Forecasting marine litter pollution in Mediterranean MPAs

PREPARED BY

THE INTERREG MED

PLASTIC BUSTERS MPAS PROJECT

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Document Information

This document (Deliverable 3.5.1) describes the deployed method within the Plastic Busters MPAs project for modelling the movement and transport of marine litter in order to identify marine litter hotspots at a Mediterranean basin scale and in more detail at the level of the four partner MPAs that act as testing sites: Cabrera Archipelago National Park, Specially Protected Area of Mediterranean Importance (SPAMI) of the Pelagos Sanctuary, Tuscan Archipelago National Park and National Marine Park of Zakynthos.

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1. Introduction

1.1. PlasticBusters MPAs in a nutshell

PlasticBusters MPAs, is a 4-year-long project Interreg Mediterranean funded project aiming to contribute to maintaining biodiversity and preserving natural ecosystems in pelagic and coastal marine protected areas (MPAs), by defining and implementing a harmonized approach against marine litter. The project entails actions that address the whole management cycle of marine litter, from monitoring and assessment to prevention and mitigation, as well as actions to strengthen networking between and among pelagic and coastal MPAs.

The PlasticBusters MPAs consolidates Mediterranean efforts against marine litter by:

- Diagnosing the impacts of marine litter on biodiversity in MPAs and identifying marine litter 'hotspots';
- Defining and testing tailor-made marine litter surveillance, prevention and mitigation measures in MPAs;
- Developing a common framework of marine litter actions for Interreg Mediterranean regions towards the conservation of biodiversity in Med MPAs.

The PlasticBusters MPAs project deploys the multidisciplinary strategy and common framework of action developed within the Plastic Busters initiative led by the University of Siena and the Sustainable Development Solutions Network Mediterranean. This initiative frames the priority actions needed to tackle marine litter in the Mediterranean and was labelled under the Union for the Mediterranean (UfM) in 2016, capturing the political support of 43 Euro-Mediterranean countries.

1.2 Global marine litter estimates and the Mediterranean Sea

Recent estimates have calculated that between 4.8 and 12.7 million metric tons of plastic waste enter the ocean in 2010 and in the absence of waste management infrastructure improvements, this input of waste is predicted to increase an order of magnitude by 2025 (Jambeck et al., 2015). Over the past several years, models have been applied to estimate plastic concentration mainly in the sea surface based on oceanic hydrodynamics and model validation using empirical data (Lebreton et al., 2012; Maximenko et al., 2012; van Sebille et al., 2015). When comparing the results from the outputs of the global forecasting models for forecasted marine plastic debris, there is an agreement in areas such as the Great Pacific Gyre but when looking into regional areas such as the Mediterranean Sea, differences between modelling approaches with their results are identified. The resolutions from predictive models strongly differ, which may be attributed to model designed for larger basins such as the Indian Ocean, in the case of Maximenko's model (Van Sebille et al., 2015). Using global estimates for modelling the Mediterranean Basin, there is a large amount of uncertainty which indicates the necessity to develop locally scaled models for the Mediterranean Sea.

The Mediterranean Sea is a semi-enclosed basin and a hotspot area for marine biodiversity but very sensitive and vulnerable to anthropogenic pressures such as pollution from marine litter. In addition to poor waste management practices, tourism recreational, and agriculture activities can account for the terrestrial inputs of marine litter into this semi-enclosed basin. Additionally, litter finds its way into the coastal and marine environment also via various pathways such as sewage outlets, waste water treatment discharges, terrestrial runoffs, river discharges, and storm water overflows. Sea-based sources include fisheries and aquaculture, maritime transport and recreational activities at sea; and commonly are considered to account for 20% of marine litter that is released into the sea, when simulating the movement and transport of marine litter at sea. In addition, the Mediterranean coasts are densely populated and maritime transport in the Mediterranean Sea accounts for 30% of the global maritime transport (Abdulla and Linden, 2008). All these factors along with the natural characteristics of this semi-closed basin with slow water exchange with the Atlantic Ocean, through the strait of Gibraltar, and the Red Sea through the Suez Canal enhances plastic pollution accumulation in this area.

1.3 Marine Protected Areas in the Mediterranean Sea

Within the European Union, the Marine Framework Strategy Directive (MFSD) requires Member States to adopt Programmes of Measures to achieve good environmental status in their marine waters which includes spatial protection measures contributing to coherent and representative networks of marine protected areas (MPAs) to protect vulnerable species and habitats European Commission, 2015. The European Union's Natura 2000, is the largest coordinated network of protected areas in the world. Natura 2000 in the marine environment is a subset of the main network with designated areas in the marine waters of 23 countries. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive. In 2006, the EU launched the EU Biodiversity Action Plan which was followed by the 2011 EU Biodiversity Strategy (EC, 2011). Target 1 of the Biodiversity Strategy is to fully implement the Birds and Habitats Directives. This included the action to complete the Natura 2000 network in the marine environment. The marine Natura 2000 network has played a key role in improving MPA coverage in the EU's seas. The network covers a specific, limited number of vulnerable marine species and habitats, affording these with legal recognition and protection. However, as the knowledge base has grown and the legal Interpretation of the directives' applicability has evolved, a limitation has become apparent. Despite providing, in principle, a coherent approach to the protection of seabirds, turtles and marine mammals, the nature directives' approach to the protection of marine fish (e.g. commercially exploited species), invertebrate species (e.g. mussels and sea stars) and marine habitats is less coherent. The Directives thus exclude significant aspects of the marine ecosystem from formal protection schemes. In response, the EU produced new legislation: in particular, the Marine Framework Strategy Directive (MSFD) aims to launch measures for achieving or maintaining GES in the marine environment by 2020. One of the measures to be implemented is the use of spatial protection measures contributing to the creation of coherent and representative networks of MPAs adequately covering the diversity of the constituent ecosystems. Furthermore, Directive 2014/89/EU establishing a framework for maritime spatial planning is to contribute to the effective management of maritime activities and the sustainable use of marine resources in the marine environment. Besides the EU legislative framework, there are several global and regional agreements, policies and legislative frameworks with envisioning the establishment of MPAs such as the UN Convention on Biological Diversity and the Sustainable Development Goals, the Protocol on Specially Protected Areas and Biological Diversity in the Mediterranean (SPA/BD Protocol) of the Barcelona Convention establishing the List of Specially Protected Areas of Mediterranean Importance (SPAMI's List) in the region in order to promote cooperation in the management and conservation of natural areas, as well as in the protection of threatened species and their habitats (EEA, 2015).

Marine litter and in particular plastics have been acknowledged as a major threat in many MPAs hampering the achievement of their conservation goals. Marine plastic pollution may originate from local sources or can be transported to the MPAs from elsewhere via winds, surface currents or rivers.

The presence and potential impacts of marine plastic pollution have documented in several MPAs such as the Pelagos Sanctuary (Fossi et al., 2017). This is especially relevant as the Pelagos Sanctuary hosts several large marine mammals and recent studies have confirmed the overlap between the plastic and the feeding areas of several mammal species (Fossi et al., 2017). Another example is Cabrera Archipelago Maritime-Terrestrial National Park in the Balearic Islands (Western Mediterranean), where plastic fragments were found deposited in the sediments in different areas of the park (Alomar et al., 2016). These plastics could not be associated with any local sources, thus indicating that they may have arrived with the currents before settling on the seafloor.

1.4 Modelling marine litter in MPAs in the Mediterranean Sea

It is essential to develop models considering the local hydrodynamics at a regional and sub-regional scale to integrate the long-term trends and the connectivity within the Mediterranean Sea and among the MPAs.

The Mediterranean Sea and the MPAs are hotspots of biodiversity and hold from 4 to 18% of the global marine diversity (Coll et al., 2012) with a high amount of endemism ranging from 10-48%. The shallow coastal waters are home to key species and sensitive ecosystems such as seagrass beds and coralligenous assemblages (Gabrié et al., 2012). These important ecosystems are at risk of encountering plastic despite their protection. By developing MPA specific dispersion models tracking how plastics move in these areas will give us insight into the fate of plastics and their potential sources.

There are current gaps in the knowledge of the impact that plastic marine litter has on MPAs in the Mediterranean Sea at both a regional and local scale. There is a need to understand the dynamics of plastics and marine litter, especially in coastal regions with models having a spatial resolution that includes the small spatial scale of most coastal MPAs. By applying long term regional climate and hydrodynamic models, we aim to trace plastic particles to determine their sources and sinks, and develop hotspots maps of accumulation areas at a Mediterranean basin scale and at the specific study areas of the project: the Cabrera Archipelago Maritime-Terrestrial National Park, the Pelagos Sanctuary, the Tuscan Archipelago National Park and the Zakynthos National Marine Park. Once these models have been developed and validated, further analyses determining the risk that marine biodiversity is facing is essential to develop tailor-made management and conservation plans at MPAs.

1.5 Aim and scope of this deliverable

Within the framework of the Plastic Busters MPAs project, a key task is the development of forecasting models identifying marine litter pollution hotspot areas in MPAs. In order to define these accumulation areas, different type of data on ocean currents, convergence areas, state-of-the-art modeling, data from satellites-based tools, meteo-ocean operational conditions and remote sensing observations (HF radars and satellite products) have been considered. For this particular task, a predictive model for the whole Mediterranean Sea, considering 4 pilot areas (Cabrera Archipelago Maritime-Terrestrial National Park, Specially Protected Area of Mediterranean Importance (SPAMI) of the Pelagos Sanctuary, Tuscan Archipelago National Park and National Marine Park of Zakynthos) has been developed according to current simulations and Lagrangian drifters (model 1). Two local modelling approaches have been applied, one for the Cabrera National Park (model 2) and another for the SPAMI of the Pelagos Sanctuary and the Tuscany Archipelago National Park (model 3). For the Cabrera Archipelago National Park the model has been built relying on the Western Mediterranean Operational forecasting OPerational system (WMOP) and anthropogenic sources. The development and implementation of a numerical model to evaluate the trend in concentration or dispersion of Plastic Marine Litter (PML) on a large marine area, the Pelagos Sanctuary and the Tuscany Archipelago National Park, has been based on the computation of tendency to accumulation/dispersion at medium-range timescales (around 1 month) using a model that includes dynamic coupling of waves and currents (Stokes drift).

It is meaningful to highlight the importance of using these three different modelling approaches to identify marine litter hotspots across the selected MPAs in the Mediterranean Sea. The first umbrella model captures the entirety of the Mediterranean Sea within a 3D perspective. This 3D model captures ML accumulations on the sea surface, vertical distribution in the water column and the sedimentation of particles simulating MPL to the seafloor at each of the pilot areas. The second and third models are small-scale models, one for the Pelagos Sanctuary and Tuscany Archipelago National Park area and the other for Cabrera National Park, which use specific very-high resolution with a specific design to capture the unique hydrodynamics and small-scale variability of the coastal regions of these areas. These high resolution models are not available across the entire Mediterranean Sea so it is essential to include for the selected MPAs enabling to cross-reference results from the forecasting ML in MPAs in an effort to validate ML hotspots to determine agreements between models.

The forecasting activity is essential for predicting the abundance of marine litter and plastics based on the oceanographic structures (convergence areas), identified by the models in order to assess impacts on biodiversity and to design the specific mitigation actions and recommendations in the different MPAs. From a management point of view, this testing and posterior validating phase is necessary in order to design and propose marine litter mitigation actions in these pilot areas of different MPAs along the Mediterranean Sea. Knowledge obtained from this task will be further transferred to other Mediterranean MPAs for the implementation of management measures, which will help to preserve marine ecosystems from the increasing problem of marine litter.

This activity is based on the development of three models for the identification and validation, at different resolutions, of marine litter (ML) hotspots areas in MPAs. The models will focus on hotspot analysis/mapping of ML accumulation areas, based on ocean currents and convergence areas, and state-of-the-art modelling and satellite-based tools, to support the implementation of targeted marine litter management measures in the most affected sites in the MPAs.

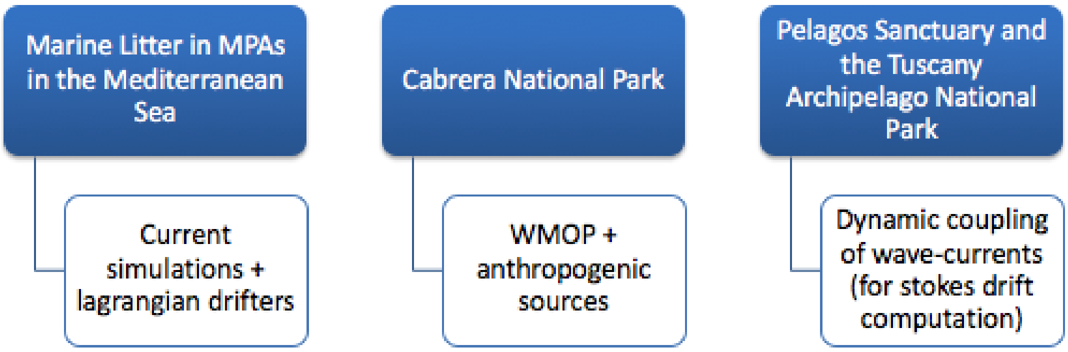

Figure 1. Modelling approaches for the Mediterranean Sea, Zakynthos National Park, Cabrera National Park, the Pelagos Sanctuary and the Tuscany Archipelago National Park.

2. Definitions and policy context

Within this document marine litter is defined as any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Marine litter can be classified in size classes as follows: macro-litter referring to items above 25mm in the longest dimension; meso-litter from 5mm to 25 mm; and micro-litter from 1µm to 5mm. Sometimes the later size class is further broken down to large micro-litter from 1mm to 5 mm and microplastic from1µm to 1mm.

The main legislative frameworks related to marine litter monitoring are the EU Marine Strategy Framework Directive (2008/56/EC, 2010/477/EC, 2017/848/EC) and the Barcelona Convention Ecosystem Approach (COP19 IMAP Decision IG.22/7) (see Box 1.1 and Box 1.2).

Box. 1.1. *The Marine Litter Descriptor, criteria, and respective Indicators within the framework of the EU MSFD.*

Marine Litter within the EU MSFD

Properties and quantities of marine litter do not cause harm to the coastal and marine environment (Descriptor 10)

Criteria D10C1 - Primary:

The composition, amount and spatial distribution of litter on the coastline, in the surface layer of the water column, and on the seabed, are at levels that do not cause harm to the coastal and marine environment.

- ✓ amount of litter washed ashore and/or deposited on coastlines, including analysis of its composition, spatial distribution and, where possible, source (10.1.1)
- ✓ amount of litter in the water column (including floating at the surface) and deposited on the seafloor, including analysis of its composition, spatial distribution and, where possible, source (10.1.2)
- ✓ amount, distribution and, where possible, composition of microparticles (in particular microplastics) (10.1.3)

Criteria D10C2 - Primary:

The composition, amount and spatial distribution of micro-litter on the coastline, in the surface layer of the water column, and in seabed sediment, are at levels that do not cause harm to the coastal and marine environment.

- ✓ amount and composition of litter ingested by marine animals (10.2.1)

Criteria D10C3 - Secondary:

The amount of litter and micro-litter ingested by marine animals is at a level that does not adversely affect the health of the species concerned.

Criteria D10C4 - Secondary:

The number of individuals of each species which are adversely affected due to litter, such as by entanglement, other types of injury or mortality, or health effects.

Box. 1.2. *The Marine Litter Operational Objectives and respective Indicators within the framework of the Barcelona Convention Ecosystem Approach and the Integrated Monitoring and Assessment Programme (IMAP)*

Marine Litter and the Barcelona Convention Ecosystem Approach

Ecological Objective 10 (EO10): Marine and coastal litter do not adversely affect the coastal and marine environment.

IMAP Common Indicator 22:

Trends in the amount of litter washed ashore and/or deposited on coastlines (including analysis of its composition, spatial distribution and, where possible, source).

IMAP Common Indicator 22:

Trends in the amount of litter in the water column including micro plastics and on the seafloor.

IMAP Candidate Indicator 24:

Trends in the amount of litter ingested by or entangling marine organisms focusing on selected mammals, marine birds, and marine turtles.

3. Modelling marine litter in the Mediterranean Sea

3.1. Objectives

The main objectives of this deliverable (D.3.5.1) are:

- The development of a baseline simulation to analyze the potential distribution of ML in the whole Mediterranean Sea.
- The identification of areas of ML accumulation and how these evolve over time in order to design targeted monitoring and mitigation actions.
- Assess hotspot accumulation areas at four study locations: the National Park of Zakynthos (Greece), the Cabrera National Park, the Tuscan Archipelago National Park and the Pelagos Sanctuary (Italy).
- To study the feasibility of implementing an operational forecasting system to improve the quality of the management of MPA in the Mediterranean.

3.2. Methodology

3.2.1. Modeling system

The modeling system used is based in two components, a hydrodynamical model reproducing the 3D velocity field in the Mediterranean (NEMOMED36) and a Lagrangian model that simulates the evolution of floating particles (Ichthyop 3.3):

- **NEMOMED36**: is a high resolution regional configuration of the core model NEMO, with 1/36 x 1/36 degrees resolution (~ 3 km), covering the period 2003 – 2013 with daily resolution(Arsouze et al. 2013). It has 50 stretched z-vertical levels (from Δz of 1 m at the surface and 460 m at the bottom) with partial step parameterization for the bottom level. The model is initialized with a 3D temperature and salinity climatology provided by MEDATLAS-II for the period 1958-1986. The boundary is only open on the west side since the model covers the whole Mediterranean Basin, there is a buffer zone where temperature and salinity are restored towards the climatology of Levitus et al. (2005). In addition, a damping of sea surface height (SSH) is done in this area towards prescribed SSH given by previous version of the model that assimilates satellite altimetry data to ensure volume conservation. River runoff is simulated as freshwater increase near the grid points where the river is supposed to be with values of the main rivers obtained from RivDis database (Vörösmarty et al. 1996). The Black Sea is considered as a river. NEMOMED36 is forced by ARPERA (downscaling down by spectral nudging using the atmospheric model ARPEGE-Climate (Déqué and Piedelievre 1995), where scales above 250 km are spectrally driven by ECMWF fields and small scales develop freely.

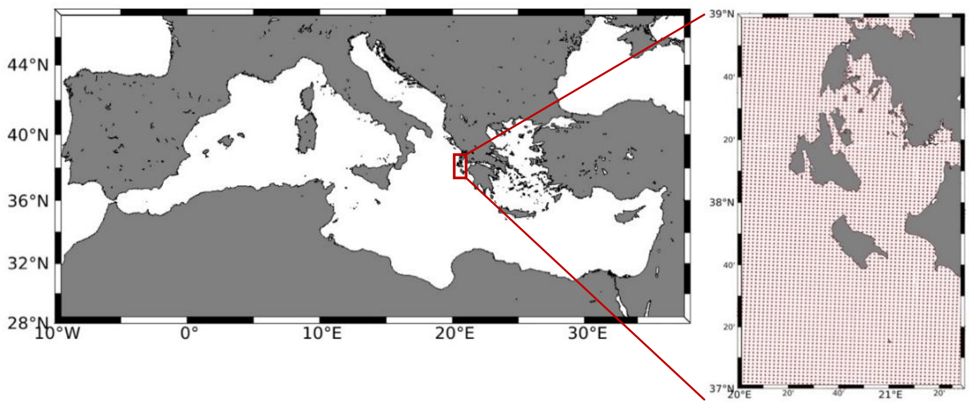

Figure 1. Model domain with an example of the model grid resolution at Zakynthos National Park.

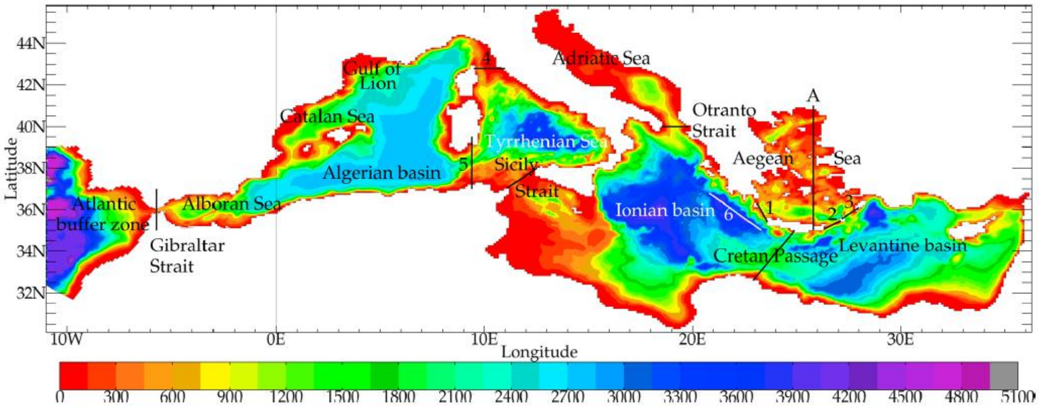

Figure 2. Model bathymetry (m) (adapted from Beuvier et al. 2010).

Several studies have previously used this model and previous versions have proven its ability to properly reproduce the main characteristics of the basin circulation, including complex processes such as the deep water formation in the Eastern Mediterranean Transient (Beuvier et al. 2010) or the deep water formation at the Gulf of Lions (Beuvier et al. 2012).

- **Ichthyop 3.3:** It is an individual based model (IBM) designed to study the effects of physical factors on the dynamics of fish eggs and larvae (Lett et al. 2008). It uses an eulerian model velocity field to infer the 3D particles trajectories resolving the movement equations through a fourth order Runge – Kutta integration scheme. Horizontal dispersion, sedimentation and beaching can be also included in the computation. The NEMOMED36 currents fields are used as the model input. Together with the options of particle release, the most relevant physical parameters of the model can be easily set by the user, which allows multiple run possibilities covering all the requirements of this study. This model has adequately been applied in several physical and biological studies focused on pollutants transport (Millet et al. 2018), particle dispersions in harbors areas (Jouanneau et al. 2013), fisheries distribution (Džoić et al. 2017) and ecosystem connectivity (D'Agostini et al. 2015). For the case of plastic particles these are virtual particles, without any mass or size.

3.2.2. Experimental modeling design

3.2.2.1 Baseline simulation

Following previous work from Jambeck et al. (2015) and Liubartseva et al. (2018), we assume a total input of 100k tons of plastic per year within the whole Mediterranean basin. This total amount is distributed into three different types of sources: cities, rivers and shipping, according to the ratio 50:30:20% respectively.

The 50k tons of plastics per year corresponding to the cities is redistributed in proportion to their population. A total of 480 coastal cities are considered. The 30k tons per year of the rivers are distributed among the fifteen main rivers within the basin in proportion to their mean discharge between 1980 and 2012, estimated by the OCHIDEE River Flow model (Ducharne et al. 2003). The Dardanelles Strait is considered a river and its contribution is computed as the sum of the main rivers discharging into the Marmara Sea and the Black Sea. The 20k tons corresponding to shipping – lanes are uniformly distributed over the regions that concentrate higher maritime traffic. Figure 3 shows the position of the different sources.

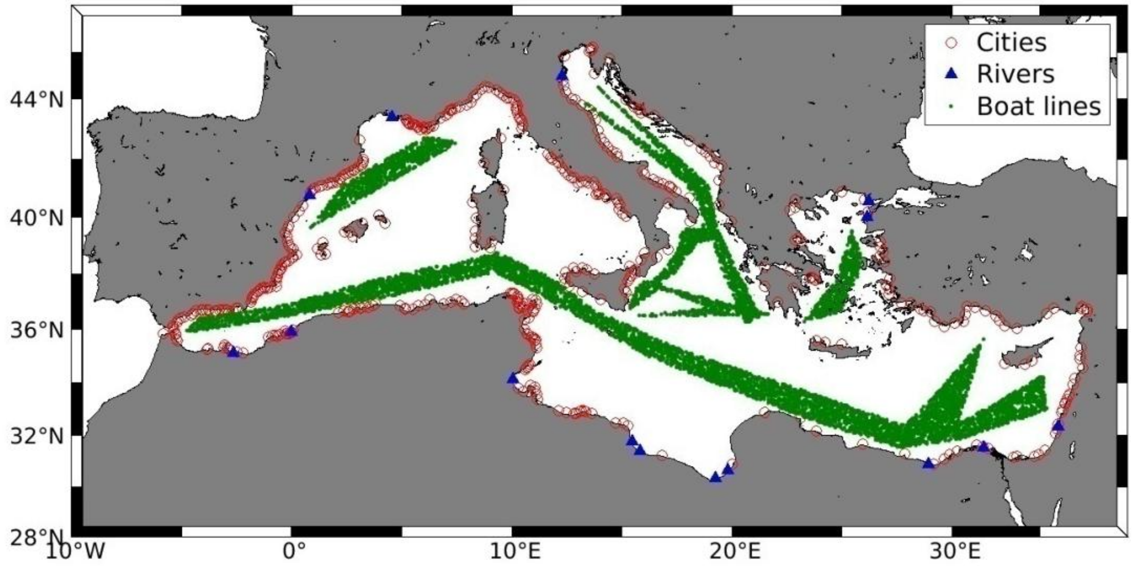

Figure 3. Position of the different plastic sources for the baseline simulation.

The experiment covers a ten-year period, between 2003 and 2013. Due to computational limitations, it has been divided in 120 monthly simulations, each one running for one year. The distribution of the particles has been carried out according to the previous considerations. A total of 41872 particles are released every month, which for the complete experiment makes a total of more than 5 million particles. The individual-based model (IBM) integrates the movement equations for each particle with a time step of 15 min, and daily outputs are recorded. The model also considers horizontal dispersion, by introducing a random component in the Eulerian horizontal velocity. The sedimentation has not been considered in the baseline run but it has been considering within the sensitivity run (see discussion). Beaching effects have not been taken into account, due to the existing uncertainties in the modeling of this process. The initial concentrations at the different source locations are represented in Figure 4.

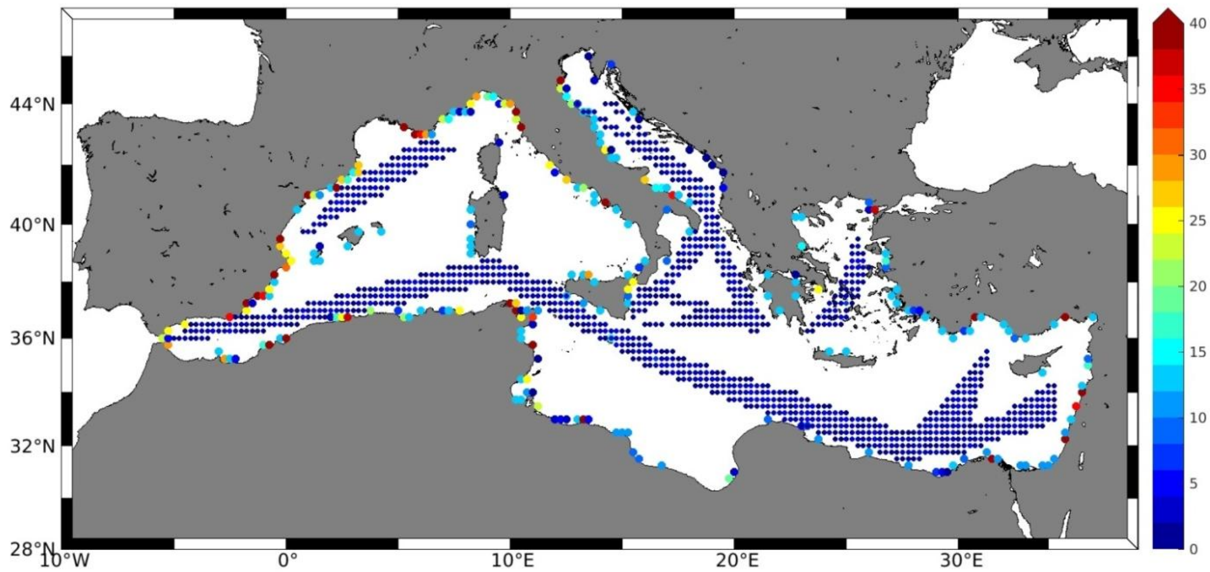

Figure 4. Spatial distribution of initial concentrations (in kg·km^{-2}) for the baseline simulation.

It is important to point out that the particles released in the simulation are defined as neutral, which means that their density is analogous to that of the water surrounding them. No positive or negative buoyancy has been assigned to the particles, so their vertical movements only depend on the vertical velocities given by the circulation model. Therefore, our results are representative of the marine litter with a density range similar to the density of the Mediterranean waters. Table 1 summarizes the specific gravity (ratio between the density of the polymers and the seawater density) for the most common polymers. The simulation results could be considered representative of the plastic with specific gravity close to 1. We see that there are a large proportion of polymers that float or sink, hence they are not well represented by this simulation. Therefore, the baseline run should be interpreted as an experiment describing the evolution of the fraction of ML that (a) behaves like neutral particles either due to their density or their shape and (b) reaches the open sea (i.e. not retained in the coastal area). Unfortunately, there are no estimates of what fraction of the total release falls into those categories. So, in order to give dimensional concentration maps we assume all the 100k Tons released per year reach the open sea and have neutral density, so each modelled particle is equivalent to a ML release of 200 kg.

Table 1. Common polymers and applications, together with their tendency to float or sink in the aquatic environment, based on their specific gravity (from GESAMP 2019).

Polymer	Common applications	Specific gravity	Behaviour
Polystyrene (expanded)	Cool boxes, floats, cups	0.02-0.64	Float
Polypropylene	Rope, bottle caps, gear, strapping	0.90–0.92	
Polyethylene	Plastic bags, storage containers,	0.91–0.95	
Styrene-butadiene (SBR)	Car tyres	0.94	
Average seawater		*1.03*	
Polystyrene	Utensils, containers	1.04–1.09	Sink
Polyamide or Nylon	Fishing nets, rope	1.13–1.15	
Polyacrylonitrile (acrylic)	Textiles	1.18	
Polyvinyl chloride	Thin films, drainage pipes, containers	1.16–1.30	
Polymethylacrylate	Windows (acrylic glass)	1.17-1.20	
Polyurethane	Rigid and flexible foams for insulation and furnishings	1.20	
Cellulose Acetate	Cigarette filters	1.22–1.24	
Poly(ethylene terephthalate) (PET)	Bottles, strapping	1.34–1.39	
Polyester resin + glass fibre	Textiles, boats	>1.35	
Rayon	Textiles, sanitary products	1.50	
Polytetrafluoroethylene (PTFE)	Teflon, insulating plastics	2.2	

3.2.2.3. Sensitivity test runs

In order to evaluate the feasibility of developing an operational prediction system, two test runs have been carried out to assess the sensitivity of the modeling system to the uncertainty in the location of release:

- TESTRUN1: 10 years of monthly simulations releasing particles from all the coastal pixels of the model grid.
- TESTRUN2: 10 years of monthly simulations releasing particles from a homogeneous grid covering the whole basin.

3.3. Results

3.3.1. Average concentration

The average concentration across the whole basin for the ten years period of the simulation is represented in Figure 5. The partial contribution of the different sources is also shown (cities, rivers, ships and the Dardanelles Strait (which is treated as a river). From now on within the text, the description of the figures will refer to the Mediterranean sub-basins. The main sub-basins are the Eastern (EMED) and Western (WMED) Mediterranean, which are separated by the narrow sill of the Strait of Sicily and have two specific thermohaline circulation (THC) systems. Each of these main basins is subdivided in smaller sub-basins which have specific current systems and mesoscale fields. This way, the EMED includes the Levantine basin, the Adriatic, Ionian and Aegean Seas. These four sub-basins are connected among them and their circulation systems influence each other. However, they also show specific patterns and processes limited by the topographic constraints and that influence the ML concentration. In the WMED the main sub-basins are the Alboran sea, the Algerian current region, the Balearic Sea and the Gulf of Lions.

The Western Mediterranean shows elevated concentration of plastics on average, with maximum values (~ 6 kg·km^{-2}) along the Catalan Coast and the Gulf of Lions (Figure 5a). Over the Balearic Sea and the Algerian current region the concentration is somewhat lower (4 – 5 kg·km^{-2}). Similarly, high values are also found in the vicinity of the Strait of Sicily (~ 6 kg·km^{-2}). On the other hand, the lowest concentrations in this sub basin are found in the Alboran Sea, the Tyrrhenian Sea and the French coast east to the Gulf of Lions (1 – 3 kg·km^{-2}). In the north-western Mediterranean, the main source pathways of marine litter are the cities (Figure 5b), especially from Marseille and Barcelona. The Ebro and Rhone rivers contribution it is also noticeable but lower in comparison to the cities (Figure 5c). The Northern current, which flows southward along the Iberian continental slope, transports the plastic inputs from these cities and rivers. In the Northern coast of Africa, the cities inputs seem to be advected northward towards the central region of the Western Mediterranean, likely an effect of the high mesoscale activity of the region (Millot et al. 1997). The ships inputs also contribute to the high concentration of ML in the area, although to a lesser extent (Figure 5e).

Across the rest of the Mediterranean Sea, three regions with different characteristics can be identified (Figure. 1a). The Adriatic shows very high concentrations (> 6 kg·km^{-2}) which may be due to the presence of densely populated cities and the input of the Po river (Figure 5b,c). The Eastern coast of the Levantine basin also shows very high concentrations (> 6 kg·km^{-2}) as a consequence of the Nile river input, which is transported northward following the large-scale circulation (Poulain et al. 2013). Conversely, in the central area of the Levantine basin and the Ionian Sea, the concentration is relatively low (< 2 kg·km^{-2}). In the Aegean Sea, the concentration is abnormally high. This is a consequence of the very high input from the Black Sea through the Dardanelles Strait, which could be overestimated, although no reliable information of its contribution is available to confirm that extent. If this contribution is not considered, the concentration in the Northern Aegean is reduced to values similar to those of the Ionian Sea, while concentrations in the Southern Aegean still remain high (Figure 5d,f). It is interesting to notice that removing the Dardanelles contribution does not affect the average concentration in the rest of the Eastern Mediterranean. If we compare the Figure 5a and 5f we can conclude that the regional circulation in the Northern Aegean retains the Black Sea input. Finally, the shipping input is relatively higher in the Eastern basin, particularly in the Adriatic and the Levantine basin (2 – 3 kg·km^{-2}), but again is low in comparison to the contributions from the cities and rivers.

3.3.2 Concentration variability

In order to identify the areas of the basin with higher/lower variability, the percentiles maps of the daily concentration of ML are shown in Figure 6b-f. The percentiles represent the concentration values below where the given percentage of all the recorded values can be found. For instance, the median (percentile 50) distribution is the value below which 50% of the concentration values can be found. We see that the median (Figure 6b) and the average concentrations (Figure 5a) are very similar, which means that the distribution of the concentration is quite symmetric. Percentile 25 and 5 represent the lower quarter and minimum values, respectively (Figure 6c,e), while percentiles 75 and 95 represents the upper quarter and maximum values (Figure 6d,f). Wide regions with very strong variability can be identified. For instance, in the central part of the Western Mediterranean, in the Adriatic or in the Aegean Seas, we can find minimum values below 1 kg·km^{-2} and maximums above 6 kg·km^{-2}. On the other hand, in the South Tyrrhenian and Northern Ionian is where the variability is lowest, the concentrations oscillates between 0.5 and 2.5 kg·km^{-2}. In the Adriatic and the Aegean the variability is also low. These regions show very high concentrations in most part of the distribution (from percentile 25 on).

Additionally, Figure 6a displays the ratio between the standard deviation and the mean value of the concentration. This parameter represents how strong the variability is with respect to the mean value at each point. This information is very useful to design field campaigns because it gives an idea of how representative the measurements are in a specific region (i.e. how close to the actual mean value) would be. In regions with high std/mean ratios, the measurements would show large variations depending on the day when they are acquired and vice versa. We can see that in general, the ratio is higher than 0.4 across the whole basin. The areas of highest variability are the Levantine basin, the Northern Aegean, Northern Adriatic and Alboran Seas, with values very close to 1 (Figure 6a). There are also areas with moderate variability (0.5 – 0.6) in the Western and Eastern basins while the regions with lower values (~ 0.4) are located in the Southern half of the Western basin, North of the Ionian Sea and South of the Levantine basin.

The seasonality of the concentration is another source of variability that is explored here. The monthly concentrations represented in Figure 7, show that in the Eastern Mediterranean the monthly variations are low. Only in the South Aegean a significant reduction of the concentration can be observed in the second half of the year. In the Western basin, an important increase in the concentrations can be observed in summer and autumn in the Balearic Sea, while in the rest of the basin the concentrations show very little seasonal changes. In other words, as the release of particles is constant throughout the year, these results suggest that seasonal variations in the circulation patterns are not enough to significantly modify the ML concentrations.

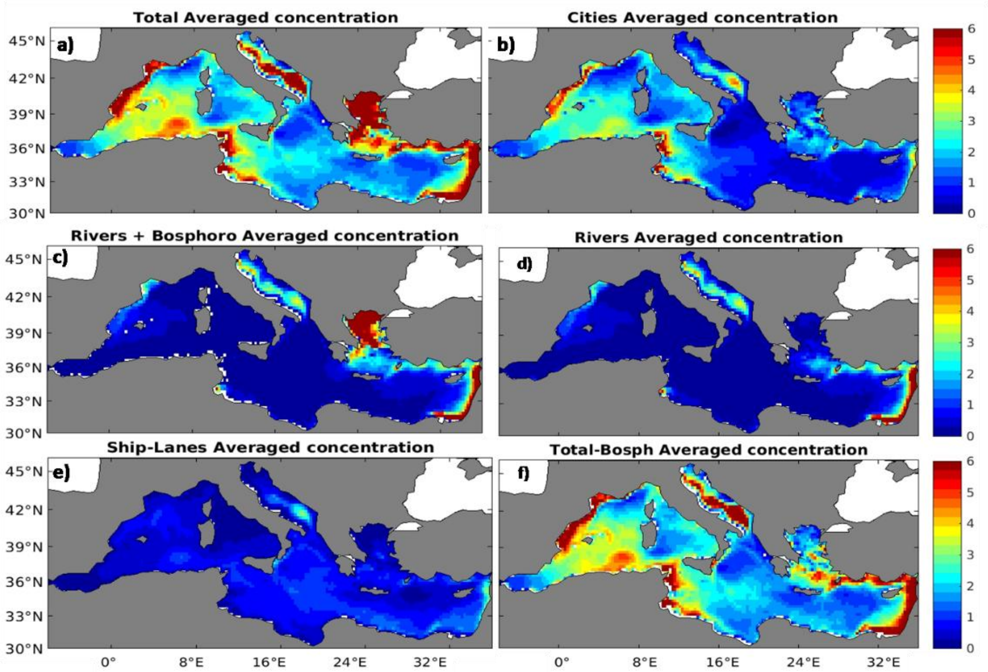

Figure 5. Concentration of marine litter (kg·km^{-2}) over the Mediterranean basin for the period 2003 – 2013: a) Average concentration from all the sources. b) Average concentration of the coastal cities c) Average contribution of the rivers, including the Dardanelles Strait) Average contribution of the rivers, not including the Dardanelles Strait) Average contribution of the ship – lanes. f) Average concentration from all the sources except the Dardanelles Strait.

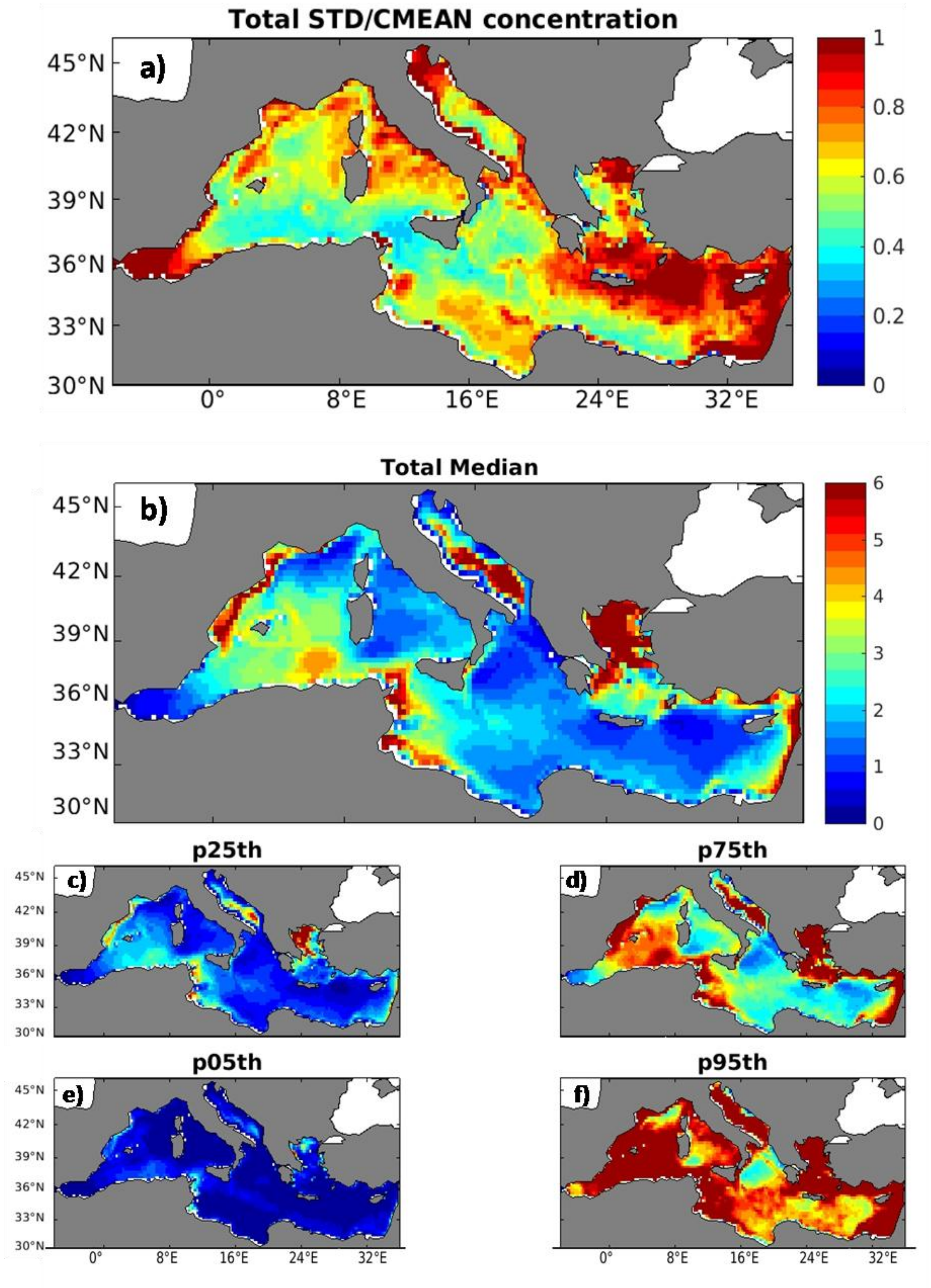

Figure 6. Spatial distribution of the variability of the concentration (kg·km^{-2}): a) Standard deviation over mean concentration ratio b) Median, c) Percentile 25, d) Percentile 75, e) Percentile 5 and f) Percentile 95.

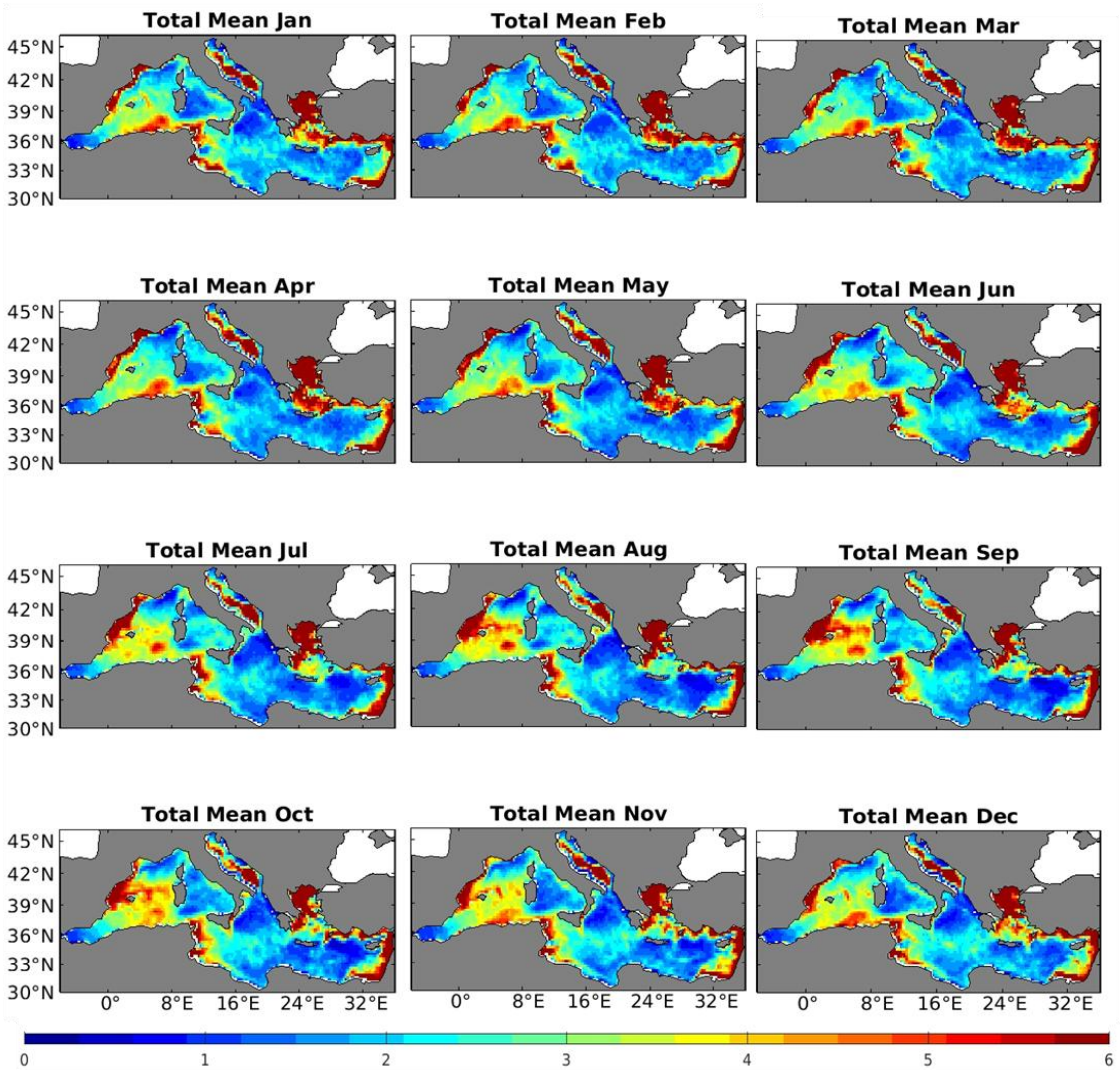

Figure 7. Monthly climatology of ML concentration (kg·km^{-2}) for the period 2003 – 2013.

3.3.3. Particle depth distribution

The capacity of the Lagrangian model used in the simulation to solve the 3D movement equations of each particle, and hence the vertical displacements, is a useful advantage. It supplies valuable information about the particle distribution that can be critical in the correct design of field campaigns. It should be highlighted that the simulated particles are considered of neutral density and are released at the sea surface, so its vertical location is the result of the vertical motion of the water parcels. The average depth of the particles and the standard deviations are displayed in Figure 8, while Figure 9 shows the histograms of the particles depth distribution for different sub-basins. We see that the fraction of the 'neutral' particles that remain on the surface is very low. The mean depth across the Mediterranean Sea is at 35 m but in the Aegean and the Levantine basins, there are a considerable amount of particles below 70 m and deeper (Figure 9d,e). Other regions where a large proportion of particles reach depths below 40 m are the Southern Adriatic and the Gulf of Lions (Figure 9g,i). All of them are well known areas of intermediate deep water formation, where the particular thermohaline properties of the surface waters in combination with the climatic conditions provoke their sinking (Roether et al. 1996; Marshall and Schott 1999; Poulain et al. 2013). However, it is worth insisting that throughout the rest of the basin most of the 'neutral' particles reside below 10 m and only in shallower coastal areas the mean depth where 'neutral' particles suspend lower than 5 m (Figure 8,9a). The range of variability with respect to the mean depth represented by the standard deviation is more homogeneous (Figure 8). Its mean value is 10 m and is only higher than 15 m in the Aegean and the Southern Adriatic. As a general result, the model finds that the water depths where most of the simulated 'neutral' particles suspend range between 15 to 45m (Figure 8,9a). Noticeably, this would be different if particles with density significantly different than that of seawater were considered.

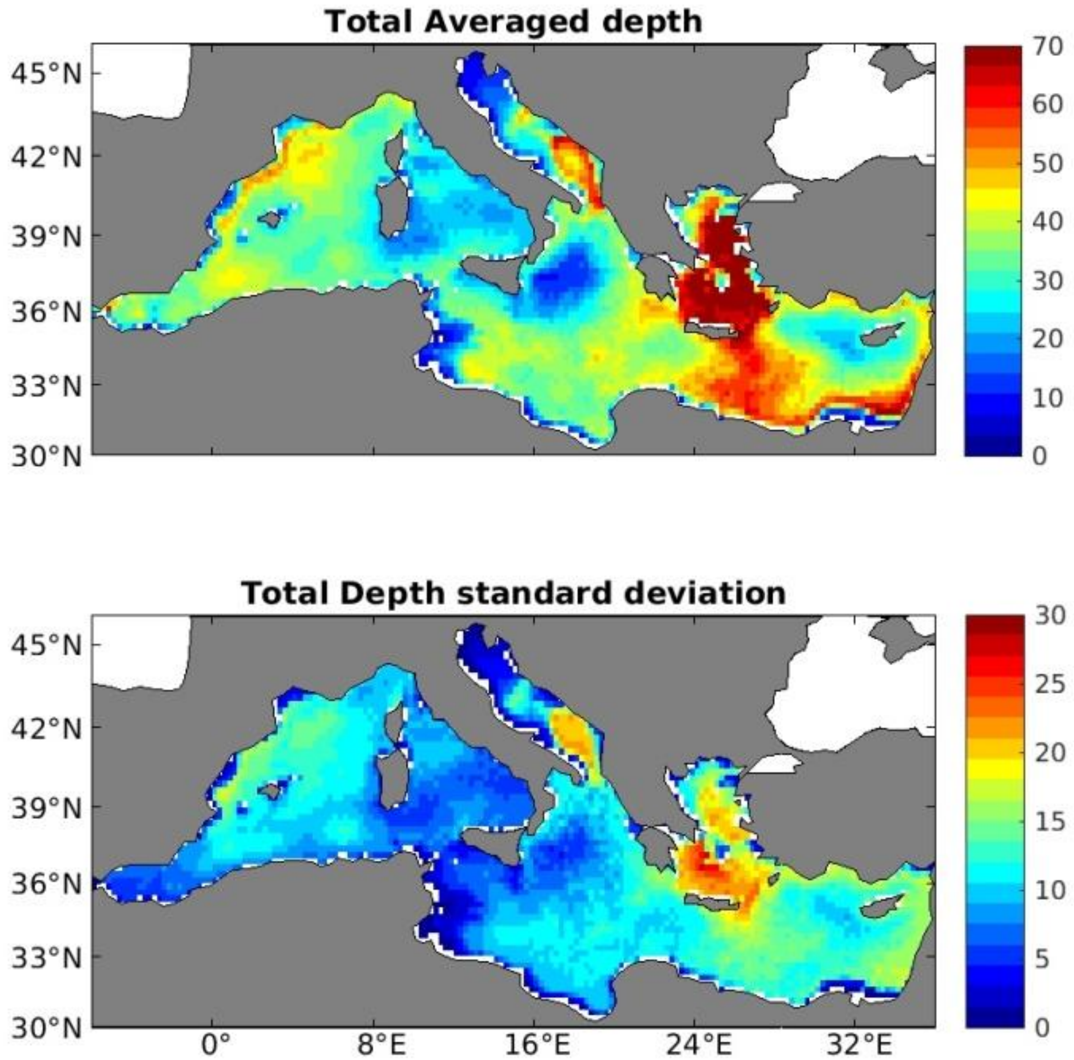

Figure 8. Mean particles depth and standard deviation (m).

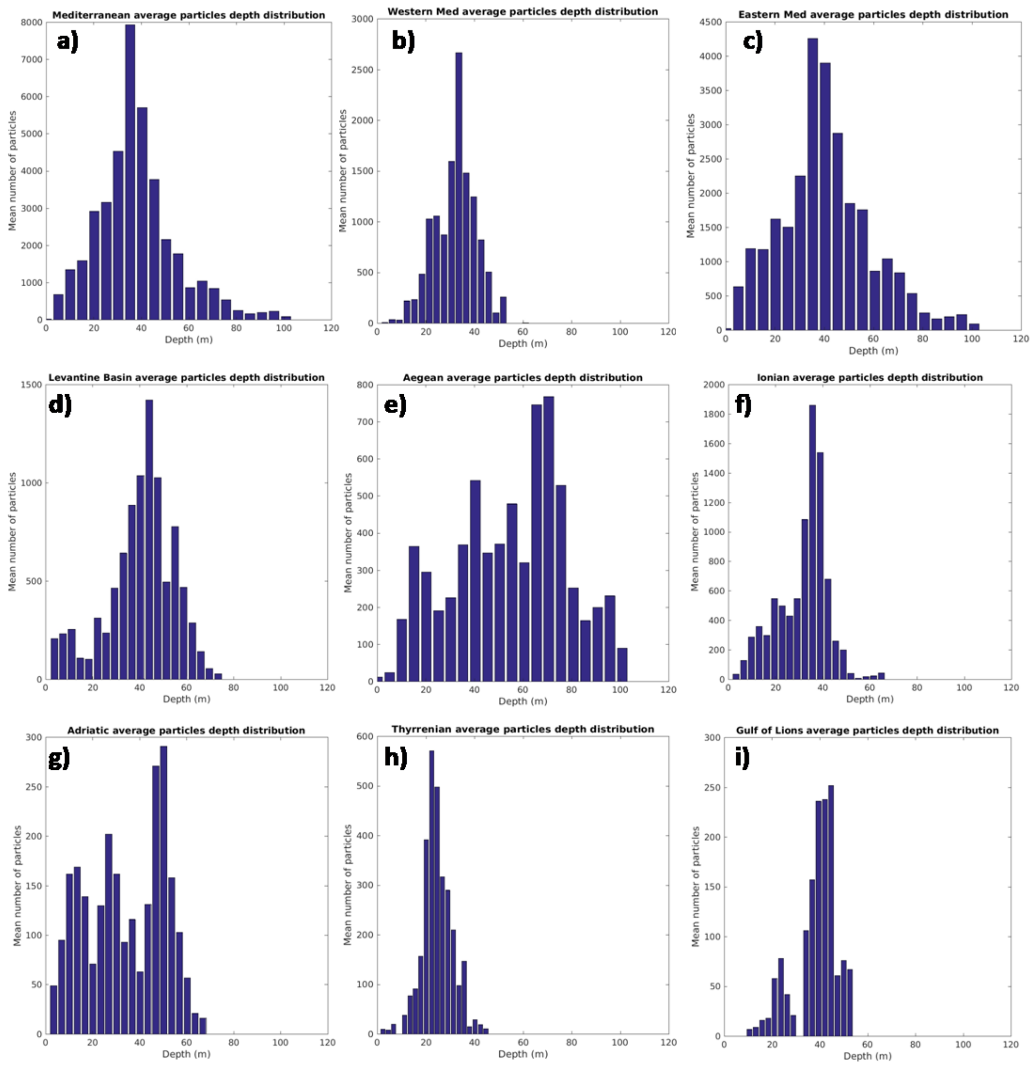

Figure 9. Histograms of the particles mean depth distribution for: a) The whole Mediterranean basin b) Western Mediterranean c) Eastern Mediterranean d) Levantine basin e) Aegean Sea f) Ionian Sea g) Adriatic Sea h) Tyrrhenian Sea i) Gulf of Lions. Note that only particles with neutral density in respect to seawater are considered.

3.3.4. Focus on Marine Protected Areas

In order to assess the potential impact of ML on Marine Protected Areas, and to produce some diagnostics comparable with the work performed by other teams of the Plastic Busters MPAs consortium, we have further elaborated on the forecasting results for the following four case study MPAs:

3.3.4.1 Zakynthos National Park

The previous results can be compartmentalized and zoomed in to focus on the Zakynthos National Park, located on the Southern coast of Zakynthos (or Zante) Island, in Greece (Figure 1), which lies in the eastern part of the Ionian Sea. We should remind here, that no land-based sources have been considered for the island. The touristic seasonality is also not included in the model, hence the inputs are constant during the year for all the sources. Figure 10 shows the average, winter and summer concentration of plastic particles in the region, together with their respective variability ratios (std/mean). The park is located on the southern shores of the island of Zakynthos, a region of general low particle concentrations, as previously commented (Figure 5a). On average, it does not exceed 1.5 – 2 kg·km^{-2} of plastic particles in the open sea region and is lower than 1 kg·km^{-2} in the region between the island and the continent, which seem to be partially isolated (Figure 10a). This reflects the fact that the island shelters that area somehow preventing the open sea pollution to reach it. Nevertheless, the MPA is on the southern part of the island, affected by open sea conditions.

Additionally, we look into the seasonal variability of ML concentration. The aim is to identify if any seasonality can be expected from the remote pollution, and to assess if the observed variability in ML could be explained by remote factors or should be attributed to local sources. Our results show that, in winter, the concentration increases in the Ionian reaching values higher than 2 kg·km^{-2} in the surroundings of Zakynthos Island, while in summer it decreases to about half of that value (fig. 10b,c). However, the summer season also shows high variability, with std values close, or even larger, than the mean value (Figure 10d,f), while in winter the std/mean ratio is smaller (~0.5) (Figure 10e). The average depths of the particles oscillate between 20 and 40 m (Figure 11). Additionally, although local sources and the seasonality of tourism are not within the focus of this studies, these may be pathways to explain the high variability during the summer months. In summary, our results suggest that the effects of remote sources would be lower in summer, even if there is large variability with values ranging from close to 0 during the winter season.

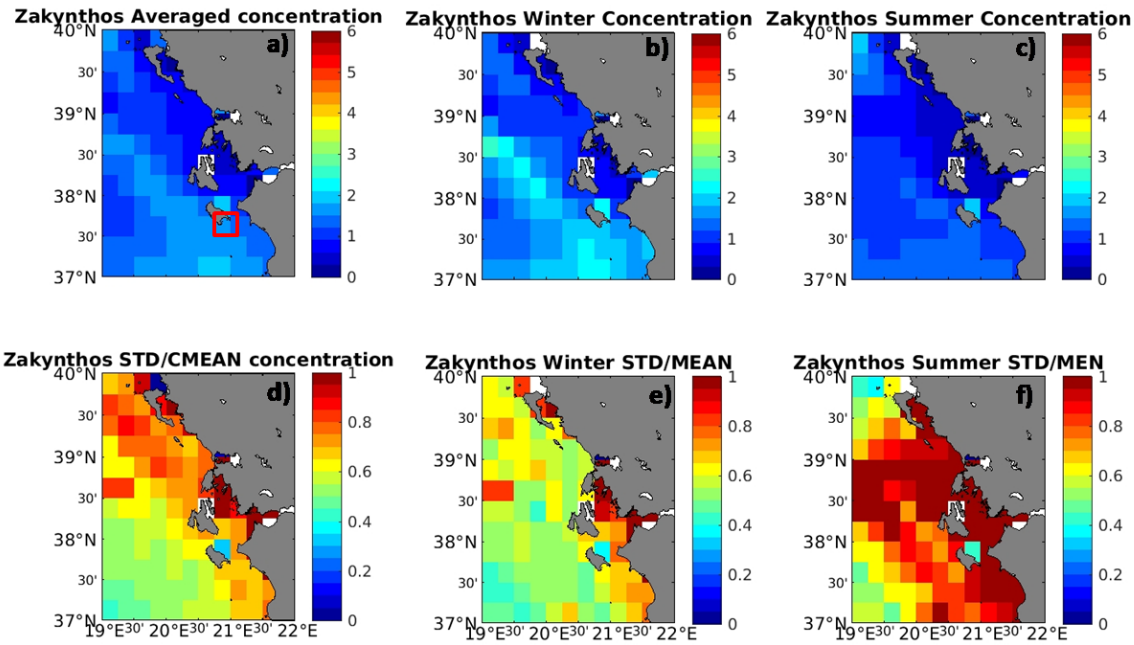

Figure 10. Summary of the results for Zakynthos National Park. a) Average concentration (kg·km^{-2}) b) Winter averaged concentration (kg·km^{-2}) b) Summer averaged concentration (kg·km^{-2}) d) Standard deviation – mean concentration ratio (kg·km^{-2}) e) Winter standard deviation – mean concentration ratio (kg·km^{-2}) f) Summer standard deviation – mean concentration ratio (kg·km^{-2}). The red square in panel a) marks the position of Zakynthos National Park.

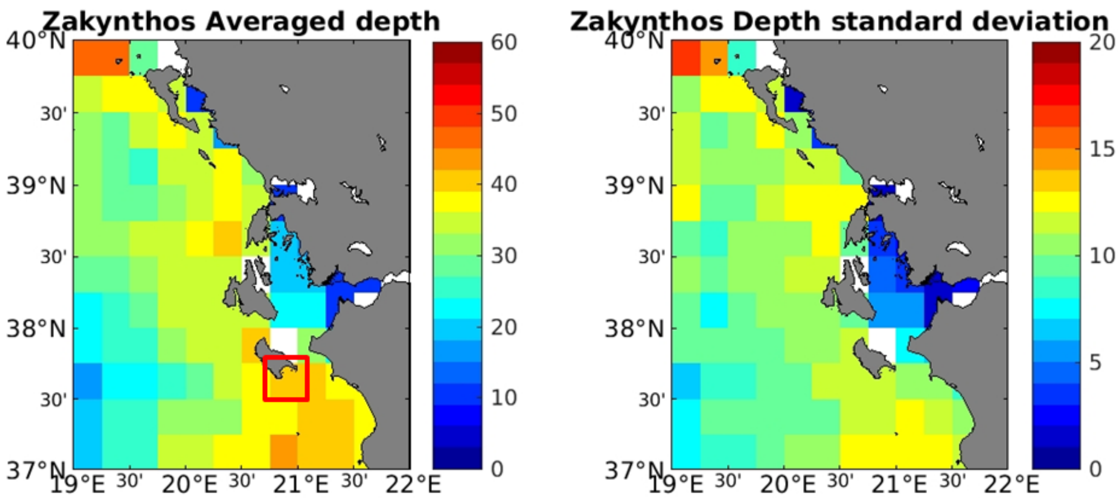

Figure 11. Average depth (m) and depth standard deviation at the particles at Zakynthos National Park. The red square marks the position of Zakynthos National Park.

3.3.4.2 Cabrera National Park

The Cabrera National Park (Spain) is located in the Balearic Sea, in the central region of the Western Mediterranean. This is a region of medium concentration of ML, with average values around 3 kg·km^{-2} (Figure 12a), but relatively close to regions with high concentrations in the north. The seasonality of the concentration is high in the whole region and also in the Cabrera National Park. The average concentration in the winter does not exceed 3 kg·km^{-2} while in summer it increases to values higher than 4.5 kg·km^{-2} (Figure 12b,c). Conversely, the variability is moderate (0.4 – 0.5), and decreases in summer to values lower than 0.3 (Figure 12d-f). The averaged depth of the 'neutral' particles ranges between 15 and 35 m (Figure 13).

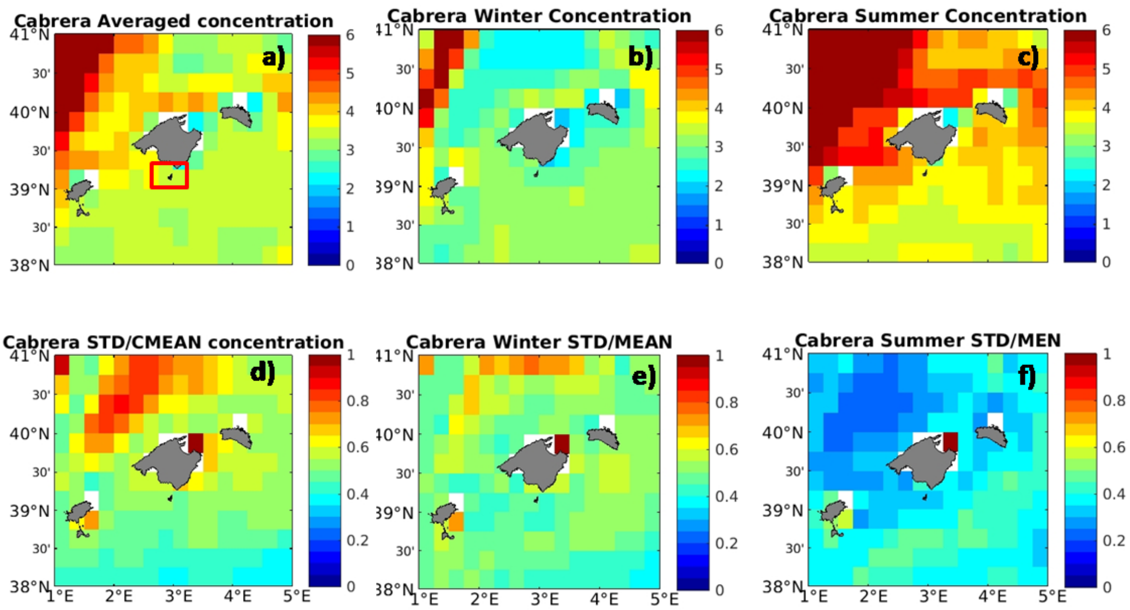

Figure 12. Summary of the results for Cabrera National Park. a) Average concentration (kg·km^{-2}) b) Winter averaged concentration (kg·km^{-2}) b) Summer averaged concentration (kg·km^{-2}) d) Standard deviation – mean concentration ratio (kg·km^{-2}) e) Winter standard deviation – mean concentration ratio (kg·km^{-2}) f) Summer standard deviation – mean concentration ratio (kg·km^{-2}). The red square in panel a) marks the position of Cabrera National Park.

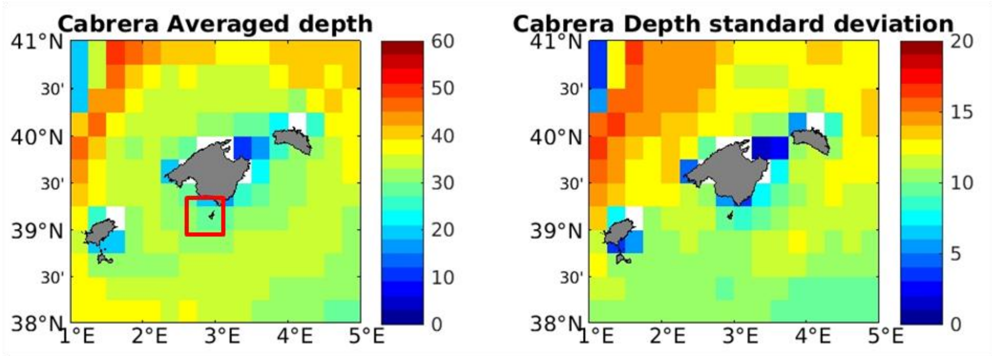

Figure 13. Average depth (m) and depth standard deviation at the particles at Cabrera National Park. The red square marks the position of Cabrera National Park.

3.3.4.3 Pelagos Sanctuary and Tuscany Archipelago National Park

The Pelagos sanctuary is a region located North of Sardinia, between the Tyrrhenian and the Ligurian Seas. The Tuscany Archipelago National park is located in the Tyrrhenian Sea, between Corsica and the Italian Coast. As commented in section 3.3.1, this is one of the areas with lower ML concentration compared to the other regions in the Mediterranean basin. Figure 14 shows that the concentration only exceeds 2.5 kg·km^{-2} in the coastal areas, due to the presence of cities. In the open sea it decreases lower than 1 2.5 kg·km^{-2} in east of Corsica and between 1.5 and 2 kg·km^{-2} in the Tuscany Archipelago region (Figure 14a). The seasonality is also more pronounced in the coastal areas, with an increase of the concentration in the winter and a decrease in the summer. In the open sea the seasonality is very low and the concentrations remain almost similar in summer and winter. The variability is relatively high in the whole region, ranging between 0.6 and 0.8, with an important increase in the summer when it reaches values higher than 0.9 in wide areas (Figure 14d-f). The depth where the 'neutral' particles suspend is deeper in the Ligurian Sea, oscillating between 25 and 45 m. In the Tuscany archipelago the particles suspend at shallower depths on average ranging between 15 and 25 m (Figure 15).

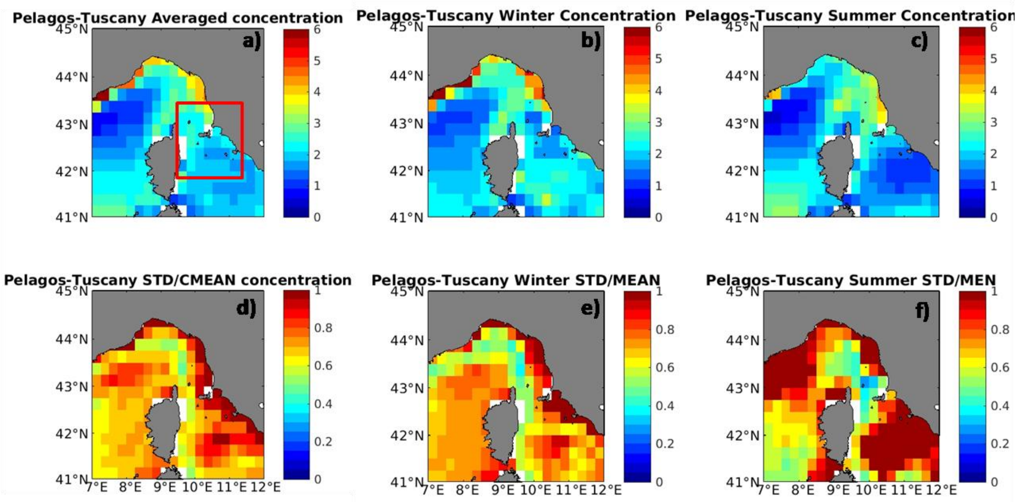

Figure 14. Summary of the results for Pelagos Sanctuary and the Tuscany Island National park. a) Average concentration (kg·km^{-2}) b) Winter averaged concentration (kg·km^{-2}) b) Summer averaged concentration (kg·km^{-2}) d) Standard deviation – mean concentration ratio (kg·km^{-2}) e) Winter standard deviation – mean concentration ratio (kg·km^{-2}) f) Summer standard deviation – mean

concentration ratio (kg·km^{-2}). The red square in panel a) marks the position of Tuscany Archipelago National Park.

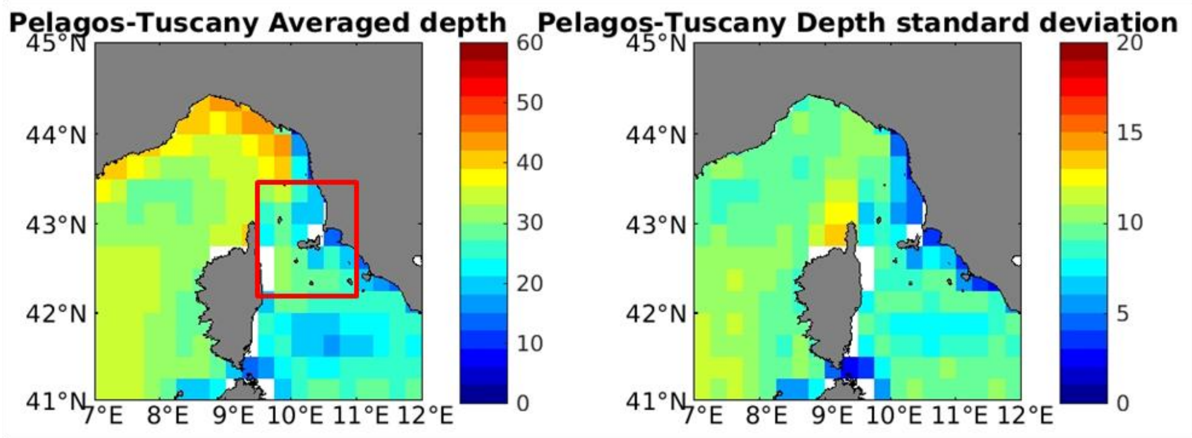

Figure 15. Average depth (m) and depth standard deviation at the particles at Pelagos Sanctuary and Tuscany Archipelago National Park. The red square marks the position of Tuscany Archipelago National Park.

3.3.5. Designing an operational forecasting system for ML concentrations

The objective of this section is to explore the feasibility of developing an operational forecasting system for marine litter in marine protected areas of the Mediterranean, which should be able to predict the areas and periods of larger concentrations. For this aim, the first step is to evaluate the sensitivity of the simulation results to the uncertainties derived from the modeling system limitations. Those existing limitations determine the predictability of the ML evolution. These uncertainties can be divided in three groups:

- Uncertainties in the release sources.
- Uncertainties in the modeled currents.
- Uncertainties in the initial conditions (the initial particles concentrations).

3.3.5.1 Sensitivity to uncertainties in the release sources

The distribution of the sources of ML has been designed based on previous works and some reasonable assumptions. However, there is no reliable information about the actual amount of pollutant releases from the different sources. On the other hand, one may think that once the pollution is in the open sea, the memory of the initial conditions is lost and the final results are unaffected by them. In order to test that extent, we run the sensitivity tests described in 3.2.2.3. The results are shown in Figure 16. If all the ML was released homogeneously along the coast the final concentration would be very low in the open Sea, except for the Aegean and Adriatic. Conversely, starting from a heterogeneous release of ML the final concentration would be much higher, with wide accumulation areas in the Ionian and Tyrrhenian Seas. This points out that the initial particles distribution is critical in the subsequent evolution of the system (note that the color scale is different).

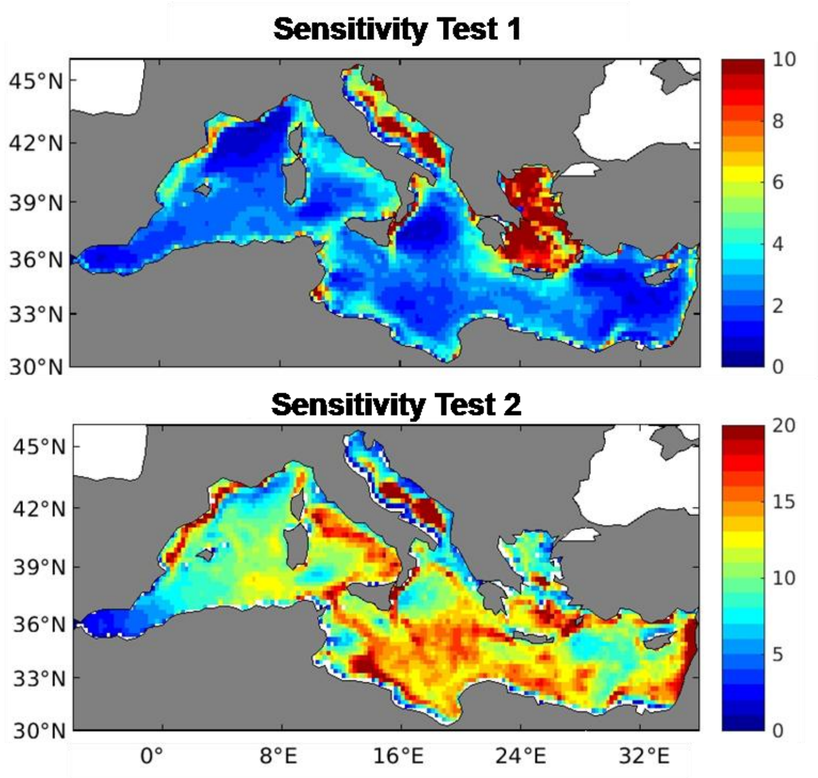

Figure 16. Average concentration for the TEST1 (upper panel) and TEST2 (lower panel) simulations (see section 2.2.3). Units are arbitrary.

3.3.5.2. Sensitivity to the uncertainties in the modeled currents.

The ability of the ocean models to reproduce the currents of the Mediterranean Sea is limited, and depends on diverse factors such as the model resolution, the boundary conditions or the data assimilation. Figure 17 summarizes the results of the comparison between 10 simulations, carried out using 3 different ocean models for the Mediterranean, with a database of current measurements from 155 current meters distributed over the whole basin (Soto-Navarro et al. *in preparation*). The x-axis represents the average time correlation with the measurements and the y-axis the ratio between the models and observations Eddy Kinetic Energy (EKE). A perfect simulation would have a correlation value and an EKE ratio of 1. We see that all the simulations are quite far from these perfect results. This distance gives an idea of the uncertainties derived from using modeled currents. Despite these limitations, the models have proven its skills in reproducing the main characteristics of the Mediterranean circulation and are able to properly reproduce complex processes such as the intermediate and deep water formation or the spatial pattern of the mesoscale field (Beuvier et al. 2010, 2012; Escudier et al. 2016; Hamon et al. 2016). On the other hand, the numerical simulations are the only tool that allows us to address the proposed objective and the simulations available are the most recent and accurate to carry out this objective.

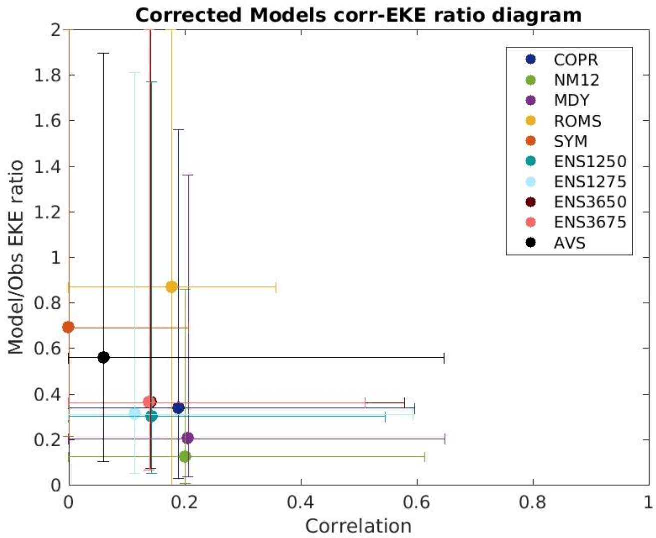

Figure 17. Average correlation between 10 simulations and a dataset of current measurements over the Mediterranean basin vs. ratio between the EKE of the simulations and the observations (from Soto-Navarro et al. in preparation).

In order to have an estimate of the impact of uncertain currents we do the following assumption. We consider that the time variability in the circulation is similar to the existing uncertainties on that circulation. Obviously, this is a simplifying approach but provided that no accurate estimates of the actual uncertainties exist, it will give us a first approach to the impact of uncertainties in the current field. In particular, we look at the RMS difference among the 120 simulations for a given time lag. As all of them start from the same initial conditions, the discrepancies among them would be the result of having different circulation patterns. Figure 18 illustrates how this source of uncertainty affects the results after 120 days of simulation. It can be seen that uncertainties are larger in regions where larger concentrations are expected, but in most cases it represents half of the actual value. In some areas like the Gulf of Gabes or the Alboran Sea, the impact of uncertain circulation is even lower.

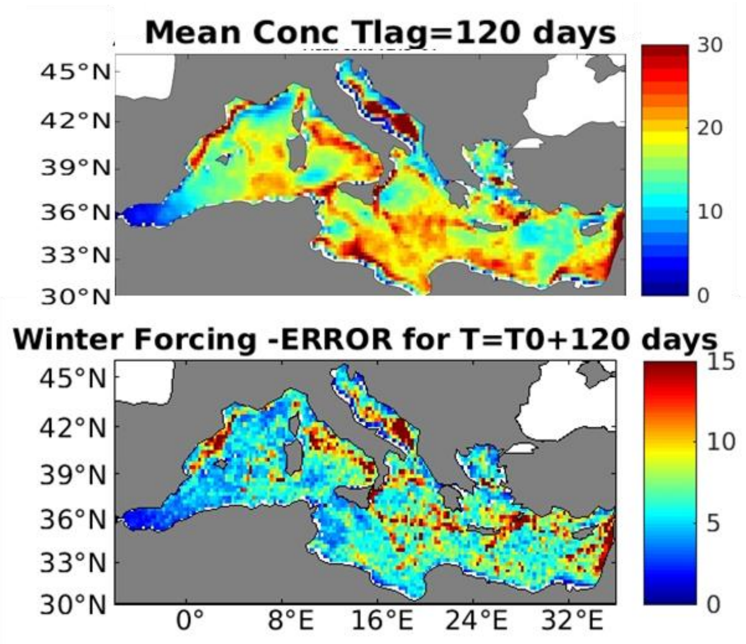

Figure 18. Average concentration and forcing error 120 days after de beginning of the simulation (arbitrary units).

3.3.5.3 Sensitivity to the initial conditions

Another source of error in the prediction of the ML concentration is the initial values used. The total amount of plastic in the basin and its distribution are based on estimations from model simulations due to the lack of actual observational data. In order to assess how error in the initial conditions would determine the accuracy of predictions we do the following. We first compute the RMS difference among all the simulations available for a given day (t0). Then we compute the RMS difference for the same simulations but at different time lags (7, 15, 21 and 31 days). As the different simulations have been run using the exact same velocity fields, the final RMS difference would be only due to the initial conditions.

Figure 19 shows a comparison of initial vs final RMS difference for different time lags (in arbitrary units). The relation is almost linear although after a certain threshold for the initial RMS difference, the final RMS difference somehow saturates. The behaviour is similar for the different time lags, although the slope is higher for shorter time lags. In other words, for predictions at 7 days, the uncertainty in the prediction, even if the current pattern was perfectly known, would be the same as the initial uncertainty. For predictions at 30 days, the final uncertainty would be a bit smaller than the initial uncertainty, but still strongly dependent on it. In other words, it is necessary to have accurate observational data to initialize the simulation to trust the predictions made by any modelling system. In certain regions this may not be the case if the source of pollution is well monitored. For instance, close to a river mouth the predictions could be better, but in general our results suggest that implementing a forecasting system for ML pollution would need further improvements.

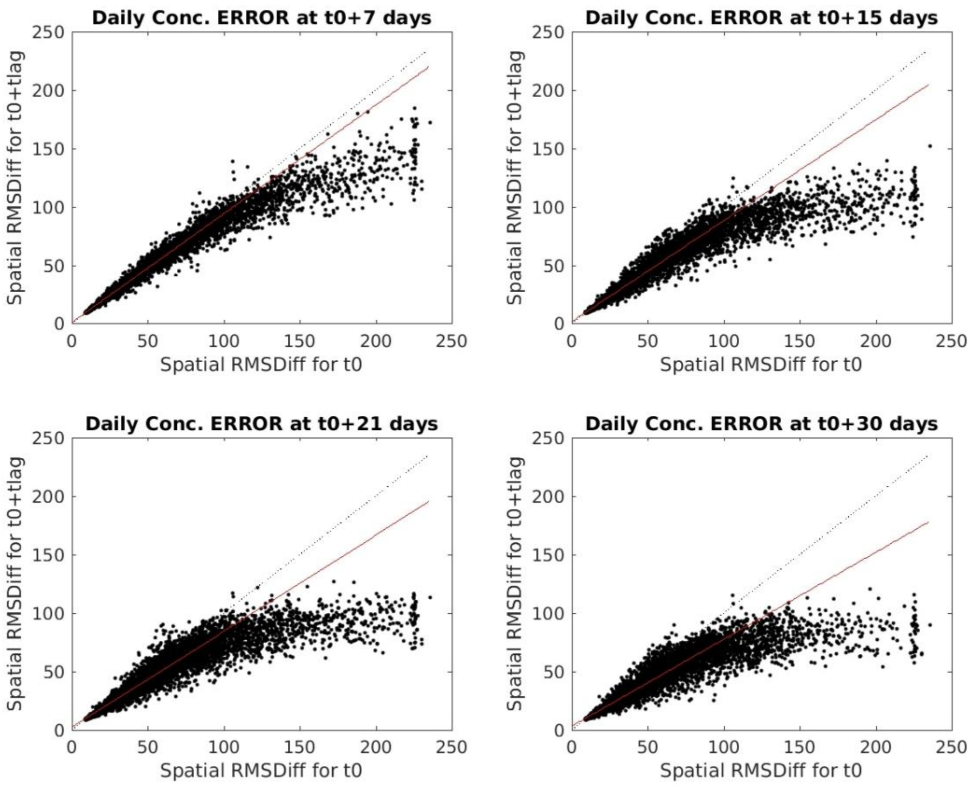

Figure 19. Spatial RMSDiff of the simulation at the initial time (t0) vs. Spatial RMSDiff at different lags (7 days, 15 days, 21 days and 30 days). Units are arbitrary.

3.4. Discussion

3.4.1 Concentration/dispersion areas in the Mediterranean basin

One of the main objectives of forecasting marine litter was to perform a realistic simulation of the ML distribution over the whole Mediterranean basin in order to identify areas of accumulation/dispersion. The results exposed in section 3 shows that in most part of the Western Mediterranean, and especially along the Catalan Coast and the Gulf of Lions, the ML concentration is very high due to the combination of the surrounding large cities and, to a lesser extent, the Rhone and Ebro rivers (Figure 5). In the Eastern basin, the accumulation areas are found in the Adriatic and Aegean Seas, and the easternmost coast of the Levantine basin. In this case, the main ML contribution comes from the rivers Nile and Po, and the outflow through the Dardanelles Strait. This latter contribution could be overestimated in the simulation as it is not clear what is the actual amount of plastic released from the Black Sea which reaches the Mediterranean Sea. If this contribution is removed, the concentration is drastically reduced in the Northern Aegean but it does not affect the rest of the Southern Aegean and neither the rest of the eastern basin. This is an interesting result because it means that the region is somehow isolated from the rest of the Mediterranean and hence the inputs from the Dardanelles Strait would only affect the local ML concentrations. The dispersion areas (i.e. areas with lower than average concentrations) in the Western Mediterranean are found in the Alboran Sea, the French coast east from the Gulf of Lions and the Tyrrhenian Sea. In the Eastern basin, the central part of the Levantine basin and the Northern Ionian Sea are the areas with lower concentrations.

Up until now, and to our knowledge, there are only two previous studies that have dealt with the simulation of ML dispersion across the Mediterranean basin. Mansui et al. (2015) performed a 1 – year simulation starting from a homogeneous ML distribution over the basin. The authors found three main accumulation zones: the central Western Mediterranean, the Tyrrhenian Sea and the Southeast Ionian Sea. Our results only agree with the first one, but they are not suitable of a detailed comparison because the initial concentrations in our simulation are very different. When the Mansui et al, (2015) results are compared to our experiment TESTRUN2, in which the initial concentrations where homogeneously distributed throughout the basin, a better agreement is found (Figure 16). In this simulation the accumulation zones of the South Ionian and Tyrrhenian Sea are present. On the other hand, additional areas of high concentration are observed in the Adriatic Sea and the Levantine basin that are not identified by these authors.

Liubartseva et al. (2018) carried out a 4.5- year simulation analogous to the one of this study, starting with a realistic ML distribution but also including beaching and sedimentation processes in the particles evolution. These two processes remove particles from the simulation and are essential to understand the differences between their results and ours. In their work the authors estimate a half life of the plastic particles between 7 and 80 days depending on the location of the source. In our simulation, the beaching and sedimentation processes are not included so all the particles remain in the sea. Therefore, our estimated concentrations are much higher but also the spatial distribution differs. Nonetheless, the location of accumulation/dispersion areas can be qualitatively compared. The results for the Western Mediterranean are in good agreement with ours, with higher concentrations in the Catalan Coast, moderate in the central area of the sub-basin and lower in the Tyrrhenian Sea. For the Eastern Mediterranean more discrepancies are found. Both simulations agree in finding accumulation zones in the North Adriatic and North of Cyprus, but their study also finds an area of relatively high concentration in the central Ionian Sea, which is not present in our simulation. Furthermore, their results show very low concentration in the Aegean Sea in contrast with our estimations, even after removing the Dardanelles contribution.

3.4.2 Design of field campaigns

A second important objective of this task is the application of the results to the design of field campaigns. For this aim, in addition to the identification of the accumulation/dispersion areas, the description of the temporal variability of ML concentration and the vertical distribution performed in section 3.2 and 3.3 are extremely useful. The areas with lower variability/mean ratios are regions where the measurement will be more representative of the mean conditions. The results show that these areas coincide with the zones of less average concentration (Figure 6). It is also important to consider the seasonal variability described in figure 7, which only shows noticeable differences between the summer and winter concentrations in the Western Mediterranean associated to the seasonality of the circulation.

Another important aspect is the vertical distribution of ML. The estimation of the particles vertical distribution has shown that most of the simulated 'neutral' particles of the basin are below the surface, in a range of 10 – 50 m on average, but with large spatial variations (Figure 8,9). This information should be considered when designing scientific surveys. However, as mentioned in section 2.2.1, the density of the particles in the simulation is neutral, i.e. is the same than that of the surrounding waters. All the vertical movements are hence consequence of the vertical displacements of the water masses in the ocean model. This is only representative of a fraction of the most common plastic produced. There is another fraction of polymers that have positive buoyancy and float, and a larger fraction with densities larger than water that will sink (table 1). All these types of plastics are not being considered in this simulation. However, it is clear that sampling ML in the surface would only capture a (probably small) fraction of the actual amount of ML existing throughout the water column.

As a proxy to illustrate the effect of the sedimentation, a simulation using the same initial concentrations but considering particles with a moderate sedimentation velocity of W_{sed} = 1 cm·s^{-1} has been run for the period 2003 -2009. The results of the average concentration are shown in Figure 20. We can see that most of all the particles rapidly sink; reaching the bottom very close to their initial positions and remaining there for the whole simulation period. The ML is concentrated in a narrow stripe close to the coast, corresponding to the position of the cities and river mouths (fig. 4). Only the small fraction corresponding to the ship – lanes inputs can be found in the open sea. This simulation is representative of the expected behavior for a large fraction of ML released into the ocean (i.e. with densities larger than seawater). Nevertheless, it should be taken into account that we release the particles in the open sea, while in practice the heavy litter would have difficulties to leave the coastal zone, which may result in the overestimation of the concentrations.

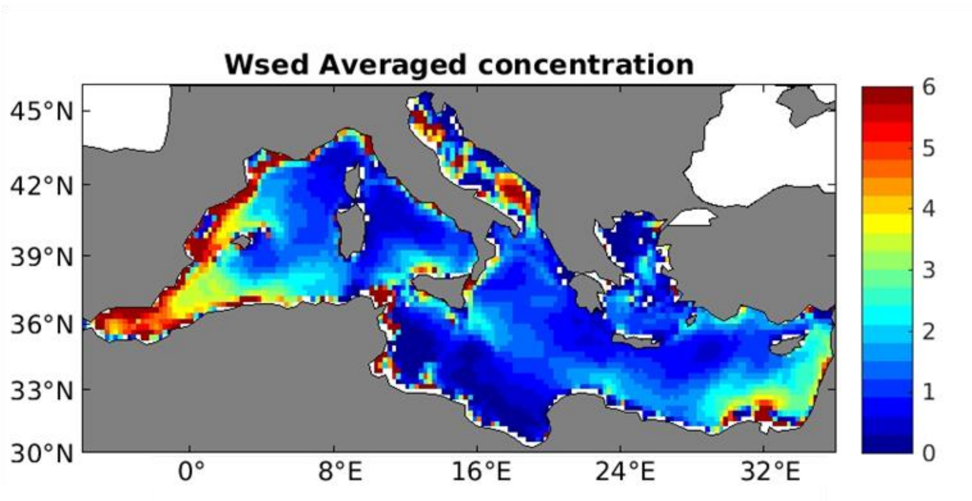

Figure 20. Average concentration (kg·km^{-2}) for a sedimentation constant velocity of Wsed = -1cm/s.

3.4.3 Feasibility of an operational prediction system

The possibility of developing accurate operational predictive models for the MPAs relies on the predictability of the system. In section 3.5 the most important sources of uncertainty that would affect the quality of a predictive model have been explored and the results show that unfortunately the system would lack the desired accuracy. The uncertainties inherent to the use of modeled currents, which induce inaccuracies in the particles trajectories, which can induce errors in the ML concentrations of up to 50%. However, the critical issue is the lack of information about the actual initial concentration of ML. Any inaccuracies in that field would directly propagate as errors in the predicted ML concentrations. Currently the information of ML concentration based on observations is very sparse in time and space yet is insufficient to be used as model initial conditions (Cózar et al. 2015; Faure et al. 2015; Ruiz-Orejón et al. 2016; van der Hal et al. 2017; Arcangeli et al. 2018). Therefore, the operational systems could only provide forecasts of potential accumulation/dispersion areas but they would be of little use unless good information on the initial conditions could be provided (i.e. close to well-known sources of pollution).

3.5. Conclusions

In response to the main objectives within task 3.5, a ten year simulation of the ML dispersion in the Mediterranean basin has been carried out. The simulation has been performed using current fields from a state-of-the-art high resolution simulation (NEMOMED36), in combination with the Lagrangian IBM Ichthyop 3.3, covering the period 2003 – 2013. A realistic distribution based on estimations of the plastic inputs from cities, rivers and ships over the whole basin have been used as initial conditions. The results have been used to identify the areas of ML accumulation/dispersion along the basin. The temporal variability of the concentration and the vertical distribution of the particles have also been described.

A special focus has been given on four MPAs (Zakynthos, Cabrera, Pelagos and Tuscany) in the Mediterranean Sea. For these 4 MPAs we did not considered any further local inputs of plastics, so that model results refer only to transported plastic waste. The results indicate that Cabrera is the most exposed MPA to ML originated remotely. Pelagos Sanctuary and Tuscany Archipelago show about half of the expected concentrations found in Cabrera, while Zakynthos is the MPA with the lowest ML concentrations. Another aspect that has been assessed is the expected seasonal variability in those regions. The goal was to assess the seasonal variability of transported litter and compare it to the observed ML. In this way we may identify the importance of remote vs local sources. Our results suggest that in Zakynthos National Park, the summer concentrations due to remote sources are lower. In the Pelagos Sanctuary and the Tuscan Archipelago, there is no clear seasonality while in Cabrera National Park, the concentrations increase in summer (~60%).

A word of caution is needed about the realism of the magnitudes shown in this work. First, the whole amount of ML released into the sea (100kTn/year) is considered to leave the coastal zone and to behave as neutrally buoyant particles. It could be expected that the actual fraction of ML under those conditions would be much lower. An example of the behavior of sinking plastics has also been produced to illustrate the difference in the final concentration. Second, our simulations do not include beaching as it is not clear what would be the appropriate way to simulate it. In any case, our simulations have no sinks of particles, so the total concentrations are also probably overestimated, although we don’t know by how much. Nevertheless, the spatial distribution is expected to be accurate, so observational records could be used to calibrate our results.

The feasibility of developing an operational forecasting system for the MPAs has also been explored. Our conclusion is that further improvement is needed due to large uncertainties in the actual concentrations of ML predictions, even under the hypothetical case of reproducing perfectly the actual currents.

3.6. References

Arcangeli A, Campana I, Angeletti D, et al (2018) Amount, composition, and spatial distribution of floating macro litter along fixed trans-border transects in the Mediterranean basin. Mar Pollut Bull 129:545–554. doi: 10.1016/j.marpolbul.2017.10.028

Arsouze T, Beuvier J, Béranger K, et al (2013) Sensitivity Analysis of the Western Mediterranean Transition inferred by four companion simulations. Rapp Comm Int Mer Médit 32442. doi: 10.1029/2008GL035146.2

Beuvier J, Béranger K, Brossier CL, et al (2012) Spreading of the Western Mediterranean Deep Water after winter 2005: Time scales and deep cyclone transport. J Geophys Res Ocean 117:. doi: 10.1029/2011JC

Beuvier J, Sevault F, Herrmann M, et al (2010) Modeling the Mediterranean Sea interannual variability during 1961-2000: Focus on the Eastern Mediterranean Transient. J Geophys Res Ocean 115:. doi: 10.1029/2009JC005950

Cózar A, Sanz-Martín M, Martí E, et al (2015) Plastic accumulation in the mediterranean sea. PLoS One 10:1–12. doi: 10.1371/journal.pone.0121762

D'Agostini A, Gherardi DFM, Pezzi LP (2015) Connectivity of marine protected areas and its relation with total kinetic energy. PLoS One 10:1–19. doi: 10.1371/journal.pone.0139601

Déqué M, Piedelievre JP (1995) High resolution climate simulation over Europe. Clim Dyn 11:321–339. doi: 10.1007/BF00215735

Ducharne A, Golaz C, Leblois E, et al (2003) Development of a high resolution runoff routing model, calibration and application to assess runoff from the LMD GCM. J Hydrol 280:207–228. doi: 10.1016/S0022-1694(03)00230-0

Džoić T, Beg Paklar G, Grbec B, et al (2017) Spillover of the Atlantic bluefin tuna offspring from cages in the Adriatic Sea: A multidisciplinary approach and assessment. PLoS One 12:1–20. doi: 10.1371/journal.pone.0188956

Escudier R, Renault L, Pascual A, et al (2016) Eddy properties in the Western Mediterranean Sea from satellite altimetry and a numerical simulation. J Geophys Res Ocean 121:3990–4006. doi: 10.1002/2015JC011371

Faure F, Saini C, Potter G, et al (2015) An evaluation of surface micro- and mesoplastic pollution in pelagic ecosystems of the Western Mediterranean Sea. Environ Sci Pollut Res 22:12190–12197. doi: 10.1007/s11356-015-4453-3

GESAMP (2019) Guidelines for the monitoring and assessment of plastic litter in the ocean. GESAMP Reports Stud 99:130

Hamon M, Beuvier J, Somot S, et al (2016) Design and validation of MEDRYS, a Mediterranean Sea reanalysis over the period 1992-2013. Ocean Sci 12:577–599. doi: 10.5194/os-12-577-2016

Jambeck JR, Gayer R, Wilcox C, et al (2015) The ocean. Clim Chang 2014 Impacts, Adapt Vulnerability Part B Reg Asp Work Gr II Contrib to Fifth Assess Rep Intergov Panel Clim Chang 347:1655–1734. doi: 10.1017/CBO9781107415386.010

Jouanneau N, Sentchev A, Dumas F (2013) Numerical modelling of circulation and dispersion processes in Boulogne-sur-Mer harbour (Eastern English Channel): Sensitivity to physical forcing and harbour design. Ocean Dyn 63:1321–1340. doi: 10.1007/s10236-013-0659-4

Lett C, Verley P, Mullon C, et al (2008) A Lagrangian tool for modelling ichthyoplankton dynamics. Environ Model Softw 23:1210–1214. doi: 10.1016/j.envsoft.2008.02.005

Levitus S, Antonov J, Boyer T (2005) Warming of the world ocean, 1955-2003. Geophys Res Lett 32:1–

4. doi: 10.1029/2004GL021592

Liubartseva S, Coppini G, Lecci R, Clementi E (2018) Tracking plastics in the Mediterranean: 2D Lagrangian model. Mar Pollut Bull 129:151–162. doi: 10.1016/j.marpolbul.2018.02.019

Mansui J, Molcard A, Ourmières Y (2015) Modelling the transport and accumulation of floating marine debris in the Mediterranean basin. Mar Pollut Bull 91:249–257. doi: 10.1016/j.marpolbul.2014.11.037

Marshall J, Schott F (1999) Open-ocean convection: Observations, theory, and models. Rev Geophys 37:1–64. doi: 10.1029/98RG02739

Millet B, Pinazo C, Banaru D, et al (2018) Unexpected spatial impact of treatment plant discharges induced by episodic hydrodynamic events: Modelling Lagrangian transport of fine particles by Northern current intrusions in the bays of marseille (France). PLoS One 13:1–25. doi: 10.1371/journal.pone.0195257

Millot C, Benzohra M, Taupier-Letage I (1997) Circulation off Algeria inferred from the Mediprod-5 current meters. Deep Res Part I Oceanogr Res Pap 44:1467–1495. doi: 10.1016/S0967-0637(97)00016-2

Poulain P-M, Bussani A, Gerin R, et al (2013) Mediterranean surface currents measured with drifters: From basin to subinertial scales. Oceanography 26:38–47. doi: 10.5670/oceanog.2011.65

Roether W, Manca BB, Klein B, et al (1996) Recent Changes in Eastern Mediterranean Deep Waters. Science (80-) 271:333–335. doi: 10.1126/science.271.5247.333

Ruiz-Orejón LF, Sardá R, Ramis-Pujol J (2016) Floating plastic debris in the Central and Western Mediterranean Sea. Mar Environ Res 120:136–144. doi: 10.1016/j.marenvres.2016.08.001

van der Hal N, Ariel A, Angel DL (2017) Exceptionally high abundances of microplastics in the oligotrophic Israeli Mediterranean coastal waters. Mar Pollut Bull 116:151–155. doi: 10.1016/j.marpolbul.2016.12.052

Vörösmarty CJ, Fekete BM, Tucker BA (1996) Global river discharge database RivDis v1.0. UNESCO Tech Doc Hydrol SC-96/WS/2:1–1008

4. Case study: Modelling the sources and the transport of floating plastic litter in the area of Cabrera Archipelago Maritime-Terrestrial National Park, Western Mediterranean Sea

4.1. Local modelling approach

The Cabrera Archipelago National Maritime-Terrestrial Park (CNP) is one of the main protected areas in the Western Mediterranean Sea, also affected by Marine Litter (ML) pollution. In this section, we describe the outputs of a model we developed in order to identify ML hotspots and their variability in the area of CNP. Previous numerical models of ML dispersion covering the Balearic Sea include models at global (Eriksen et al. 2014; L. C.-M. Lebreton, Greer, and Borrero 2012) and Mediterranean scale (Liubartseva et al. 2018; Zambianchi, Trani, and Falco 2017; Mansui, Molcard, and Ourmières 2015). While other regional numerical models have been implemented in other regions of the Mediterranean, like the Adriatic (Liubartseva et al. 2016), the Ligurian (Fossi et al. 2017; Aliani and Molcard 2003) or Aegean Seas (Politikos et al. 2017), no high resolution regional models have been developed specifically focusing on the ML dispersion in the Western Mediterranean to date. The 2km-resolution WMOP hydrodynamic model developed at SOCIB is used in this study to generate such refined ML dispersion estimates in the area of CNP.

4.2. Materials and methods

4.2.1. Modelling floating litter inputs into the Western Mediterranean Sea

4.2.1.1. Land-based sources

To model floating litter inputs into the Western Mediterranean Sea, recent plastic emission estimates of coastal population (Jambeck et al. 2015) from national to regional level were downscaled given that all countries in the Western Mediterranean Sea, except Algeria, share their coasts with other basins (i.e., Atlantic Ocean, Central Mediterranean Sea). Plastic waste estimates were aggregated into 200 input points that were located regularly across the coastline of the study area (Figure 1) taking into account the increase in summer tourism.

For land based sources, a recent global database of river plastic emissions was used (Lebreton et al. 2017). From the 583 river inputs located within the study area, we filtered out those that represented less than 0.001% of the plastic emissions (n=416, Figure 1). From the selected 167 river inputs, we used rainfall data to assign lower, midpoint and upper plastic emissions estimates on a daily basis.

4.2.1.2. Ocean-based sources

To estimate plastic emissions, we assumed that ocean-based sources accounted for 20% of the overall plastic emissions (Liubartseva et al. 2018). We used an original AIS database generated by SOCIB using MarineTraffic API, which covers the Western Mediterranean from 2012 to present. This database included raw AIS data (>700 million ship positions of GPS data at 5-min intervals). Vessel types were categorized into three groups (Koutsodendris et al. 2008; Tubau et al. 2015): domestic (i.e. cargo, passenger and tanker vessels), fishing and recreational. A gridded product was calculated on a daily basis to estimate navigation time on each cell (Figure 1). Similarly to previous work (Liubartseva et al. 2018), random locations and dates of marine inputs were distributed proportionally to navigation time estimates per vessel category.4.2.2. Modelling the transport of particles

A seven-year long free-run simulation of the 2km-resolution WMOP model (Juza et al. 2016; Mourre et al. 2018) was used to describe the variability of surface currents over the period 2012-2014. The daily average Stokes drift provided by the CMEMS Mediterranean Sea 2006-2017 waves hindcast (Korres et al., 2019) was added to these currents to represent the contribution of surface ocean waves. Using these total currents, a Lagrangian trajectory model (based on the TRACMASS algorithm)(Döös, Kjellsson, and Jönsson 2013) was applied to simulate ocean trajectories from land-based (i.e. coastal population and rivers) and ocean-based sources (i.e. marine traffic) of marine litter pollution across the Western Mediterranean basin. Particles were released every 3 days and drifted during a 6-month period driven by model surface currents. For this application we modified the outputs of trajectory model to store the origin, mass weight, and age of all individual particles. The Lagrangian model system stopped the simulation of a particle when it reached the coast or the boundaries of the oceanographic model domain. However, beaching of the particles might not be permanent. Particles can either be washed off from the coast to the surface or remain within the coast moving at very low speeds. Following previous works (Liubartseva et al. 2018), we conducted a post-processing of the simulated trajectories and defined that a particle reached the land definitely when remained within the coastline for a period of 5 days or longer.

4.3. Floating marine litter in Cabrera National Park

Simulations were analyzed in terms of beaching events and accumulation zones in the area of Cabrera National Park and surrounding waters, south of Mallorca Island in Figure 1. The analysis covered a 3-year integration period starting in May 2012, after an initial period of 4 months of spin-up, which allowed to distribute particles over the basin from initial conditions in January 2012. Floating particles were aggregated in geographical bins with a horizontal resolution of 0.1 degrees on a daily basis, and averaged along the study period. Similarly, beached particles in Cabrera National Park were aggregated on a daily basis and standardized by the coastline length of Cabrera (59 km) (Balaguer et al. 2019).

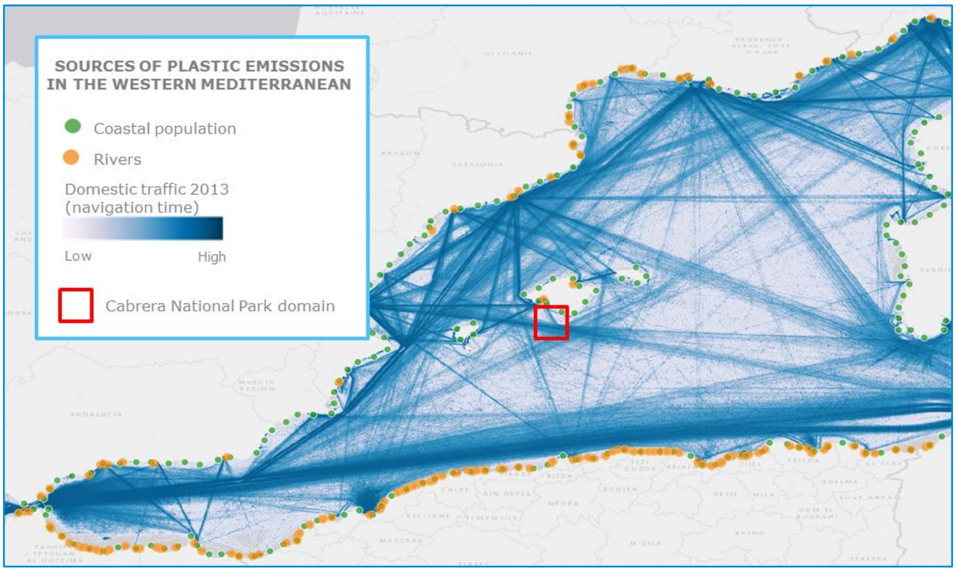

Figure 1. Spatial distribution of floating litter inputs in the Western Mediterranean.

4.4. Results and discussion

4.4.1. Plastics floating on the sea surface

The spatial distribution of the averaged floating plastic at the surface in the area of the CNP for the period 2012-2014 is illustrated in Figure 2. Concentrations have been averaged over the four seasons to characterize the associated seasonal variability. The figure shows a significant increase of the plastics concentration in summer and autumn with respect to winter and spring, with a marked peak in the summer season. This variability could be directly related to the annual variability of plastics inputs associated with tourism. While the average concentration of plastics simulated in these experiments in the area of the CNP is around 2 kg km^{-2} in winter, it reaches 10 kg km^{-2} in summer.

Moreover, the spatial distribution of plastic concentration around Cabrera Island is not homogeneous, the eastern side showing a concentration on average twice as large as that of the western side.

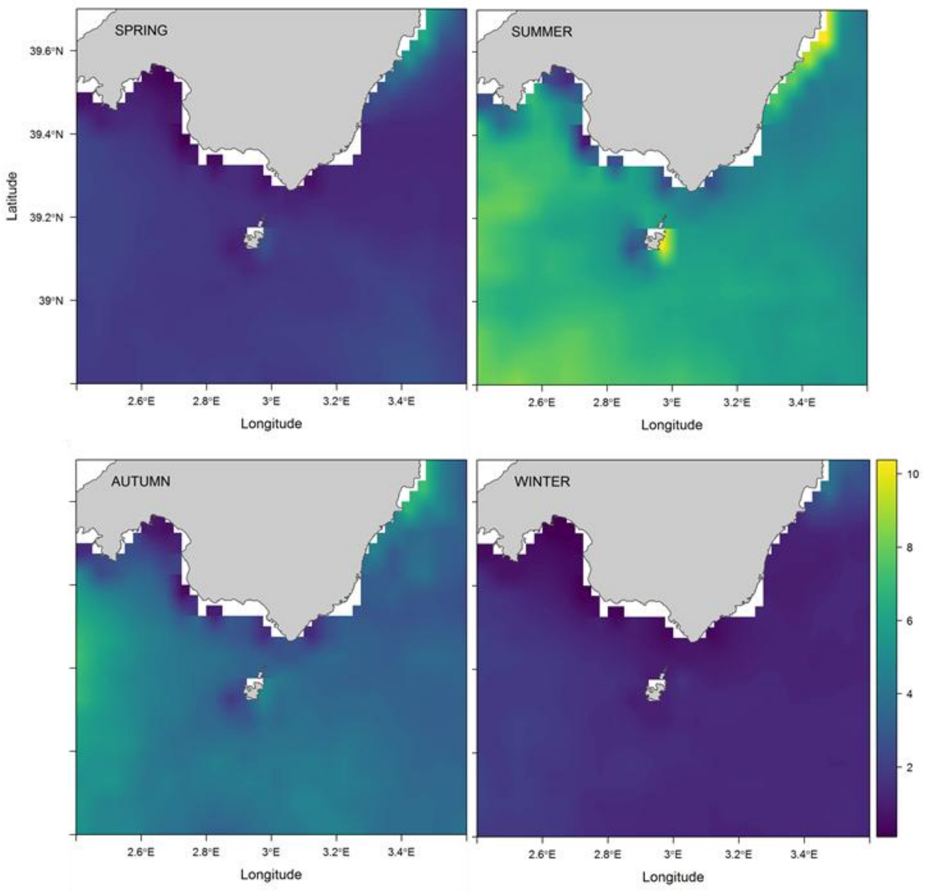

Figure 2. Averaged map of plastic litter concentration (kg km^{-2}) at the sea surface per season for the period 2012-2014.

4.4.2. Plastics reaching Cabrera National Park

4.4.2.1. Origin

Figure 3 provides an illustration of the virtual particles trajectories reaching CNP for a given starting date, allowing us to track the origin of the particles reaching this marine protected area. The map shows all the particles that were released on 1 August 2015 and that reached the area of CNP afterwards. It reveals the diversity of origin locations potentially affecting the CNP.

Based on this kind of analysis, we processed all the particles released during 2012-2014 in order to characterize the main origin areas of the particles that ended up in Cabrera. Figure 4 presents the spatial distribution of these origin locations. The map shows that the main areas of origin of CNP ML are the coasts of Mallorca and Ibiza islands, the Iberian peninsula and the Moroccan and Algerian shorelines. Land-based sources are found to account for approximately half of the ML reaching the CNP. Considering their origin by country, the simulations indicate that Algeria would be the main contributor to plastic litter in CNP, followed by Spain and Morocco. While Spain contributes with the closest land-based inputs to CNP, the higher contributions of Algeria and Morocco would be attributed to their higher rates of mismanaged plastic treatment, a factor that placed these two countries among the top 20 countries of mismanaged plastic waste at global level (Jambeck et al. 2015).

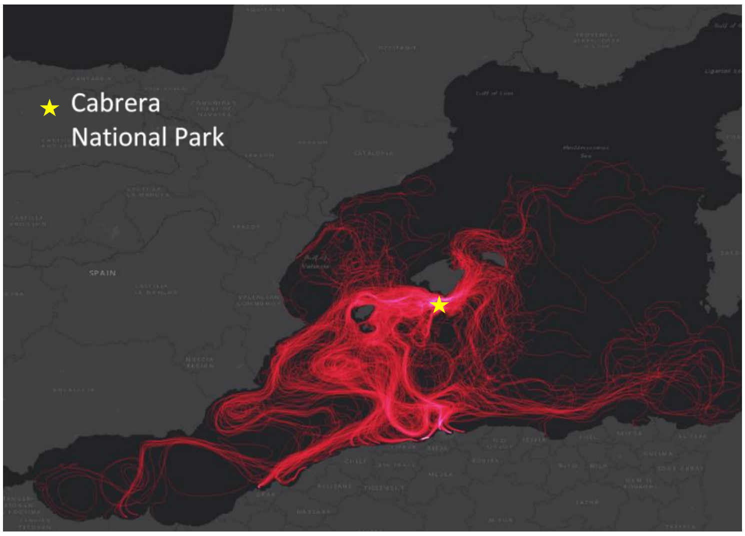

Figure 3. Virtual Lagrangian particles released on 1st Aug 2015 from coastal population inputs that reached Cabrera National Park.

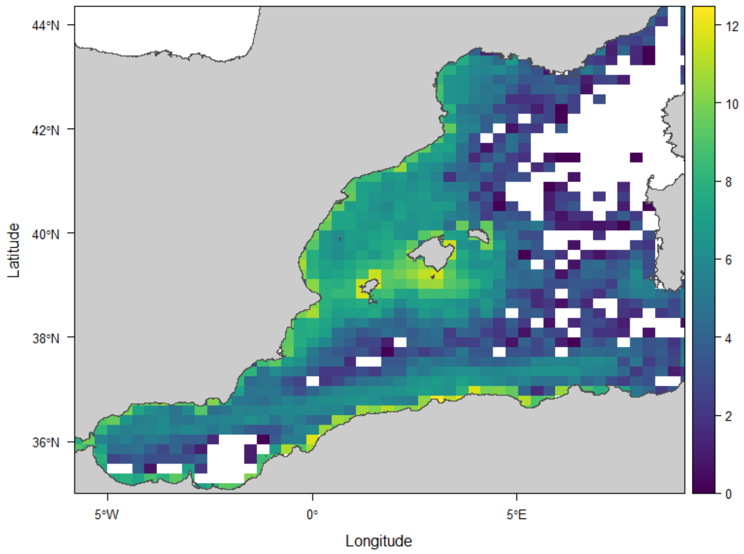

Figure 4. Spatial distribution of the origin location of particles that reached Cabrera National Park.

4.4.2.2. Beached litter

The daily flux of beached plastics into the coastline was 4.91 ± 10.28 kg km^{-1} day^{-1} (mean ± SD). In terms of orders of magnitude, this result is in good agreement with a previous model (Liubartseva et al. 2018), that reported an average for the overall Balearic Islands of 4.6 kg km^{-1} day^{-1}.

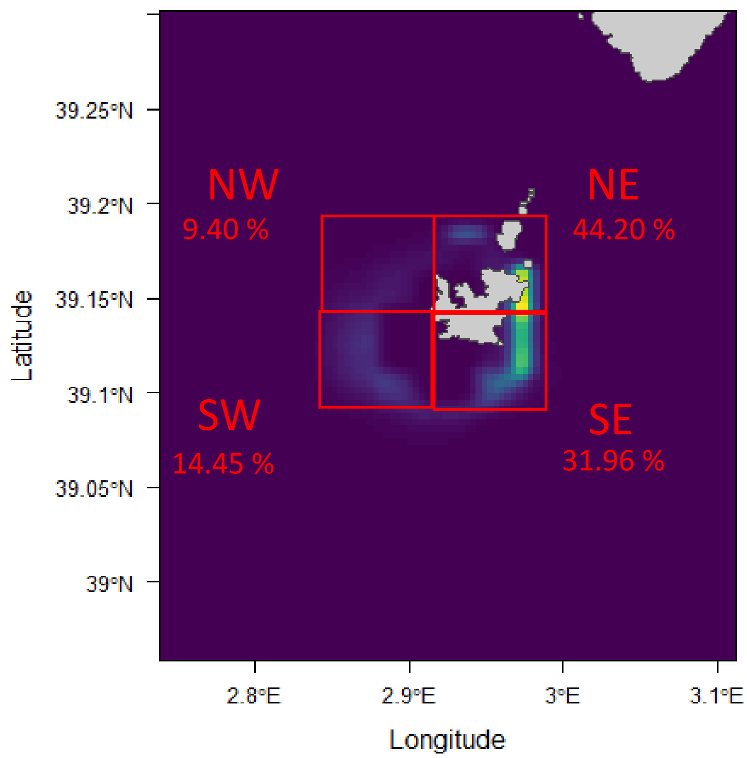

Figure 5. Density map of beached particles with percentage contribution per geographical quadrant around Cabrera Island.

The analysis of the spatio-temporal variability of the beached particles is illustrated in Figure 2 and Figure 6. Daily distribution of plastic litter fluxes (kg km-1 day-1) onto Cabrera National Park coastlines per quadrant. The blue lines represent the 30-day low-pass filtered time series.

The CNP coastline is first divided in four quadrants to identify the areas of the coastline which are the most sensitive to the reception of ML. Figure 5 illustrates the overall distribution of beached particles in these quadrants. The NE quadrant is the one that receives the largest number of particles in our simulations (44.20%), followed by the SE quadrant. Around 75 % of the particles that end up beached in Cabrera coastline are found in the eastern part of the archipelago. The sampling campaign for the CPN has been designed implementing these results to collect data for the validation phase.

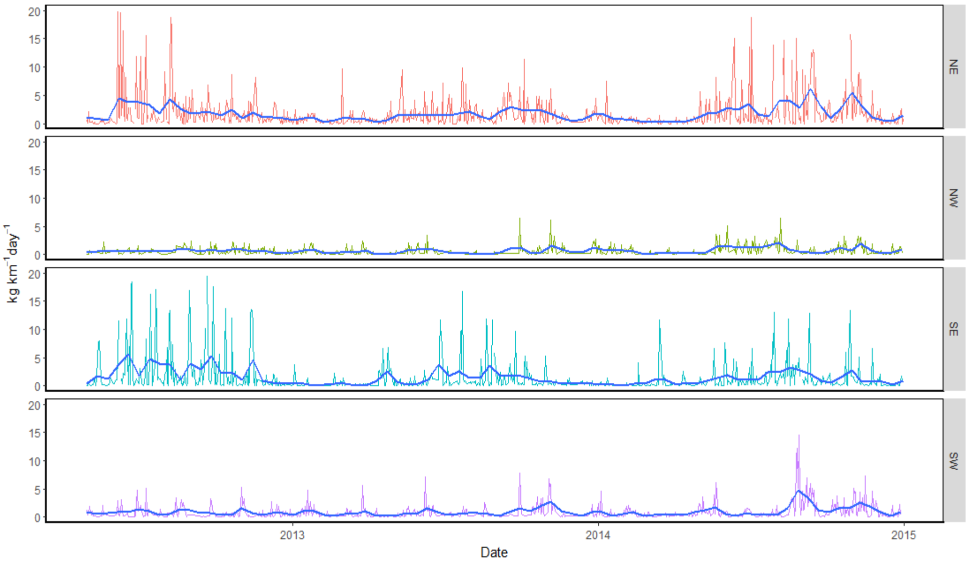

Figure 6. Daily distribution of plastic litter fluxes (kg km-1 day-1) onto Cabrera National Park coastlines per quadrant. The blue lines represent the 30-day low-pass filtered time series.

Figure 6 provides the temporal variability of ML beaching in these four quadrants. It shows how the ML beaching variability is influenced by the seasonal variability associated with the ML inputs, but also significantly modulated by the interannual variability of the hydrodynamic conditions. On short time scales, particles beaching is generally observed as short episodes of a few days associated with the short-term winds and rain events interacting with the current mesoscale ocean conditions.

The half-life of floating particles (i.e., the time after release for which 50% of the particles remain at the sea surface) that reached the coast of Cabrera was 44 days for ocean-based sources and 57 days for land-based sources. On a monthly basis, there is an increase of beached plastics during summer months, peaking in August and September. Such pattern is in agreement with previous works in the Balearic islands (Martínez-Ribes et al. 2007).

4.5. Conclusions

This report presents the methodology and results of high-resolution ML dispersion simulations in the CNP. These have allowed to provide regional maps of accumulation areas and their seasonal variability, to identify the origin of ML reaching the area of the CNP and to estimate the spatial and temporal variability of beaching plastics in Cabrera. The main outcomes can be summarized as follows: 1) the simulated concentration of plastics litter shows a significant seasonal variability with a marked maximum in summer; 2) ML reaching Cabrera mainly origins from the coast of Spain, Morocco and Algeria, the later being the main contributor; 3) the eastern side of the archipelago receives approximately 75 % of the ML that ends up beaching in Cabrera and 4) the temporal variability of beaching is influenced not only by the seasonal variability of the inputs but also by the oceanic variability at interannual, seasonal, mesoscale and daily time scales.

4.6. References

Aliani, Stefano, and Anne Molcard. 2003. "Hitch-Hiking on Floating Marine Debris: Macrobenthic Species in the Western Mediterranean Sea." *Hydrobiologia* 503: 59–67. doi:10.1023/B:HYDR.0000008480.95045.26.

Balaguer, Pablo, Guillem X Pons, and Miquel Mir-Gual. 2019. "The Rocky Coasts of Balearic Islands." In *The Spanish Coastal Systems*, 115–41. doi:10.1007/978-3-319-93169-2.

Cózar, Andrés, Marina Sanz-martín, Elisa Martí, J Ignacio González-gordillo, Bárbara Ubeda, José Á Gálvez, Xabier Irigoien, and Carlos M Duarte. 2015. "Plastic Accumulation in the Mediterranean," 1–12. doi:10.1371/journal.pone.0121762.

Döös, Kristopher, Joakim Kjellsson, and Bror Jönsson. 2013. "TRACMASS—A Lagrangian Trajectory Model." In Preventive Methods for Coastal Protection: Towards the Use of Ocean Dynamics for Pollution Control, edited by T Soomere and E Quak, 225–249. Springer International Publishing.

Eriksen, Marcus, Laurent C.M. Lebreton, Henry S. Carson, Martin Thiel, Charles J. Moore, Jose C. Borerro, Francois Galgani, Peter G. Ryan, and Julia Reisser. 2014. "Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea." *PLoS ONE* 9 (12): 1–15. doi:10.1371/journal.pone.0111913.

Fossi, Maria Cristina, Teresa Romeo, Matteo Baini, Cristina Panti, Letizia Marsili, Tommaso Campan, Simonepietro Canese, et al. 2017. "Plastic Debris Occurrence, Convergence Areas and Fin Whales Feeding Ground in the Mediterranean Marine Protected Area Pelagos Sanctuary: A Modeling Approach." *Frontiers in Marine Science* 4 (May): 167. doi:10.3389/fmars.2017.00167.

Jambeck, Jenna R, Roland Geyer, Chris Wilcox, Theodore R Siegler, Miriam Perryman, Anthony Andrady, Ramani Narayan, and Kara Lavender Law. 2015. "Plastic Waste Inputs from Land into the Ocean" 347 (6223).

Juza, M., B. Mourre, L. Renault, S. Gómara, K. Sebastián, S. Lora, J. P. Beltran, et al. 2016. "SOCIB Operational Ocean Forecasting System and Multi-Platform Validation in the Western Mediterranean Sea." *Journal of Operational Oceanography* 9 (sup1). Taylor & Francis: s155–66. doi:10.1080/1755876X.2015.1117764.

Korres G., M. Ravdas and A. Zacharioudaki. 2019. "Mediterranean Sea Waves Hindcast (CMEMS MED-Waves 2006-2017) (Version 1). Copernicus Monitoring Environment Marine Service (CMEMS) https://doi.org/10.25423/CMCC/MEDSEA_HINDCAST_WAV_006_012.

Koutsodendris, Andreas, George Papatheodorou, Ourania Kougiourouki, and Michalis Georgiadis. 2008. "Benthic Marine Litter in Four Gulfs in Greece, Eastern Mediterranean; Abundance, Composition and Source Identification." *Estuarine, Coastal and Shelf Science* 77 (3): 501–12. doi:10.1016/j.ecss.2007.10.011.

Lebreton, L.C.-M., S.D. Greer, and J.C. Borrero. 2012. "Numerical Modelling of Floating Debris in the World's Oceans." *Marine Pollution Bulletin* 64 (3): 653–61. doi:10.1016/j.marpolbul.2011.10.027.

Lebreton, Laurent C.M., Joost Van Der Zwet, Jan Willem Damsteeg, Boyan Slat, Anthony Andrady, and Julia Reisser. 2017. "River Plastic Emissions to the World's Oceans." *Nature Communications* 8. Nature Publishing Group: 1–10. doi:10.1038/ncomms15611.

Liubartseva, S., G. Coppini, R. Lecci, and E. Clementi. 2018. "Tracking Plastics in the Mediterranean: 2D Lagrangian Model." *Marine Pollution Bulletin* 129 (1): 151–62. doi:10.1016/j.marpolbul.2018.02.019.

Liubartseva, S., G. Coppini, R. Lecci, and S. Creti. 2016. “Regional Approach to Modeling the Transport of Floating Plastic Debris in the Adriatic Sea.” *Marine Pollution Bulletin* 103 (1–2). Elsevier Ltd: 115–27. doi:10.1016/j.marpolbul.2015.12.031.

Mansui, J., A. Molcard, and Y. Ourmières. 2015. “Modelling the Transport and Accumulation of Floating Marine Debris in the Mediterranean Basin.” *Marine Pollution Bulletin* 91 (1). Elsevier Ltd: 249–57. doi:10.1016/j.marpolbul.2014.11.037.

Martínez-Ribes, Lorena, Gotzon Basterretxea, Miquel Palmer, and Joaquin Tintore. 2007. “Origin and Abundance of Beach Debris in the Balearic Islands.” *Scientia Marina* 71 (2): 305–14. doi:10.12681/mms.413.

Mourre, Baptiste, Eva Aguiar, Mélanie Juza, Jaime Hernández-Lasheras, Emma Reyes, Emma Heslop, Romain Escudier, et al. 2018. *Assessment of High-Resolution Regional Ocean Prediction Systems Using Multi-Platform Observations: Illustrations in the Western Mediterranean Sea*. doi:10.17125/gov2018.ch24.

Politikos, Dimitrios V., Christos Ioakeimidis, George Papatheodorou, and Kostas Tsiaras. 2017. “Modeling the Fate and Distribution of Floating Litter Particles in the Aegean Sea (E. Mediterranean).” *Frontiers in Marine Science* 4 (June): 1–18. doi:10.3389/fmars.2017.00191.

Tubau, Xavier, Miquel Canals, Galderic Lastras, Xavier Rayo, Jesus Rivera, and David Amblas. 2015. “Marine Litter on the Floor of Deep Submarine Canyons of the Northwestern Mediterranean Sea: The Role of Hydrodynamic Processes.” *Progress in Oceanography* 134. Elsevier Ltd: 379–403. doi:10.1016/j.pocean.2015.03.013.

Zambianchi, Enrico, Marilisa Trani, and Pierpaolo Falco. 2017. “Lagrangian Transport of Marine Litter in the Mediterranean Sea.” *Frontiers in Environmental Science* 5 (February): 1–15. doi:10.3389/fenvs.2017.00005.

5. Case study: Modelling Marine Litter in the Specially Protected Area of Mediterranean Importance (SPAMI) of the Pelagos Sanctuary and the Tuscan Archipelago National Park

The Pelagos Sanctuary for Mediterranean Marine Mammals is the only pelagic Marine Protected Area in the Mediterranean Sea, designated as one of the Specially Protected Areas of Mediterranean Importance (SPAMI) (Fossi et al., 2017). This marine area, located in the north-western Mediterranean Sea, is characterized by high offshore productive frontal features that attract a variety of large marine vertebrates including eight cetacean species (Coll et al., 2012). This exceptional biodiversity coexists with high human pressure (Fossi et al., 2013; Pinzone et al., 2015), including plastic pollution (Collignon et al., 2012; Fossi et al., 2012; Cózar et al., 2015). High concentrations of microplastics and plastic additives (phthalates) have been detected in neustonic samples collected in the Pelagos Sanctuary for Mediterranean Marine Mammals (Fossi et al., 2016). Therefore, in the frame of the Plastic Busters MPA project it is important to produce model for determining hotspot areas in this marine mammal sanctuary.

The objectives of the activity herein described are therefore not linked to a basin-scale assessment regarding the distribution and re-distribution of plastic marine litter and downscaling results in a limited area, but rather to:

1) to provide support for the planning of the envisaged observation campaigns in terms of: identification of the optimal sampling points, contribution to the identification of hot-spot and cold-spot areas, fronts and convergence areas, and

2) in a second phase, elaborate in detail observational data, with a high-resolution modelling approach, to constitute a model of interpretation from the results obtained, in relation to their intrinsic uncertainty.

5.1. Modelling in the Pelagos Santuary and the Tuscan Archipelago National Park

This activity is based on the application of hydrodynamic and lagrangian models, as a tool for the identification of ML hotspots areas in the SPAMI of the Pelagos Sanctuary, with a particular emphasis on the the Tuscan Archipelago National Park (PNAT) area. The model has focused on hotspot analysis/mapping of ML accumulation areas, based on the estimation of ocean circulation through state-of-the-art numerical models, satellite-based and HF radars tools, to support the implementation of targeted marine litter management measures in the most affected sites in the investigated SPAMI. This activity is essential for the characterization of marine litter, micro- and macro-plastics and the assessment of their abundance in the oceanographic structures (convergence areas), identified by the model also to properly design observation surveys.

The North-Western Mediterranean is characterized, from an oceanographic point of view, by the presence of some peculiar characteristics. While the general circulation follows a markedly cyclonic trend, the currents are not permanent neither in direction nor in intensity (Artale et al., 1994). They are modulated, on the surface, by the atmospheric forcing which has a greater variability and by the presence of coasts, islands, and a complex system of straits and channels (such as the Corsica channel).

Such a great variability, especially on the sea surface, can have a time scale of variation within the order of a few days or less. This does not exclude the possibility that specific oceanographic conditions may occur. Even in this area, that are not permanent but recurrent, and these may contribute to the persistence and tendency to accumulate marine litter in certain areas, even for time periods of the order of a few days and weeks.

As for the hydrodynamic models to adopt, many operational oceanographic services are based on the adoption of complex models, with adequate resolution to represent mesoscale dynamics, and they normally adopt data assimilation methods to reduce the uncertainty associated to the hydrodynamic prediction. This is the case of the European operational services Copernicus (Copernicus Marine Environmental Monitoring Service, CMEMS). On this basis, regional/coastal services can be built using data produced by CMEMS (ie, as initial and boundary conditions), realizing so-called Copernicus downstream services.

As stated before, the modeling strategy that that has been adopted for the Pelagos Sanctuary area and in PNAT is aimed at developing a set of operational services that run as downstream services of CMEMS products, in order to:

- support the marine litter's observation surveys (first phase)
- provide quantitative estimates on the presence of concentration areas (hot-spot areas) for PML (Plastic Marine Litter) whose spatial and temporal variability should be better studied also in relation to the presence of specific marine habitats of some pelagic species (second phase).Moreover, the estimate of PML distribution should also require a proper assessment of the real contribution of individual ML sources in contributing to the plastic pollution in this part of the Mediterranean (second phase).

The models implemented for the Pelagos Sanctuary aim at providing information in a form that can significantly improve not only the design of observation surveys, but also land and sea management choices. These models consist of a set of high-resolution models implemented on a wide area of the Western Mediterranean Sea and they include

1) the implementation of a lagrangian model to understand the dispersion of passive particles, that are mainly driven by hydrodynamic processes; this model can be run directly on CMEMS data products available for the Mediterranean Sea;
2) the implementation of a high-resolution coupled wave-current ocean model, nested on available CMEMS products for the Mediterranean Sea covering a wide part of the Western Mediterranean Sea at a 1/72° deg resolution (with a nesting factor of 1:3 w.r.t. CMEMS products);
3) the implementation of a model of concentration of ML to allow for the spatial distribution of marine litter data (mainly surface plastics and microplastic) available for the area. This model will describe the “most likely” concentration of marine litter (analysis and forecast) based on a Lagrangian approach, using the hydrodynamics fields computed by the previous model.

At present, the outputs of the some of the above services are made available to project partners and associated partners (i.e. University of Siena, ISPRA, CIMA and others) in the form of dedicated bulletins used to better plan and possibly modify the observing activities (i.e. to plan observation points).

The details of such models are described below.

Lagrangian model: many lagrangian models were adopted by several users to track floating particles (such as larvae) and they can include specific modules to characterize, for instance, some biological parameters (in the case of larval dispersion: mortality, settlement, etc.) or pollutant behavior (in the case of oil spills). We used the model GNOME (General NOAA Operational Modeling Environment) that is a tool devloped by the Office of Response and Restoration's (OR&R) Emergency Response Division. It is used for predicting the fate and transport of pollutants (including oil spills) or other elements spilled in water represented as Lagrangian elements (LEs), and their movement and properties are tracked over time. It allows to predict: how wind, currents, and other processes might move and spread LEs on the water; how these predictions are affected by uncertainty in observations and forecasts for ocean currents and wind. GNOME, used in the so-called Diagnostic Mode, enables to incorporate the output of atmospheric and oceanic circulation models. GNOME is based on open-source code, and may be freely used and distributed at no charge.

Ocean model: This model is an extension of the ocean model operational at LaMMA Consortium over a wider area. This enlargement of the regional circulation model is necessary both to allow to provide environmental data into a wider area than the present one, and mainly because the concentration estimates obtained by dispersion models implemented on a limited area domain, require a larger external domain, so as to be affected as little as possible of boundary effects.

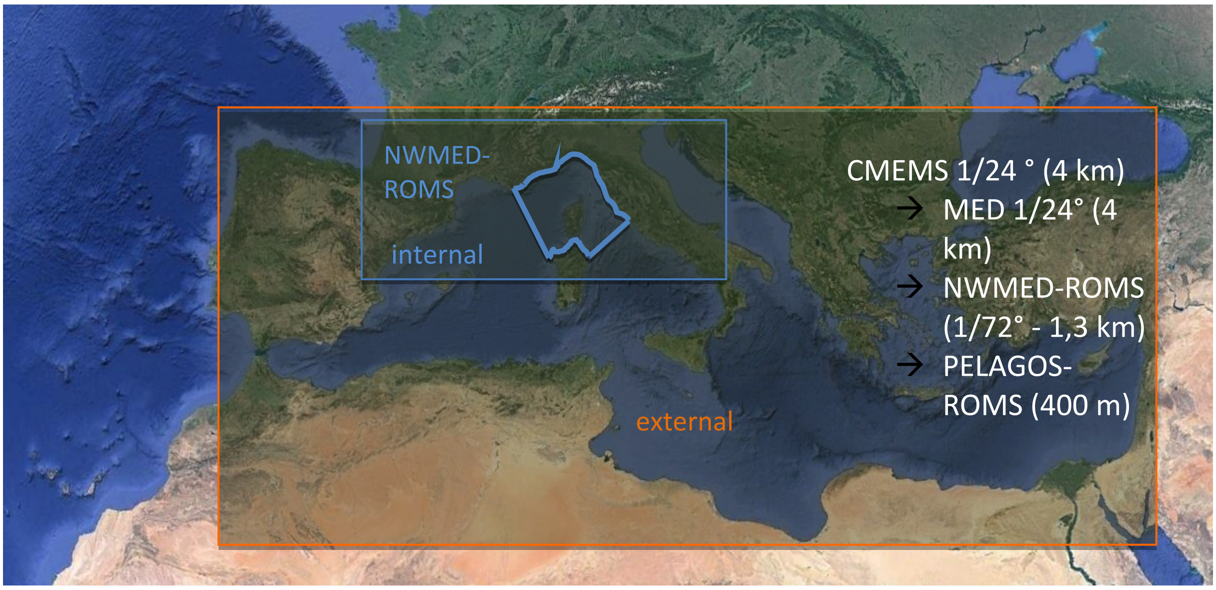

Figure 1. Computational domains of high resolution models and CMEMS data.

The previous operational version, has shown to give reliable results in terms of an accurate circulation estimates at a regional level: http://www.lamma.rete.toscana.it/en/currents-lamma-roms-model

Such regional model is an implementation of ROMS (Shchepetkin and McWilliams 2005) in an area which includes the Tyrrhenian Sea, the Ligurian Sea, and the western portion of the Mediterranean Sea with a western boundary at the east of Toulon. Such a previous version had a horizontal resolution of 2 km and a vertical discretization of 30 sigma-levels, while the present one (NWMED-ROMS) has a horizontal resolution of 1/72° (around 1.2 km) with a nested model (on the Tuscan Archipelago area) with a resolution of 1/216° (around 400 m). Nesting procedures were realized on the basis of the native nesting algorithms developed and recently improved by the ROMS developers team at the Rugers University, leaded by Hernan Arango (Warner et al. 2010).

The bathymetry has been extracted from the EMODNET dataset. It has a resolution of about 300 m. The model is configured with a third-order upstream horizontal advection while the horizontal viscosity v_E and the diffusivity v_K are described by a harmonic operator with coefficients respectively equal to 3 m^2/s and 0.3 m^2/s. The closure scheme is the General Length Scale turbulence closure. Air-sea interactions are imposed using fluxes derived from an implementation of the WRF-ARW model over the central Mediterranean area at 3 km resolution, which is implemented at LaMMA. ECMWF analysis data were used as initial and boundary conditions for air-sea forcing. Turbulent fluxes on the ocean/atmosphere interface are estimated using bulk flux formulation (Fairall et al. 1996). Turbulent momentum, heat and mass exchange processes are realistically reproduced in the model taking into account latent/sensible heat fluxes, radiative heat flux (including the effect of cloud cover), evaporation and precipitation.

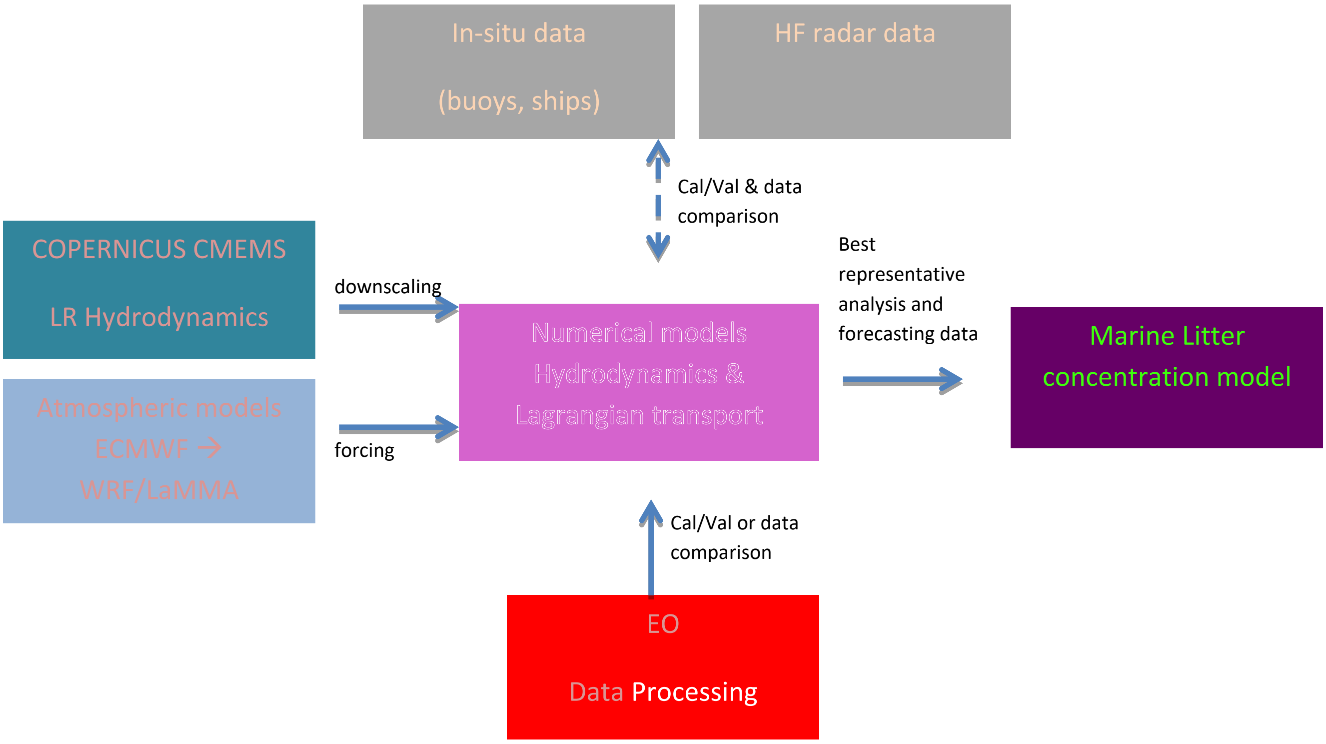

Figure 2. Description of the components of the proposed applications and their interaction.

In order to fit the first objective of this regional modelling activity, the hydrodynamics is split in two operational modes which will be maintained for the whole duration of the project:

Analysis of the last 25-30 days. The lagrangian models downscaling ocean model is run both on CMEMS analysis data over the last previous 25-30 days, and also using the NWMED-ROMS high-resolution model taking both initial conditions and boundary conditions from COPERNICUS analysis. There is no further data assimilation in regional model.

Forecast of the next 5-days. The lagrangian model is run on CMEMS forecast data over the next 5 days, as well as using the NWMED-ROMS high-resolution model forecast data, taking initial conditions from the previous analysis (so that to minimize model spin-up) and boundary conditions from COPERNICUS forecast.

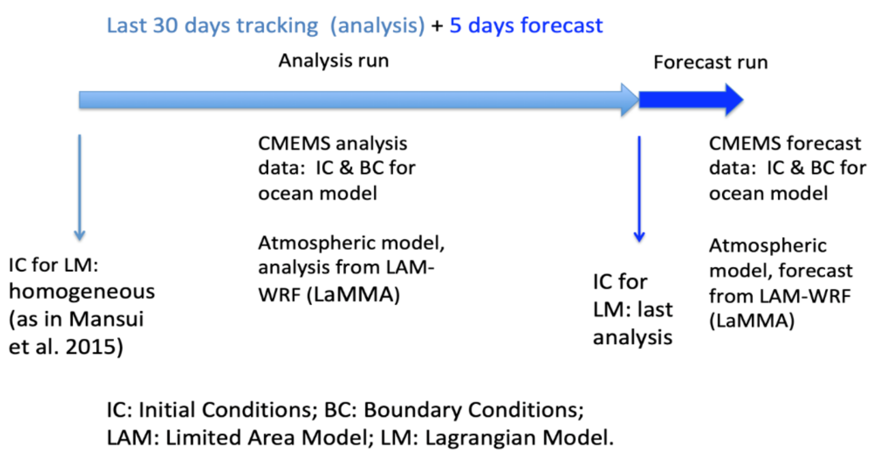

Figure 3. Initial and boundary conditions for the model.

5.2. The "Marine Litter" concentration model

The particle distribution at time *t* has been estimated using homogeneous initial conditions (Mansui et al., 2015), therefore the tendency to accumulation vs dispersion can be estimated, rather than an absolute particle concentration.

The concentrations have been calculated as the ratio between an initial concentration and the concentration at time *t*. These concentrations will be obtained in a computational grid that can be different from that of the hydrodynamic model. The grid size of the ML concentration model shall be small enough to take into account of significant hydrodynamic features (such as marine fronts), but not too small (in any case not less than the resolution of the hydrodynamic model), to maintain the statistical significance in the computation of concentrations.

Since the concentrations obtained are dimensionless, it will also be possible, in a second phase, through the comparison directly between model data and observations, to provide quantitative estimates on the distribution of the concentration in the different areas of the model. A similar approach was followed in the recent past by Fossi et al. (2017) with interesting results from the point of view of the comparison between observed and simulated concentrations.

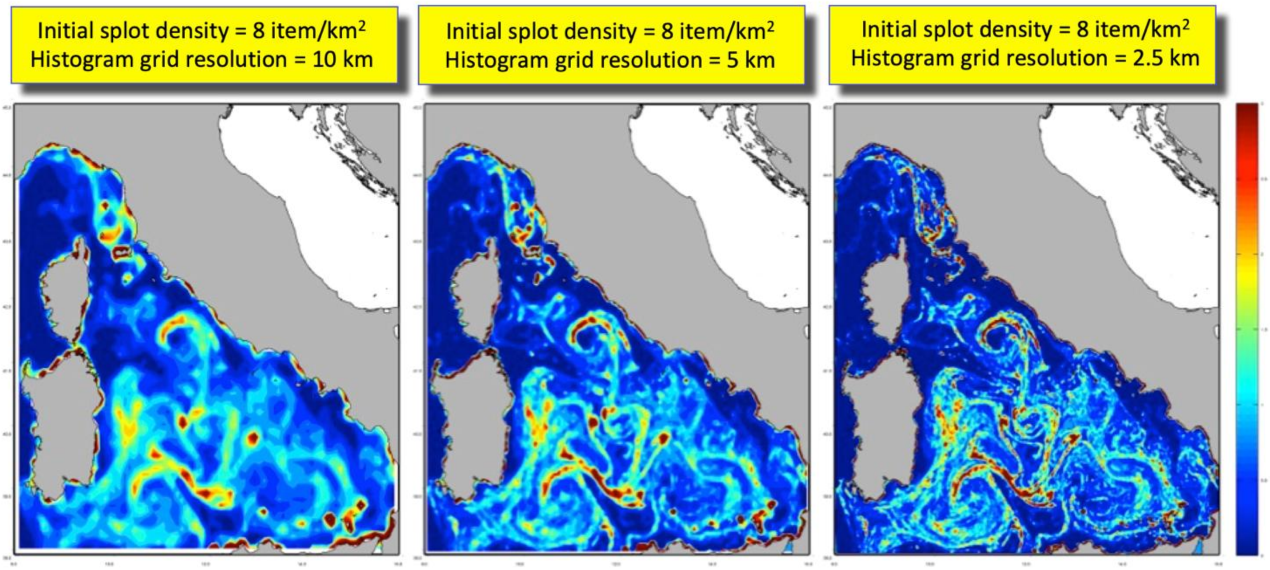

Figure 4. Effects of the size of the grid for the computation of concentrations on the model estimates.

5.3. Estimation of residence times

The time scale used for producing reliable concentration maps depends on the residence time of the hydrodynamic structures to force the accumulation/dispersion of ML in certain areas. It is believed that these scales, in the North-Western Mediterranean sea, are less than one month, as for instance in the Adriatic, which has different characteristics and has more persistent hydrodynamic structures with greater retention times, they were estimated in about 40 days (Liubarsteva et al. 2015).

The estimate of residence time has an important practical implication, because it gives a measure of the number of days that is important to simulate in order to highlight the presence of hot spots areas. This has important consequences on:

- persistency: tendency for the accumulation of ML in specific areas for days (starting from same initial conditions different forecast times can be compared)

- effects of initial conditions on ML simulations: the system tends to lose memory of the homogeneous initial conditions after some days, and the main differences can be attributed to uncertainties in the hydrodynamic predictions. In general, it is better to advance the solution from the situation of homogeneous initial concentration, but, in order to have a reliable model for operational forecasts, the hydrodynamic forecast that forces the Lagrangian dispersion model should not lose reliability. This effect can be in part limited by using analysis CMEMS data as much as possible. This evaluation requires the evaluation of the model performances, at a certain forecast time, starting from different initial times (IC), eg. 20-30-40 days.

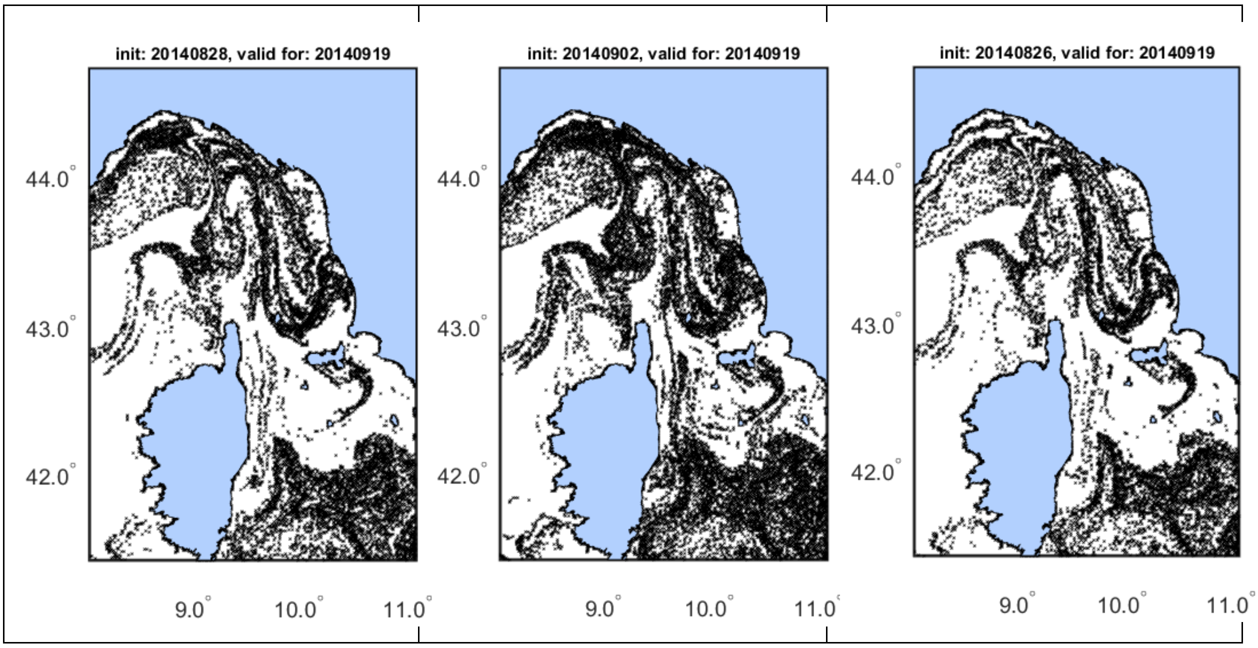

Figure 5. Example of a Lagrangian forecast for a given forecast time and different initial conditions to evaluate the tendency for persistency.

The validation of hydrodynamic data is additionally aided by the availability of a recently installed operational HF radar network (at 13.5 MHz) that allows to validate the surface current data, in particular in the area of convergence between the Eastern and Western Corsica current (North-East of Cap Corse and around Capraia). This is particularly important in order to better validate the results in the Tuscan Archipelago area. HF radar data is also essential for real-time driving of Lagrangian dispersion models based on observation data.

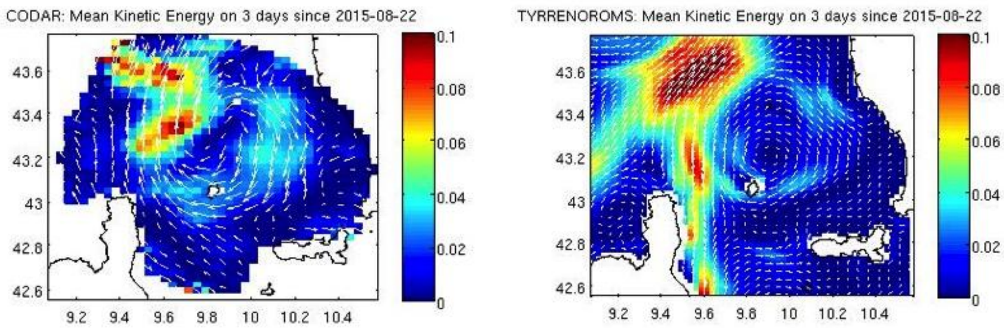

Figure 6. Example of comparison between the HF radar data and the circulation model on the Ligurian Sea and Tuscan Archipelago.

5.4. Contribution to ML observation campaigns for the identification of observation points using CMEMS ocean data

In order to provide support for the planning of the observation campaigns performed by project partners (University of Siena, CIMA and ISPRA, the lagrangian dispersion and concentration model of ML was run over a period of the last three years (2016-2018) on the Mediterranean basin. In this period CMEMS data at a resolution of 1/24° were available (unfortunately only for this period and not for the previous one). Concentration data were obtained after 30 days of simulation after an initial uniform distribution of passive particles on a regular grid at a resolution of 1 km.

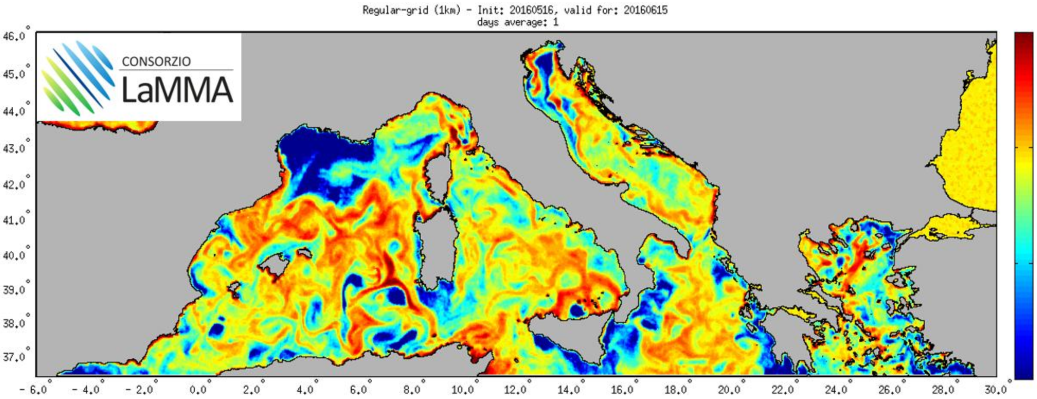

Figure 7. Lagrangian dispersion and concentration model of ML was run over a period of the last three years (2016-2018) on the Mediterranean basin. In this period CMEMS data at a resolution of 1/24° were available.

These short-term concentrations may not represent situations valid at long term timescales (such as those described in the previous parts of the deliverable), but rather represent a simple tendency of accumulation and dispersion, in potential terms, assuming the presence of marine litter concentrations in this area and in the neighboring ones. We believe that this approach is sufficiently correct for the purposes of this part of the work, because it limits the errors deriving from unknowable effects, such as the degradation and sinking processes of plastic particles. Such a basin-scale simulations were then analyzed with a greater detail on the Pelagos Sanctuary area and in the period foreseen by the campaigns.

For each year (2016-2018), daily data was first averaged over the entire period of interest (ie. 1-2 weeks). Then, in order to highlight the presence of likely hot-spot and cold-spot areas for the different distribution obtained in different years, two different concentration indices were provided, indicated as Index_1 and Index_2 (Figures 8-13). These are defined, respectively, by multiplying and by averaging the maps of non-dimensional concentrations produced for each year simulated. These two indices have a different statistical significance and can both be useful in different cases. The first index is useful to better identify the presence of seasonal hot-spot areas, as the multiplication tends to highlight with greater contrast ML potential accumulation areas (by penalizing areas were low-values close to zero were found even on a single year). The latter index provides a smoother ML distribution that may be used to take into account the uncertainty and error of the models and the temporal variability of accumulation processes.

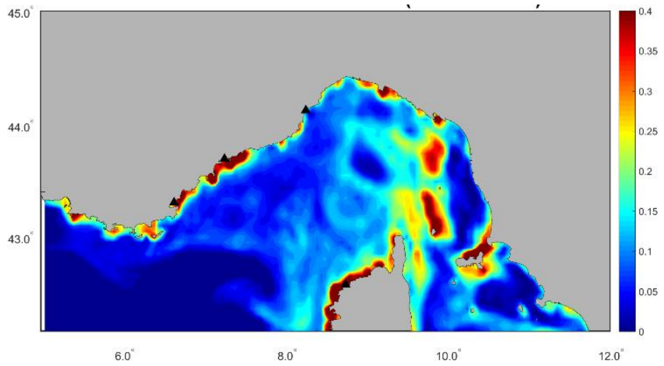

Figure 8. Plastic concentration Index_1, averaged on the campaign period: 20 May – 02 June, zoomed on 'Pelagos Sanctuary'.

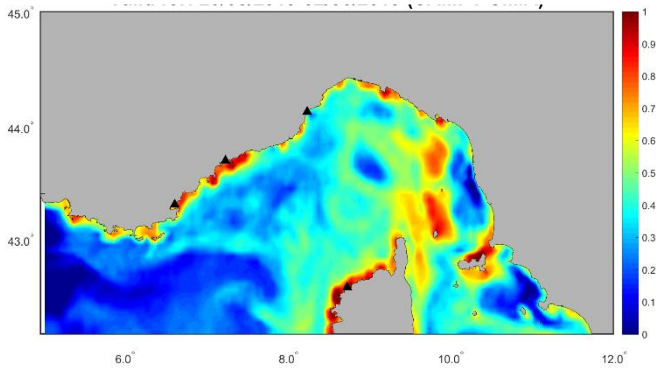

Figure 9. Plastic concentration Index_2, averaged on the campaign period: 20 May–02 June, zoomed on 'Pelagos Sanctuary'.

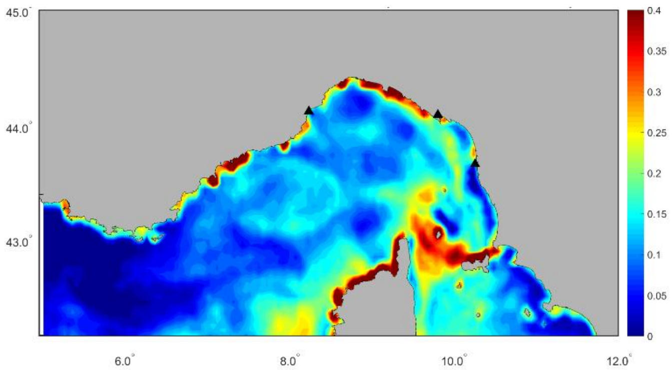

Figure 10. Plastic concentration Index_1, averaged on the campaign period: 8 June – 15 June, zoomed on 'Pelagos Sanctuary'.

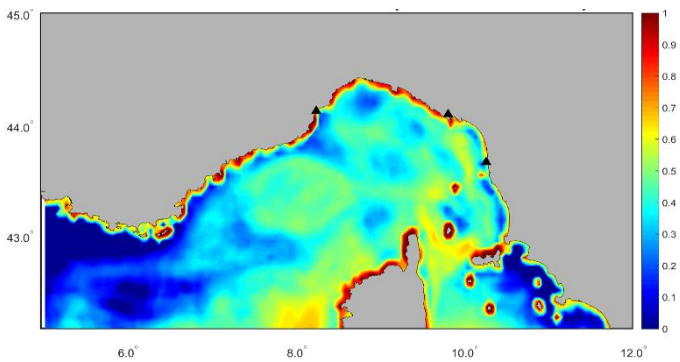

Figure 11. Plastic concentration Index_2, averaged on the campaign period: 8 June – 15 June, zoomed on 'Pelagos Sanctuary'.

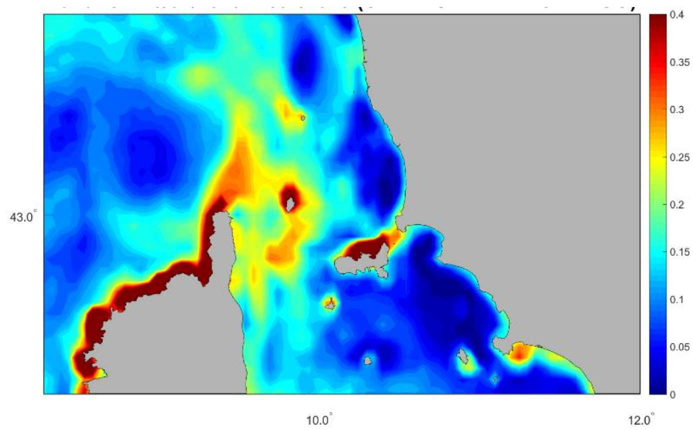

Figure 12. Plastic concentration Index_1, averaged on the campaign period: 15 July – 22 July, zoomed on 'Tuscany Arcipelago'.

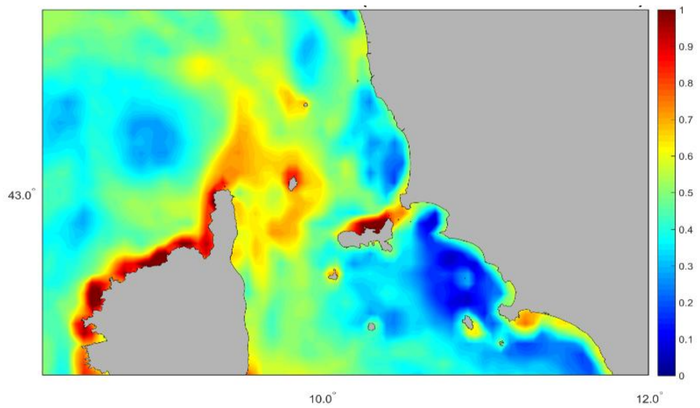

Figure 13. Plastic concentration Index_2, averaged on the campaign period: 15 July – 22 July, zoomed on 'Tuscany Arcipelago'.

Other maps of interest can be obtained enabling the 'beaching' option during the simulation. That is, all the plots that touch the coastline are turned upside down and disabled. The most evident effects of this option are represented by the edge effect along the islands where the major accumulations occur. Normally the default option does not include any stranding. However, the maps obtained with or without this option do not differ much, and although with a different concentration index value, we found that the distribution of hotspots and cold-spots are practically the same.

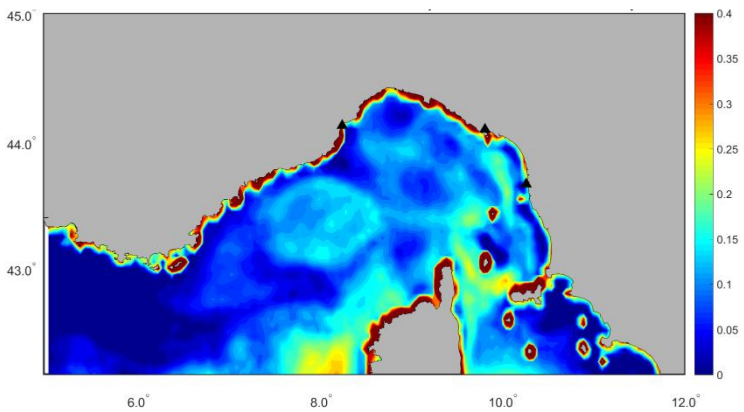

Figure 14. Plastic concentration Index_1, averaged on the campaign period: 8 June – 15 June, zoomed on 'Santuario Pelagos' with beaching option enables.

Additionally, the modelling approach permits real-time simulations of ML concentration models executed daily with updated CMEMS data. This allows for an updated forecast for the next five days.

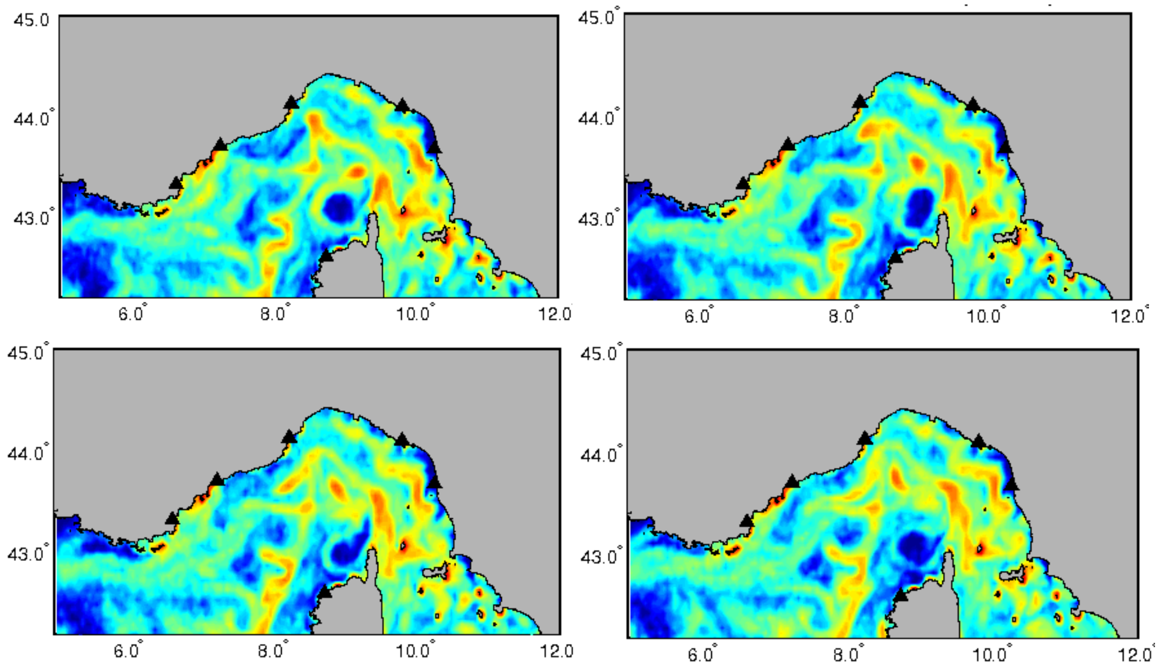

Figure 15. Example of daily map produced for bulletin during the campaign period. The movement and formation of hot/cold-spot can be observed.

5.4.1 The LaMMA bulletin

A bulletin describing the potential distribution of surface microplastics in the marine area of the Pelagos Sanctuary is produced and released within the project partners from LaMMA for the microplastic sampling campaigns (Testing activities in the Pelagos Sanctuary and the PNAT summer 2019 realized by UNISI and ISPRA). The methodologies used for the prediction of microplastics distribution, previously described, are mainly based on the estimates from hydrodynamic models for marine currents, assuming passive behavior of marine litter. Moreover, modeling presents a certain degree of uncertainty, and the identification of the exact dispersion area of microplastics is affected by great uncertainty, especially over long periods of time. The areas of greater accumulation and dispersion are called "potential" because the actual presence of debris is linked to the availability of this type of debris in neighboring areas, assuming a uniform initial concentration of the particles (simulating microplastics items) and running the model for 30 days. The areas of microplastics potential accumulation are referred to as "hot spots", while those of potential dispersal are referred to as 'cold spots'. The concentration is calculated as a dimensionless parameter representing the relationship between the number of particles present at a certain time and the initial number of particles in the initial cell. The microplastics map of concentration is calculated for five days after the date of the bulletin release (Figures 16 and 17). In order to provide also a map summarizing the period situation, partially offsetting the errors of uncertainty of the model, a map of average concentration on all simulation days is also provided.

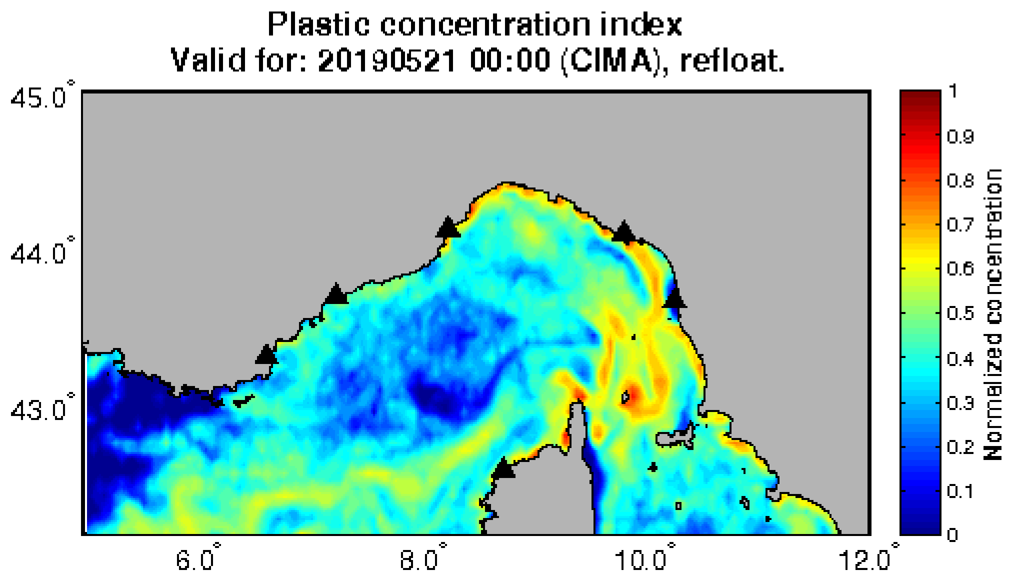

Figure 16: Plastic concentration index map for sampling campaign (21 May 2019)

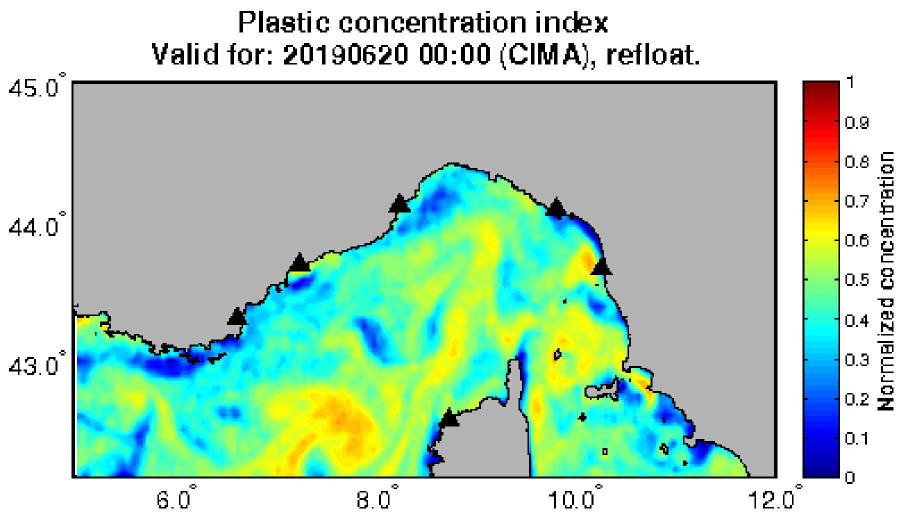

Figure 17: Plastic concentration index map for sampling campaign (20 June 2019)

5.4. Final remarks

Many planned activities will be fully implemented in the subsequent phases of the project, in particular when we will have observation data available.

As previously described, this activity will require the explicit use of high resolution hydrodynamic models in a manner similar to that described to the work of Fossi et al. 2017, where significant correlations between the levels of PML observed and those estimated through the application of numerical models were found.

Finally, the PML distribution maps, calibrated on the data collected during the campaigns, will also be carried out on different periods reprocessed from past years. The period of interest will be chosen on the basis of the availability of habitat distribution data, in order to carry out the cross-mapping activity linked to the evaluation of the environmental risk, as envisaged by the project (Figure 15).

5.5. References

Artale V., Astraldi M., Buffoni G., and Gasparini G. P., Seasonal variability of gyre-scale circulation in the northern Tyrrhenian Sea, Journal Of Geophysical Research, Vol. 99, No. C7, Pages 14,127-14,137, July 15, 1994.

Brandini C, Taddei S, Fattorini M, Lapucci C, Fossi MC, Baini M, Panti C, and Galgani F, Numerical models for Marine Litter distribution in the North-Western Mediterranean Sea, towards a seasonal characterization of concentration. European Geosciences Union, General Assembly 2018 - EGU2018-17078.

Coll, M., Piroddi, C., Albouy, C., Ben Rais Lasram, F., Cheung, W. W. L., Christensen, V., et al. (2012). The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves: the Mediterranean Sea under siege. Glob. Ecol. Biogeogr. 21, 465–480. doi: 10.1111/j.1466-8238.2011.00697.

Collignon, A., Hecq, J.-H., Glagani, F., Voisin, P., Collard, F., and Goffart, A. (2012). Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Mar. Pollut. Bull. 64, 861–864. doi: 10.1016/j.marpolbul.2012.01.011

Cózar, A., Sanz-Martín, M., Martí, E., González-Gordillo, J. I., Ubeda, B., Gálvez, J. Á., et al. (2015). Plastic accumulation in the Mediterranean Sea. PLOS ONE 10:e0121762. doi: 10.1371/journal.pone.0121762

Fossi MC, Romeo T, Baini M, Panti C,Marsili L, Campani T, Canese S, Galgani F, Druon J-N, Airoldi S, Taddei S, Fattorini M, Brandini C and Lapucci C (2017) Plastic Debris Occurrence, Convergence Areas and Fin Whales Feeding Ground in the Mediterranean Marine Protected Area Pelagos Sanctuary: A Modeling Approach. Front. Mar. Sci. 4:167. doi: 10.3389/fmars.2017.00167

Fossi, M. C., Marsili, L., Baini, M., Giannetti, M., Coppola, D., Guerranti, C., et al. (2016). Fin whales and microplastics: the Mediterranean Sea and the Sea of Cortez scenarios. Environ. Pollut. 209, 68–78. doi: 10.1016/j.envpol.2015.11.022

Fossi, M. C., Panti, C., Marsili, L., Maltese, S., Spinsanti, G., Casini, S., et al. (2013). The Pelagos Sanctuary for Mediterranean marine mammals: Marine Protected Area (MPA) or marine polluted area? The case study of the striped dolphin (Stenella coeruleoalba). Mar. Pollut. Bull. 70, 64–72. doi: 10.1016/j.marpolbul.2013.02.013

Liubartseva, S., Coppini, G., Lecci, R., Creti, S., Regional approach to modeling the transport of floating plastic debris in the Adriatic Sea. Marine Pollution Bulletin (2015) http://dx.doi.org/10.1016/j.marpolbul.2015.12.031.

Mansui J., Molcard A., Ourmières Y., Modelling the transport and accumulation of floating marine debris in the Mediterranean basin, Marine Pollution Bulletin 91 (2015) 249–257

Pinzone, M., Budzinski, H., Tasciotti, A., Ody, D., Lepoint, G., Schnitzler, J., et al. (2015). POPs in free-ranging pilot whales, sperm whales and fin whales from the Mediterranean Sea: influence of biological and ecological factors. Environ. Res. 142, 185–196. doi: 10.1016/j.envres.2015.06.021

Warner, J.C., Geyer, W.R., Arango, H.G., 2010. Using a composite grid approach in a complex coastal domain to estimate estuarine residence time. Comput. Geosci. 36, 921–935.

Concluding remarks

The results from this deliverable depict the outputs obtained from several modelling approaches in order to identify marine litter accumulation patterns in Mediterranean MPAs. Overall the three modelling approaches highlight the importance of capturing ML hotspots using regional and local modelling approaches due to the data availability and resolution of models for each target area.

The forecasting model for the Mediterranean Sea explored the seasonal patterns and the vertical distribution of ML throughout the Mediterranean Basin within the target MPAs and in the different sub-basins. For the Cabrera National Park and the Pelagos Sanctuary and the Tuscan Archipelago (PNT), forecasted models showed seasonal variability of ML concentrations within the MPAs. The overall results identify the concentrations in Zakynthos National Park to have high seasonal variability, which may be attributed to the high tourism in the region. Cabrera National Park also observed high seasonality with marine litter concentrations increasing during the summertime (~60%). The Pelagos Sanctuary and the PNT on the other, no clear seasonality was observed offshore but in the coastal areas a high seasonality was observed with high variability.

The Cabrera National Park model has highlighted the seasonality and the spatial distribution of marine litter in this MPA at a finer scale. An increased amount of marine litter accumulates in the summer season compared to the winter months (in agreement with the Mediterranean model) while spatially the eastern side of the island has a tendency to accumulate higher concentrations of marine litter compared to the western coast of the park. For Cabrera National Park, due to the availability of high resolution currents from the WMOP model in this area, this model was able to capture the beaching occurring in this area, which builds on the limitations from the Mediterranean model which wasn't able to capture the high variability of coastal currents throughout the Mediterranean.

For the Pelagos Sanctuary and the PNT, the modelling approach provided support for the planning of survey campaigns to identify the optimal sampling points for hot-spot and cold-spot accumulation areas in addition to the fronts and convergence areas. The localized data available for this region allowed for real-time forecasting for monitoring ML in these two regions. The results from these local models was used during a pre-testing campaign to validate the modelling approach and megafauna was observed in areas where microplastics were quantified with sea surface trawls. The next step is to integrate the results from the survey campaign into the models to develop risk assessments of vulnerability for the marine fauna observed in these areas which will be addressed in the next steps of the Plastic Busters MPAs project.

The unique hydrodynamic characteristics of each MPA highlights the essentiality to use models with high resolution when available to compare approaches and identify patterns within these areas. This requires data gathering using remote sensing, Lagrangian drifters, HF Radar and real data on environmental variables and water movements from the study areas, thus modelling has to be conducted by scientists which have in situ data from the MPAs. Despite the application of three different modelling approaches, the models were in agreement for accumulation areas, which could be considered as forecasting validation prior to the campaigns between models. Overall the results from the forecasting models serve as a basis for identifying modelled ML concentrations in the MPAs within the Mediterranean Sea which serve as a baseline for identifying areas for the monitoring campaigns as well as the seasonality of the surveys, and the data collected during the survey campaigns will be used to validate the forecasting models.

THE PLASTIC BUSTERS MPAs PARTNERSHIP