan

coasts or in the southern Levantine.

The lack of data is a common issue for the floating marine litter modeling community when validating simulations. Some authors (e.g. Politikos et al., 2017; Zambianchi et al., 2017) have opted to partially or totally compare their outcomes with micro-plastic samplings. While more micro-plastic surveys are currently available in the Mediterranean basin than FML observation studies, micro- and macro-debris distributions at the sea surface may be quite different, as reported by Suaria et al. (2018) and Palatinus et al. (2019) who showed no clear overlap in the central Mediterranean and the Adriatic Sea. Fig. 6b shows micro-plastic data from several surveys conducted in the Mediterranean basin using a common measurement unit. Some discrepancies between this and the offshore macro debris density are obvious: for example, between the Balearic and Sardinian islands, or in the southern Adriatic Sea, where low to medium micro-plastic concentrations were recorded during summer. Similar discrepancies can be observed in coastal areas. Recently, Pedrotti et al. (2016) found a clear relationship between micro-plastic concentrations in the northwestern Ligurian Sea and their distance to land. The highest plastic concentrations were found in the first kilometer adjacent to the coastline or in waters distant from the land. However, a macro debris survey carried out in the same area by Di-Méglio and Campana (2017) confirmed that high FML densities are mainly found on the edge of the Northern Current (Ourmieres et al., 2018), i.e. where the lowest micro-plastic concentrations were recorded. Consequently, caution is warranted when extrapolating results from macro- to micro-litter, or more specifically, when comparing FML modeling results to micro-plastic concentrations. Accumulation patterns of micro-plastics and macro debris are not necessarily located at the same places. The differences in distribution of these two broad categories of floating marine litter appear to result from their distinct origins and their drivers working at different spatio-temporal scales (Suaria et al., 2018; Palatinus et al., 2019), and requiring suitable set-ups for their modeling.

6. Conclusion

As Liubartseva et al. (2018) have pointed out, a well-defined model framework for marine litter has not yet been established in the Mediterranean basin. The different model set-ups, as well as the hypotheses assumed by different authors to model the transport and accumulation of floating marine litter, lead to more or less significant discrepancies. However, our model results fit well with the majority of FML observational data at the sea surface. Our simulation map could be used to fill the gaps in previous simulation studies on Mediterranean FML distribution, and could also be valuable in the framework of environmental impact studies. For example, such large-scale modeling could support the development of the Descriptor 10 ("Marine Litter") bio-indicators for the Marine Strategy Framework Directive and the Barcelona Convention.

Before implementing new environmental measures, the further development of floating marine litter transport modeling would benefit from more comparisons with observational data (e.g. vertical migration of litter, item fragmentation, interaction with biota, etc.). New large aerial surveys (western and central Mediterranean) will soon be available, and efforts will need to be made to achieve a coordinated way to monitor litter distribution with the southern and eastern Mediterranean regions.

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References	Region	Date	Observation platform	Mean abundance (items/km^2)	Item Size
Aliani and Molcard (2003a)	Ligurian Sea	07/1997	RV	14-25	Large items
Aliani et al. (2003b)	Ligurian Sea	08-09/2000	RV	1.5-3 items	Large items
Arcangeli et al. (2018)	NW Med. c Tyr. Sea S. of Bonifacio Ligurian Sea Ionian Sea Adriatic Sea	10/2013 - 09/2016	PF	2.5±0.3 2.1±0.4 2.4±0.4 1.8±0.2 1.9±0.2 4.7±0.5	> 20 cm
Campana et al. (2018)	NW Med. Tyr. Sea S. of Bonifacio	10/2013 - 09/2016	PF	2.8±0.4 1.80 2.3±0.4	> 20 cm
Carlson et al. (2017)	Adriatic Sea	03, 11 and 12/2015	RV	74.78-114.75	> 2.5 cm
Constantino et al. (2019)	E Levantine	06-07/2017	RV	232 ± 325	> 2.5 cm
Di-Méglio and Campana (2017)	NW Med.	2006-2015 summers	SV	4.03-37.49	> 1 cm
Fossi et al. (2017)	Pel. Sanct.	09/2014	RV	175.24	> 2.5 cm
Mc Coy (1988)	E Med.	07-08/1986	RV	< 2.5	Megalitter
Morris (1980a)	c Med.	08/1979	FP	2000	> 1.5 cm
Ourmieres et al. (2018)	NW Med.	10/2006 - 10/2008	SV	0-51	> 1 cm
Pettex et al. (2012a)	NW Med.	winter 2011/2012	AP	1-50*	> 50 cm
Pettex et al. (2012b)	NW Med.	summer 2012	AP	1-200*	> 50 cm
Suaria and Aliani (2014)	NW Med. Algerian SB c Tyr. Sea S Tyr. Sea NW Ionian Sea S. of Sicily Sicilia Sea c. Adriatic Sea SW Adriatic Sea SE Adriatic Sea S. of Otranto	05-10/2013	RV	19.3-30.7 10.9-52.9 4.9 24.1 21.6 10.4 6.3 54.6 52.1 25.8 12.9	> 2 cm
Topçu et al. (2010)	Aegean Sea	08/2008	-	0-3.52	-
Zeri et al. (2018)	Adriatic Sea	10-12/2014 04-07/2015	SV	251 ± 601	> 2.5 cm

Appendix 1: Studies reporting surface observations of meso- and mega-litter in the Mediterranean basin, from 1980 to 2019. Abbreviations: (regions) NW Med. = northwestern Mediterranean, c Tyr. Sea = central Tyrrhenian Sea, S. of Bonifacio = Strait of Bonifacio and Pel. Sanct. = Pelagos Sanctuary; (observation platforms) RV = Research Vessel, PF = Passenger Ferry, SV = Sailing Vessel, FP = Fixed Platform and AP = Airplane. * Mean abundance unit for Pettex et al. (2012a,b) is items/obs.

References	N^o Samples	Net mesh	Sampling nets	Years of Sampling	Abundance	Units	Region
Baini et al. (2018)	24	330 μm	Manta trawl	2013-2014	69,191 ± 83,244	items/km^2+ SD	W Med. Sea
Collignon et al. (2012)	40	333 μm	Manta trawl	2010	116,000	items/km^2	NW Med. Sea
Collignon et al. (2014)	38	200 μm	WP2	2011-2012	115,000	items/km^2	NW Med. Sea
Constant et al. (2018)	13	333 μm	Manta trawl	2016	0.05-0.45	items/m^3	NW Med. Sea
de Hann et al. (2019)	21	335 μm	Manta trawl	2015	0.11 ± 0.09	items/m^2	NW Med. Sea
de Lucia et al. (2014)	30	500 μm	Manta trawl	2013	0.15 ± 0.11	items/m^3	W Med. Sea
Faure et al. (2015)	41	330 μm	Manta trawl	2012	130,000	items/km^2	NW Med. Sea
Fossi et al. (2017)	21	330 μm	High speed Manta trawl	2014	0.082 ± 0.079	items/m^2+ SD	NW Med. Sea
Gajšt et al. (2016)	17	300 μm	Neuston net	2014	472,000 ± 201,000	items/km^2	Adriatic Sea
Gündoğdu et al. (2017)	7	333 μm	Manta trawl	2016	0,376	items/m^2	NE Levantine basin
Güven et al. (2017)	17	333 μm	Manta trawl	2015	140,418 ± 120,671	items/km^2+ SD	NE Levantine basin
Palatinus et al. (2019)	28	308 μm	Manta trawl	2015	127,135 ± 294,847	items/km^2+ SD	Adriatic Sea
Panti et al. (2015)	27	200 μm	WP2	2012-2013	0.17 ± 0.32	items/m^3+ SD	W Med. Sea
Pedrotti et al. (2016)	33	333 μm	Manta trawl	2013	21,000-5,780,000	items/km^2	NW Med. Sea
Ruiz-Orejón et al. (2016)	71	333 μm	Manta trawl	2011	147,500 ± 25,051	items/km^2+ SD	Whole Med. Sea
Ruiz-Orejón et al. (2018)	20	333 μm	Manta trawl	2014	900,324	items/km^2	NW Med. Sea
Schmidt et al. (2017)	43	780 μm	Manta trawl	2014-2016	112,000	items/km^2	NW Med. Sea
Suaria et al. (2016)	74	200 μm	Neuston net	2013	1.25 ± 1.62	items/m^2	W Med. Sea and Adriatic Sea
van der Hal et al. (2017)	108	333 μm	Manta trawl	2013-2015	7.68 ± 2.38	items/m^3	SE Levantine basin
Vianello et al. (2015)	2	Not Specified	Manta trawl	2014	12.19±20.13 (winter) 1.01±1.02 (spring)	items/m^3	NW Adriatic Sea
Vianello et al. (2018)	16	330 μm	Manta net	2014	1.21	items/m^2	NW Adriatic Sea
Zeri et al. (2018)	65	330 μm	Manta trawl	2014-2015	315,009 ± 568,578	items/km^2	Adriatic Sea

Appendix 2: Studies reporting samplings of micro-litter on Mediterranean surface waters..

References	Domain	Meteo-Oceano. Data	Distribution of inputs Spatial	Temporal	Interaction with coastline	Number of particles	Time of integration
Carlson et al. (2017)	Adriatic Sea	AdriaROMS4.0 based currents (1/45^o)	75 inputs from observed litter positions	Instantaneous release	Beaching	9398	60 days (forward/backward)
Coppini et al. (2018)	Mediterranean Sea	Ocean currents and Stokes drift provided by the Mediterranean Forecasting System, coupled to the WaveWatch-III model (CMEMS)	inputs from largest Mediterranean rivers, coastal cities and shipping lanes	Every day release (January 2013 - May 2017)	Beaching, stagnation and recirculation offshore	~ 10^7	-
Eriksen et al. (2014)	World's oceans	dataset provided by US Navy's Global Atmospheric Prediction System and HYCOM/NCODA ocean circulation model	inputs from urban development within watersheds, coastal population and shipping traffic	Not Specified	Beaching	Over 10^{10}	Not Specified
Fossi et al. (2017)	Pelagos Sanctuary	Tyrreno-ROMS based currents (August-September 2014, 1/45^o)	2 km x 2 km homogeneous grid	Everyday release (40 runs)	Beaching	10^2 for each model cell	15 days
Lebreton et al. (2012)	World's oceans	6-year dataset provided by US Navy's Global Atmospheric Prediction System and HYCOM/NCODA ocean circulation model (1/12^o)	inputs from impervious surface area, coastal population and shipping lanes	Releases evenly distributed over each year	Beaching	Over 9.6 x 10^{10}	30 years
Liubartseva et al. (2016)	Adriatic Sea	Lagrangian model dataset based on ECMWF wind and AFS currents (2009-2015, 1/45^o)	inputs from largest Adriatic rivers, cities and shipping lanes	One release in 10 days (2009-2015)	Beaching after 10-day stagnation	In the Markov chain model: over 6 x 10^{10}	6 years (2009-2015)
Liubartseva et al. (2018)	Mediterranean Sea	NEMO-WW3 based currents (1/16^o), operated under the Copernicus Marine Environment Monitoring Service (CMEMS)	inputs from largest Mediterranean rivers, coastal cities and shipping lanes	Everyday release (1 January 2013 - 30 June 2017)	Beaching, stagnation and recirculation offshore	~ 1.8 x 10^{10}	4.5 years
Mansui et al. (2015)	Mediterranean Sea	NEMO-MED12v75 based currents (2001-2010, 1/12^o)	10 km x 10 km homogeneous grid	Everyday release (3287 runs)	Beaching, stagnation and recirculation offshore	25500 particles/run, total: over 83 x 10^6	Two advection times: 3 months and 1 year
Politikos et al. (2017)	Aegean Sea	POM based currents (1990-2009, 1/15^o)	7 realistic clusters of sources	3 runs: every 3 months, or every month	Beaching	~ 10^4/year	1 year
Shchekinova and Kumkar (2018)	central Mediterranean Sea	Leeway model, dataset provided by the CMEMS (2013-2017, 1/16^o)	homogeneous deployment (1/16^0)	Not Specified	Not Specified	Not Specified	30 days
Zambianchi et al. (2017)	Mediterranean Sea	Historical drifter dataset of drogued or non-drogued drifting buoys (last 30 years, ~ 50 km model bin size)	2 runs: coastal initial distribution (CID) or homogeneous initial distribution (HID)	Not Specified	No beaching	In the Markov chain model: 1556/run for CID and 1174/run for HID	4 advection times: 3 months, 1, 3 and 10 years

Appendix 3: Studies modeling the transport and accumulation of floating marine litter in the Mediterranean basin and relevant parameters.

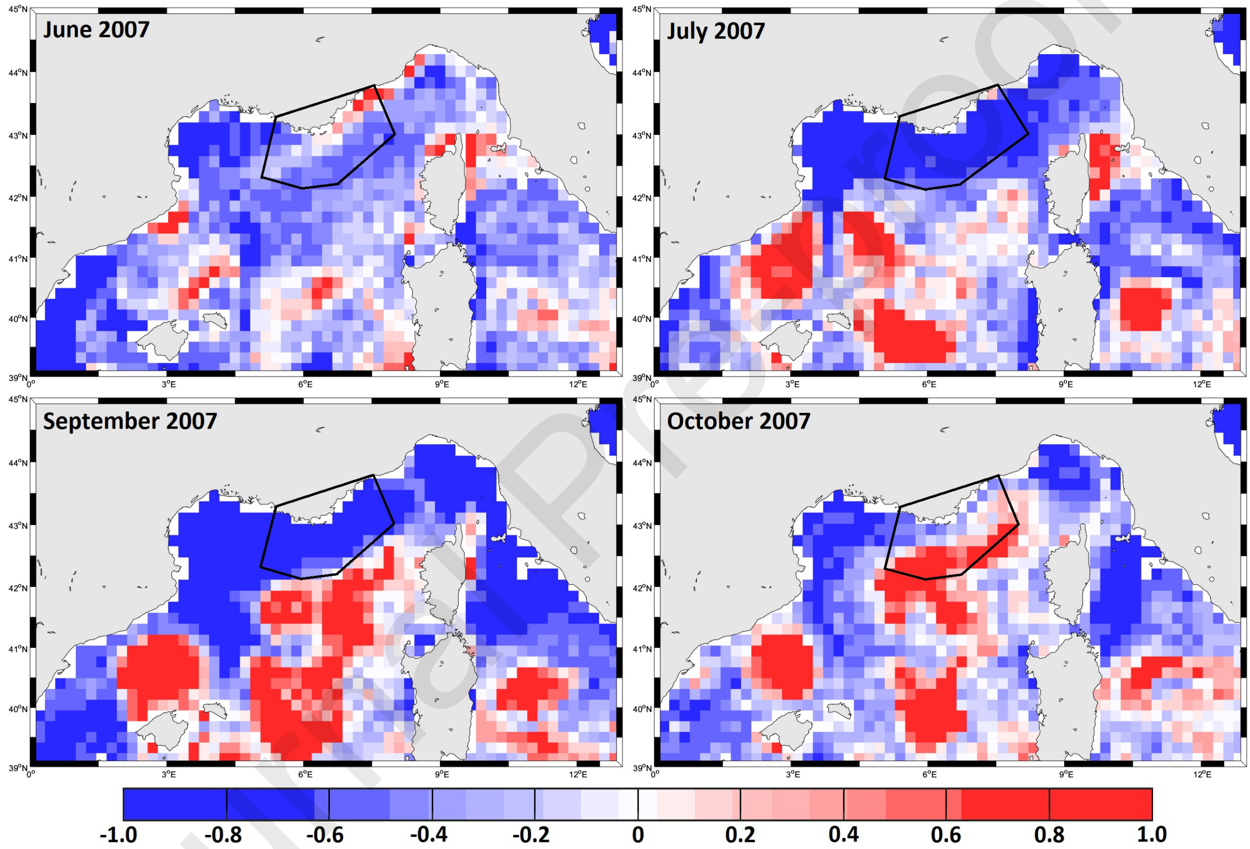

Figure 5: Monthly binning densities from June to October 2007. The study domain used for FML observations in studies by Di-Méglio and Campana (2017) and Ourmieres et al. (2018) is defined by a black outline. Since August 2007 is quite similar to July and September, it is not shown.

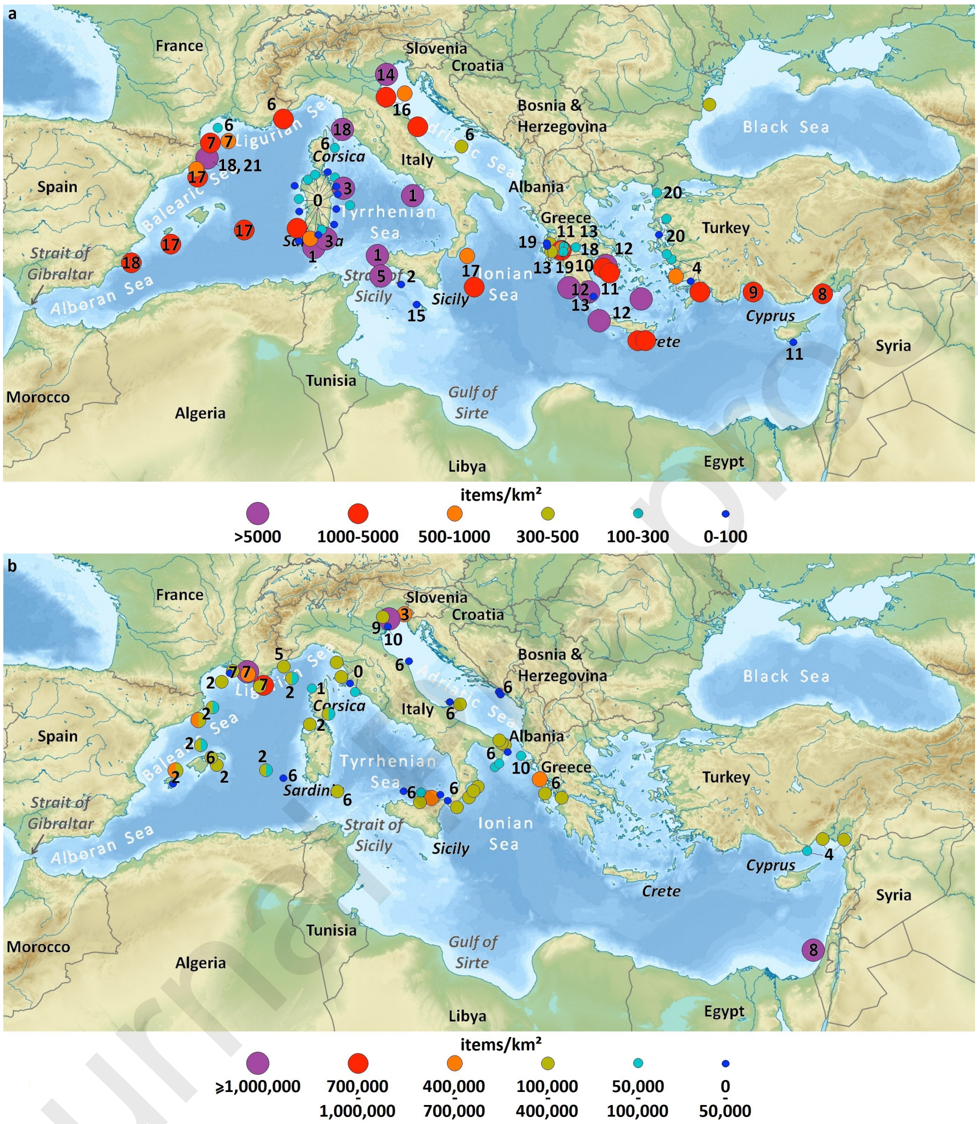

Figure 6: Location of geographic regions in the Mediterranean Sea where research has been conducted on (a) seafloor litter and (b) surface micro-plastic densities (in items/km^2). Abundance is represented by two groups (one for seabed litter and another for micro-plastics) of six gradations. Each is distinguished by the marker sizes and colors. Marker labels indicate the reference for each study. For seabed litter studies: (0) Alvito et al. (2018), (1) Angiolillo et al. (2015), (2) Cannizzaro et al. (1995), (3) Cau et al. (2017), (4) Cerim et al. (2014), (5) Consoli et al. (2018), (6) Galgani et al. (2000), (7) Galgani et al. (1996), (8) Gündoğdu et al. (2017), (9) Güven et al. (2013), (10) Ioakeimidis et al. (2015), (11) Ioakeimidis et al. (2014), (12) Katsanevakis and Katsarou (2004), (13) Koutsodendris et al. (2008), (14) Melli et al. (2017), (15) Mifsud et al. (2013), (16) Pasquini et al. (2016), (17) Pham et al. (2014), (18) Sánchez et al. (2013), (19) Stefatos et al. (1999), (20) Topçu et al. (2010), (21) Tubau et al. (2015). For micro-plastic studies: (0) Baini et al. (2018), (1) Collignon et al. (2014), (2) Faure et al. (2015), (3) Gajšt et al. (2016), (4) Güven et al. (2017), (5) Pedrotti et al. (2016), (6) Ruiz-Orejón et al. (2016), (7) Schmidt et al. (2017), (8) van der Hal et al. (2017), (9) Vianello et al. (2018), (10) Zeri et al. (2018). The following studies were discarded because of the units of measurement or other reasons that prevented comparison with other studies: Alomar et al. (2016), Bingel et al. (1987), Collignon et al. (2012), de Lucia et al. (2014), Eryaşar et al. (2014), Fabri et al. (2014), Faure et al. (2012), Galgani et al. (1995), Galil et al. (1995), García-Rivera et al. (2017), Katsanevakis et al. (2007), Kornilios et al. (1998), Pace et al. (2007), Panti et al. (2015), Ramirez-Llodra et al. (2013), Strafella et al. (2015), Suaria et al. (2016), Vianello et al. (2015).

- The spatio-temporal distribution of floating litter was predicted at the Mediterranean level with a model coupled with a literature review

- The main litter accumulation patterns are located in the western and central sub-basins

- Litter in the Levantine sub-basin strand locally without outflow to other Mediterranean sub-regions

- Macro and micro-litter spatial accumulation patterns are not correlated.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: