

Organisation **Hellenic Centre for Marine Research (HCMR)**  
Department **Institute of Oceanography (IO)**



## D9.3

Advanced advection diffusion modelling tool

Date: 26/6/2025

Doc. Version: V3

doi: [10.5281/zenodo.18244997](https://doi.org/10.5281/zenodo.18244997)



### Document Control Information

Settings	Value
<b>Deliverable Title</b>	Advanced advection diffusion modelling tool
<b>Work Package Title</b>	WP9 Data Modelling and Data Sharing
<b>Deliverable number</b>	D9.3
<b>Description</b>	Reports the implementation of Lagrangian particle drift models coupled with hydrodynamical/biogeochemical models, used to identify the distribution patterns, plastic pollution hot spots and potential risk for ecosystems in two regions (Mediterranean and Hardangerfjord/Norway).
<b>Lead Beneficiary</b>	HCMR-IO
<b>Lead Authors</b>	Kostas Tsiaras (HCMR), Michael Bedington (NIVA)
<b>Contributors</b>	Georgios Eleftheriou (HCMR), Georgios Triantafyllou (HCMR), Shamil Lakubov (NIVA), Andrew Luke King (NIVA)
<b>Submitted by</b>	Kostas Tsiaras
<b>Doc. Version (Revision number)</b>	V3
<b>Sensitivity (Security):</b>	Public
<b>Date:</b>	[Issue Date]

### Document Approver(s) and Reviewer(s):

NOTE: All Approvers are required. Records of each approver must be maintained. All Reviewers in the list are considered required unless explicitly listed as Optional.

Name	Role	Action	Date
<b>Gabriele Pieri</b>	Review #1	<i>Approve</i>	3/04/2025
<b>Daniel Lukats</b>	Review #2	<i>Review and approve</i>	26/6/2025

### Document history:

The Document Author is authorized to make the following types of changes to the document without requiring that the document be re-approved:

- Editorial, formatting, and spelling
- Clarification

To request a change to this document, contact the Document Author or Owner.

Changes to this document are summarized in the following table in reverse chronological order (latest version first).

Revision	Date	Created by	Short Description of Changes
<b>V0</b>	02/04/2025	Kostas Tsiaras	Skeleton created
<b>V1</b>	19/06/2025	Kostas Tsiaras	First complete version submitted to reviewers
<b>V2</b>	25/06/2025	Kostas Tsiaras	Revised version addressing reviewers comments

<b>V3</b>	26/06/2025	Kostas Tsiaras	Revised version addressing reviewers comments
-----------	------------	----------------	---

### Configuration Management: Document Location

The latest version of this controlled document is stored in <location>.

Nature of the deliverable		
<b>R</b>	Report	X

Dissemination level		
<b>PU</b>	Public	X

### ACKNOWLEDGEMENT

This report forms part of the deliverables from the NAUTILOS project which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101000825. The Community is not responsible for any use that might be made of the content of this publication.

NAUTILOS - New Approach to Underwater Technologies for Innovative, Low-cost Ocean observation is an H2020 project funded under the Future of Seas and Oceans Flagship Initiative, coordinated by the National Research Council of Italy (CNR, Consiglio Nazionale delle Ricerche). It brings together a group of 21 entities from 11 European countries with multidisciplinary expertise ranging from ocean instrumentation development and integration, ocean sensing and sampling instrumentation, data processing, modelling and control, operational oceanography and biology and ecosystems and biogeochemistry such, water and climate change science, technological marine applications, and research infrastructures.

NAUTILOS will fill-in marine observation and modelling gaps for chemical, biological and deep ocean physics variables through the development of a new generation of cost-effective sensors and samplers, the integration of the aforementioned technologies within observing platforms and their deployment in large-scale demonstrations in European seas. The fundamental aim of the project will be to complement and expand current European observation tools and services, to obtain a collection of data at a much higher spatial resolution, temporal regularity, and length than currently available at the European scale, and to further enable and democratise the monitoring of the marine environment to both traditional and non-traditional data users.

NAUTILOS is one of two projects included in the EU’s efforts to support of the European Strategy for Plastics in a Circular Economy by supporting the demonstration of new and innovative technologies to measure the Essential Ocean Variables (EOV).

More information on the project can be found at: <http://www.nautilus-h2020.eu>.

### COPYRIGHT

© NAUTILOS Consortium. Copies of this publication – also of extracts thereof – may only be made with reference to the publisher.

## TABLE OF CONTENTS

<b>ACKNOWLEDGEMENT</b> .....	<b>3</b>
<b>COPYRIGHT</b> .....	<b>3</b>
<b>TABLE OF CONTENTS</b> .....	<b>4</b>
<b>EXECUTIVE SUMMARY</b> .....	<b>5</b>
<b>LIST OF FIGURES</b> .....	<b>7</b>
<b>LIST OF TABLES</b> .....	<b>8</b>
<b>LIST OF ACRONYMS AND ABBREVIATIONS</b> .....	<b>8</b>
<b>I. INTRODUCTION</b> .....	<b>9</b>
<b>II. METHODOLOGY</b> .....	<b>11</b>
Mediterranean.....	11
Hardanger Fjord System.....	14
<b>III. SIMULATIONS RESULTS</b> .....	<b>15</b>
Mediterranean.....	15
Hardanger Fjord System.....	22
<b>IV. DISCUSSION</b> .....	<b>27</b>
Mediterranean.....	27
Hardanger Fjord System.....	29
<b>V. IMPACT OF NAUTILOS-LIKE OBSERVATIONS ON PARTICLES ADVECTION DIFFUSION OCEAN FORECASTING</b> .....	<b>30</b>
<b>VI. CONCLUSIONS AND RECOMMENDATIONS</b> .....	<b>32</b>
<b>VII. REFERENCES</b> .....	<b>33</b>

## EXECUTIVE SUMMARY

Deliverable D9.3 describes the activities carried out in WP9 Task 9.3 on the development of coupled hydrodynamic/particle drift models and their implementation to assess the distribution of plastics in the marine environment, identify hotspots and investigate the potential risk to ecosystems. Two coupled drift models covering different marine environments and scales were adapted for this purpose: a basin-scale model for the Mediterranean Sea and a regional/local model for the Hardangerfjord in Norway.

In the Mediterranean, a Lagrangian Individual Based Model (IBM), coupled with the HCMR basin-scale hydrodynamic/biochemical model, was used to track the fate of floating plastics from major land-based sources (cities, rivers etc.). Different sizes and types of plastics were considered, taking into account the most important processes (advection from currents, Stokes drift, vertical/horizontal mixing, wind drag, beaching, biofouling). The simulated plastics distributions were validated against available in situ data. The plastics dispersion patterns were investigated in relation to land-based sources distribution, ocean circulation and biofouling induced sinking. The simulated distribution of micro- and macroplastics was also overlaid with key ecological habitats, such as Cetacean Critical Habitats and Natura2000 sites to assess the potential risk from plastic pollution.

For the Hardangerfjord, a new module for the OpenDrift Lagrangian model was developed to parameterize biofilm growth and biofouling induced sinking, considering various processes (colonization, biofilm growth, grazing). The Lagrangian model was forced by the operational fjord-scale hydrodynamic model ROMS-ROHO, to simulate the dispersion of plastics, originating from numerous aquaculture sites in the area. The plastics dispersion patterns, effect of biofouling and connectivity among aquaculture sites were investigated, considering the possibility of plastics particles acting as vectors of infection.

An important part of Task 9.3 was also to assess how NAUTILOS-like observations might improve simulations of micro- and macroplastic distributions, employing the Observing System Simulation Experiment (OSSE) methodology, developed within T9.1. In the context of the OSSE approach, simulations with a coarse resolution (Forecast Model, FM) model were performed to evaluate the benefit from assimilating a relatively higher amount (+40%) of new NAUTILOS-like “synthetic” observations (temperature/salinity profiles) in the plastic dispersion model skill. The “synthetic” observations were obtained from the fine resolution hydrodynamic model simulation, being considered as the Nature Run (NR). The simulated distribution of plastics with the coarse model was then evaluated against the NR plastics distributions, being considered as the “truth”. In the Mediterranean, the macroplastics forecast skill presented a small but noticeable improvement with additional post-NAUTILOS ocean observations, while the microplastics forecast skill was not significantly affected, which was attributed to the microplastics relatively lower residence time at surface (as compared to macroplastics), due to biofouling induced sinking. In the Hardangerfjord, the assimilation of a higher amount of post-NAUTILOS ocean observations (temperature and salinity profiles) also resulted in relatively small differences in the microplastics distribution, as short distance transport (stranding) is predominantly affected by (wind driven) near surface currents, while long distance transport is mostly controlled by energetic tidal straits. These two primary drivers for microplastics transport were not significantly influenced by the assimilation of additional temperature and salinity profiles. On the other hand, considering the quite

complex bathymetry of the Hardangerfjord area, the model resolution affecting the successful representation of the coastline (i.e. beaching) and current jets, had an important impact on microplastics transport. The results from model simulations in both areas provided useful insight on the effect of various factors (model resolution, biofouling, ocean circulation) on the distribution of plastics.

## LIST OF FIGURES

Figure 1 - Mediterranean model domain and bathymetry (m). Major Rivers, straits and regional seas are indicated. ....	12
Figure 2 - Source inputs of plastics from river runoff (top left), macroplastics from coastal cities (top right), and microplastics (>300 $\mu\text{m}$ ) from wastewater discharge (bottom) (Tsiaras et al., 2021). ....	13
Figure 3 - Location of aquaculture sites used as start locations (red spots) within the model domain. ....	15
Figure 4 - Mean (2010-2013) distribution of macroplastics>20 cm (bottom, items/ $\text{km}^2$ ) and microplastics>300 $\mu\text{m}$ (top, items/ $\text{m}^2$ ) concentration in the Mediterranean Sea, as derived from the 4-year simulation of the NR ( $\sim 5$ km resolution, MED20). ....	16
Figure 5 - Mean (2010-2013) macroplastics>20cm (left, items/ $\text{km}^2$ ) and microplastics>300 $\mu\text{m}$ (right, items/ $\text{m}^2$ ) concentration, simulated with the NR model ( $\sim 5$ km resolution, MED20), against available in situ data (see Tsiaras et al., 2021). ....	17
Figure 6 - Box plots, indicating the range, median and 25 <sup>th</sup> /75 <sup>th</sup> percentiles, of mean (2010-2013) simulated macroplastics>20cm (left, items/ $\text{km}^2$ ) and microplastics >0.3mm (items/ $\text{m}^2$ ) concentration, against in-situ data (see Figure 5). ....	17
Figure 7 - Simulated annual mean (0-150m) bacterial biomass ( $\text{mgC}/\text{m}^3$ ) (left bottom), deep maximum depth (m) of microplastics (350 $\mu\text{m}$ ) (left top) and vertical distribution of microplastics (350 $\mu\text{m}$ ) concentration (items/ $\text{m}^3$ ), averaged in the Levantine basin (blue line), Gulf of Lions (orange line) and Alboran Sea (right). ....	18
Figure 8 - Important ecological habitats (Cetacean Critical Habitats, Natura2000 sites) and aquaculture (finfish, shellfish) sites in the Mediterranean (top) and mean simulated microplastics>0.3mm and macroplastics>20cm concentrations (items/ $\text{km}^2$ , bottom), averaged over different ecosystems layers (CCH, Natura2000, finfish/shellfish aquaculture). ....	19
Figure 9 - Cetacean Critical Habitats (CCH, right) and Natura2000 (left) areas, classified with low (blue dots), medium (green dots) and high (red dots) pollution risk from microplastics>0.3mm (top) and macroplastics> 20cm (bottom). The risk index is calculated based on the averaged area plastics concentration ( $C_{av}$ ), being lower or higher from the 25 <sup>th</sup> ( $C_{25}$ ) and 75 <sup>th</sup> ( $C_{75}$ ) basin-scale (see Figure 4percentiles (i.e. low: $C_{av}<C_{25}$ , medium: $C_{25}<C_{av}<C_{75}$ , high: $C_{av}>C_{75}$ ). ....	19
Figure 10 - Annual mean sea surface height (SSH, m), simulated with MED20 Nature Run (NR, top) and MED10, assimilating 78 ( $AM_{r78}$ ) and 110 ( $AM_{r110}$ ) randomly selected TEM/SAL profiles, along with SSH/SST surface data. Randomly selected TEM/SAL profiles are indicated. ....	21
Figure 11 - Box plots (left) and Taylor diagrams (right) of macroplastics >20 cm (top) and microplastics >30 $\mu\text{m}$ (bottom) assimilation experiments (Assim78, Assim110) against free run (Med10free) and Nature Run (Med20). ....	22
Figure 12 - Concentration of microplastics (particles per $\text{m}^2$ ) in the nature run with non-biofouling particles. The concentrations should be taken to show relative impact rather than absolute numbers as they will scale with the input (here 10,000 particles per aquaculture site). ....	23
Figure 13 - Concentration of microplastics (particles per $\text{m}^2$ ) simulated with the coarse resolution model, assimilating pre-NAUTILOS (left) and post-NAUTILOS (right) observations. ....	23

Figure 14 - Concentration of microplastics (particles per m<sup>2</sup>) in the nature run using biofouling particles.....24

Figure 15 - - Concentration of microplastics (particles per m<sup>2</sup>) in the pre-NAUTILOS (left) and post-NAUTILOS (right) driven run when using biofouling. ....24

Figure 16 - The distance the particles travelled from their start point to the end of the model run for the nature run (top), pre-NAUTILOS (middle) and post-NAUTILOS (bottom) forcing and using the non-biofouling (left column) and biofouling (right column) models.....25

Figure 17 - Number of site connections. ....26

Figure 18 - Taylor diagram of sea surface height (SSH) (top) and relative RMSD for SSH, SST, TEM and SAL (bottom) of the assimilation models (AM) compared to the free model run (FM) for the selected variables, computed over the entire model domain, as a function of the number of uniformly distributed assimilation points (up to the first 140 locations). ....28

## LIST OF TABLES

Table 1 - Relative RMSD (RRMSD) decrease (%) in assimilation runs (Assim78, Assim110) compared to the free run ((AM/FR-1)\*100) for micro- and macroplastics.....28

## LIST OF ACRONYMS AND ABBREVIATIONS

Abbreviation	Definition
<b>NAUTILOS</b>	New Approach to Underwater Technologies for Innovative, Low-cost Ocean Observation
<b>OSSE</b>	Observing System Simulation Experiment
<b>IBM</b>	Individual Based Model
<b>MP</b>	Microplastics
<b>NR</b>	Nature Run
<b>FM</b>	Forecast Model
<b>AM</b>	Assimilation Model
<b>SSH</b>	Sea Surface Height
<b>SST</b>	Sea Surface Temperature
<b>TEM</b>	Temperature
<b>SAL</b>	Salinity
<b>CCH</b>	Cetacean Critical Habitats
<b>MPA</b>	Marine Protected Area

## I. INTRODUCTION

The global production of plastics has been continuously increasing since the 1950's, reaching more than 300 million tons in recent years (PlasticsEurope, 2020). A significant amount of plastics may end up in the marine environment, raising concern for wildlife and human health. Plastics may affect marine organisms through ingestion and/or entanglement, while microplastics (MPs) that represent the smaller size class (particles <5 mm), may interact with low trophic-level organisms (i.e., phytoplankton and zooplankton) and their predators, finding their way up the food chain and human diet. The interaction of MPs with marine organisms and organic matter (e.g. attachment of heavier organic matter/biofouling, ingestion by zooplankton/fish etc) has been hypothesized as a potential explanation of their observed decreased concentration in surface waters (e.g. Cozar et al., 2014). The fate of plastics in the marine environment is determined by various physical (waves, currents, wind) and biogeochemical (e.g., biofouling) processes. Thus, numerical models taking into account the most important processes and source inputs provide useful tools for the assessment of marine litter pollution. The simulated distribution of plastics can be used to identify hot-spot and accumulation areas in the marine environment, particularly in relation with ecologically and commercially important areas (e.g. Marine protected areas, aquaculture sites etc.).

Deliverable D9.3 describes the activities carried out in WP9 Task 9.3 on the development of coupled hydrodynamic/particle drift models and their implementation to assess the distribution of floating macro- (>5mm) and microplastic (<5 mm) marine litter particles, to identify hotspots of plastic pollution and to assess the risk to ecosystems. Within this framework, specific modules have been developed to describe the interaction of plastics with living organisms and organic matter (e.g. biofouling), a process that is important, particularly for the fate of microplastics (MP). An additional part of Task 9.3 was to assess how NAUTILOS-like observations can improve simulations of micro- and macroplastic distributions. In the absence of available in situ data from NAUTILOS developed sensors early in the project, the Observing System Simulation Experiment (OSSE) methodology, developed within T9.1, was employed, using "synthetic" observations from a fine resolution model (Nature Run). Two coupled drift models covering different marine environments and scales were adapted for this purpose: a basin-scale model for the Mediterranean Sea and a regional/local model for the Hardangerfjord in Norway.

The Mediterranean Sea is a semi-enclosed basin that is considered a hot-spot for plastic pollution (e.g. Lebreton et al., 2012), which may be attributed to its densely populated coastline; combined with the limited outflow of surface waters, given the anti-estuarine water exchange with the Atlantic Ocean (water flows out at depth and in at the surface). In the Mediterranean, a Lagrangian Individual Based Model (IBM), coupled with the HCMR basin-scale hydrodynamic/biochemical model, was used to track the fate of floating plastics from major land-based sources (cities, rivers etc.). Different sizes and types of plastics were considered, taking into account of the most important processes (advection from currents, Stokes drift, vertical/horizontal mixing, sinking, wind drag, beaching, biofouling).

In the Hardangerfjord, a new module for the OpenDrift Lagrangian model was developed to parameterize biofouling induced sinking, as a function of various processes (colonization, growth, grazing and zooplankton ingestion). The Lagrangian model was forced by the

operational fjord-scale hydrodynamic model ROMS-ROHO, to simulate the dispersion of plastics, originating from the high density of aquaculture sites which are found in the area.

The following sections describe the methodologies applied for each of the two pilot sites, followed by the results of the simulations and a discussion of the main findings in relation to the objectives of the NAUTILOS project.

## II. METHODOLOGY

### MEDITERRANEAN

---

The transport and fate of macro- and microplastics from major land-based sources in the Mediterranean Sea (see Figure 1) was simulated, applying a Lagrangian particle drift model, based on Pollani et al. (2001). The model includes different properties of plastic particles (e.g. density, size, type), considering both physical (wind, waves, ocean currents, beaching) and biogeochemical (sinking due to biofouling) processes. The particle drift model is coupled to a 3-D hydrodynamic model, based on the Princeton Ocean Model (POM; Blumberg and Mellor, 1983) and a comprehensive biogeochemical model, based on the European Regional Seas Ecosystem Model (ERSEM; Baretta et al., 1995), which provides bacterial biomass that is used to parameterise biofilm growth on microplastics. Both models are currently operational as part of the POSEIDON prediction system ([www.poseidon.hcmr.gr](http://www.poseidon.hcmr.gr); Korres et al., 2007; Kalaroni et al., 2020a, b) and more details are provided in Deliverable D8.6. In addition, the waves forcing (Stokes drift, wave period and significant wave height), based on the WAM Cycle 4.5.4 wave model (Gunther and Behrens, 2012), also operational within POSEIDON (Ravdas et al., 2018) was obtained off-line from Copernicus Marine Service (CMEMS; [marine.copernicus.eu](http://marine.copernicus.eu)). Finally, the hydrodynamic model's atmospheric forcing, including the wind components responsible for the wind drag of specific macroplastics (bottles and foam), is obtained from the POSEIDON weather forecast system.

For computational efficiency, the Lagrangian drift model follows the concept of Super-Individuals (SI; Scheffer et al., 1995), with each SI representing a group of particles, sharing the same attributes (position, density, origin, type). The SI's position, described by its Cartesian coordinates, is updated every time-step, based on the 3-D displacement, produced by every component (currents, waves etc), which is obtained with bi-linear interpolation at the SI location. The particles' displacement includes the processes of:

- Advection from ocean currents (obtained from the hydrodynamic model).
- Waves Stokes drift (obtained off-line from the wave model output).
- Wind drag of partly submerged macroplastics (e.g. bottles, foam).
- Random movement in the horizontal, depending on the horizontal diffusion coefficient (obtained from the hydrodynamic model).
- Random movement in the vertical, depending on the turbulent vertical diffusion coefficient (obtained from the hydrodynamic model) and waves (obtained off-line from the wave model output).
- Increase of particle density with time due to biofouling, which is parameterized as a function of bacterial biomass (obtained off-line from the biogeochemical model output)
- Buoyancy/sinking, depending on the particles' diameter/size and density.
- Retention/burial of particles in the beach.

Four size classes (350, 500, 1000, and 2000  $\mu\text{m}$ ) of microplastics particles (<5 mm) and five types/sizes (5 mm – 2 cm, 2 – 20 cm, >20 cm bottles, >20 cm bags, >20 cm foam) for macroplastics (>5 mm) were considered in the model based on available data from the Mediterranean Sea that have been used for the validation of the model.

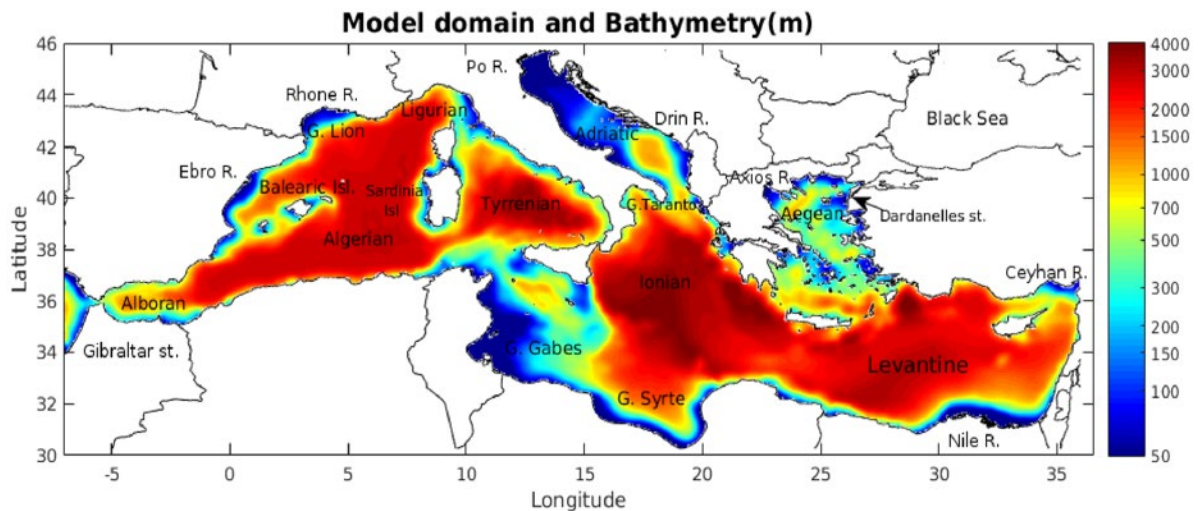


Figure 1 - Mediterranean model domain and bathymetry (m). Major Rivers, straits and regional seas are indicated.

A uniform background initial concentration was adopted for each type/size class, based on the basin-scale median abundance from available in situ data. A simplified parameterization of biofilm growth has been included in the model, as a function of bacterial abundance (obtained from the biogeochemical model) that is considered a proxy for the biofouling community. The biofilm growth rate is assumed to be mainly controlled by detachment and colonization rates (Kiorboe, 2003), being faster for smaller particles. Based on the adopted formulation, smaller size microplastics (e.g. 350um, 500um) are gradually sinking due to the buoyancy loss resulting from the attachment of heavier biofilm. More details on the different processes parameterization in the model may be found in Tsiaras et al. (2021). Three main input sources of plastics were considered (see Figure 2): (a) MPs from coastal cities municipal wastewater discharge, (b) MPs and macroplastics from river discharge, as a function of accumulated plastics production and monthly river runoff, obtained from Lebreton et al. (2017), and (c) macroplastics from coastal cities (beaches, harbours, etc.), distributed along the coastline as a function of population density (Tsiaras et al., 2021).

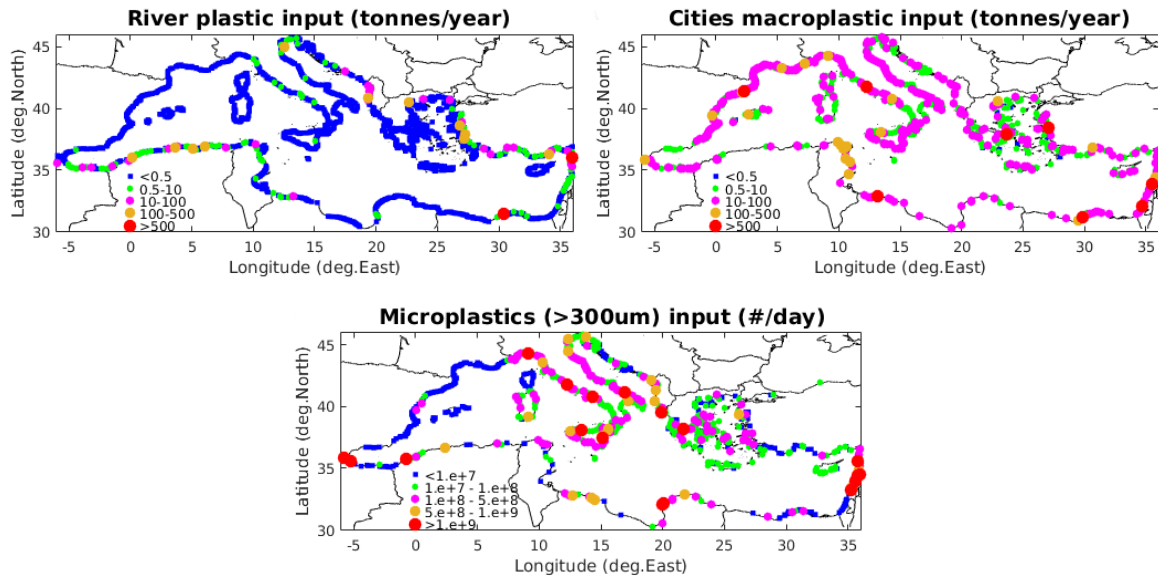


Figure 2 - Source inputs of plastics from river runoff (top left), macroplastics from coastal cities (top right), and microplastics (>300  $\mu\text{m}$ ) from wastewater discharge (bottom) (Tsiaras et al., 2021).

To study the dispersion and aggregation patterns of plastics in the Mediterranean Sea, particle drift simulations were performed with the fine resolution ( $1/20^\circ \times 1/20^\circ$ ,  $\sim 5$  km) basin-scale model MED20. Following the concept of the Observing Systems Simulation Experiments (OSSE) implemented within NAUTILOS project (see Deliverable D8.6 and D9.1), additional simulations were performed with a coarser resolution model ( $1/10^\circ \times 1/10^\circ$ ,  $\sim 10$  km) MED10 to evaluate the benefit from assimilating new NAUTILOS-like “synthetic” observations (temperature/salinity profiles and sea surface height/temperature) in the plastic dispersion model skill. As in T9.1, a hybrid ensemble Kalman filter (see Deliverable D8.6 and D9.1 for more details) was employed to assimilate “synthetic” observations in MED10 model. In the OSSE context, the “synthetic” observations were obtained from the fine resolution MED20 hydrodynamic model simulation, being considered as the Nature Run (NR). Similarly, the coarse resolution MED10 model is considered the Forecast Model (FM) and the simulated distribution of plastics was evaluated against MED20 distributions, being considered as the “truth”. All experiments were performed over a 4-year period, with constant atmospheric forcing from 2010, for which OSSE experiments were performed in Deliverable D9.1. The plastics model simulations were expanded over three additional years, allowing to obtain more representative plastics distributions, following the initial homogeneous concentrations. Thus, the results presented are the average from these 4-year simulations.

Simulations with the coupled hydrodynamic/plastics dispersion Mediterranean model were used to:

- 1) Identify plastics dispersion patterns and potential accumulation hotspots.
- 2) Validate simulated micro- and macro-plastic distributions against in situ data.
- 3) Investigate the interaction of plastics with marine organisms and its effect in their distribution.

4) Overlap simulated plastics distributions with important ecological habitats and aquaculture sites to identify areas that are potentially threatened from plastic pollution.

5) Conduct OSSE experiments assimilating synthetic hydrodynamic data from the NR to assess the impact on the distribution of plastics in the FM.

#### HARDANGER FJORD SYSTEM

---

Aquaculture sites are recognised as a source of microplastics (Gomiero et al. 2020, Wu et al. 2023), which are problematic both as they are often sited in low population areas, which might otherwise not have a significant input of plastics and because of the risk that they can act as a vector for disease transmission from farm to farm, or to wild fish populations (Mohsen et al. 2022). The use of a biofouling module is particularly important in this case since the biofilm may enhance the ability of microplastics to act as a disease vector (Cholewińska et al 2022).

OpenDrift (Dagestad et al. 2018) is a particle drift model developed by MetNO, which has been used for a variety of applications such as oil spills, search and rescue, and larval dispersal. Whilst it has been used for multiple studies of microplastics it did not have a module to represent biofouling of microplastics. We implemented equations from Kooi et al. 2017 to represent the modification of vertical settling speeds due to biofouling. This contains four processes:

- Collision with algae
- Growth of algae on the particles
- Grazing of algae on the particle
- Respiration of algae on the particles

These are updated at every model timestep based on the ambient local concentrations of phytoplankton. When the particle lands on the seabed, the biofouling is removed and the particle can be resuspended in the same way as the original plastics model.

The particle tracking model is run offline, forced by saved hydrodynamic and biogeochemical fields. For the Hardanger fjord these were obtained from the ROHO model system, which is based on ROMS ocean model (Shchepetkin et al., 2005), covering the Hardanger Fjord area, described in more detail in Deliverables D8.6 and D9.1 for more details). The biogeochemistry model ERSEM (Butenschon et al. 2016) was run coupled to the ROHO models, as described in Deliverable D9.2.

There is no wave component to the model so inclusion of Stokes drift was not possible, however for the fjordic environment this is unlikely to be a significant factor. The release locations for the particles were the aquaculture sites within Hardangerfjord. There are over 300 licensed aquaculture sites within the Hardangerfjord system and surroundings. Of these, 264 were selected as some sites were too close to the coast to be represented in the model (see Figure 3).

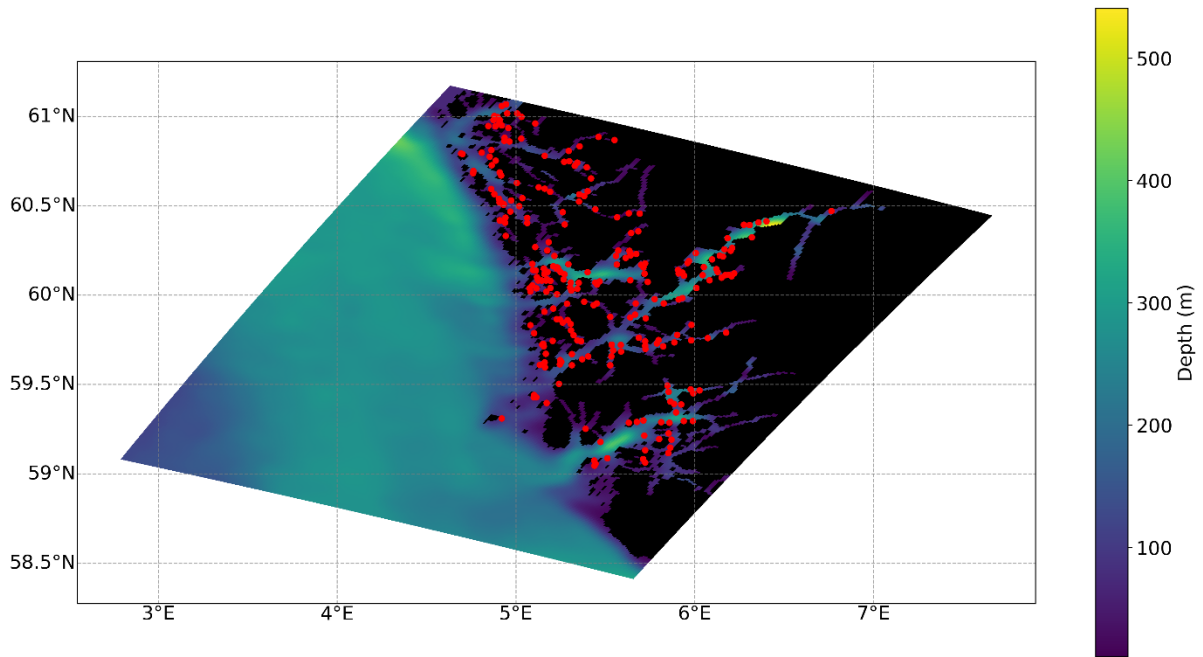


Figure 3 - Location of aquaculture sites used as start locations (red spots) within the model domain.

There is a large variety of plastic types released from aquaculture sites; we chose to parameterise for polypropylene microplastic. Polypropylene is widely used for amongst other things marine ropes. It has a density of  $\sim 900\text{kg/yr}$  meaning it is positively buoyant, whilst other significant sources of plastic, for example the nylon, which comprises the nets of the open cages, are negatively buoyant. Floating particles are more likely to be transported further therefore we model these as a worst case for connectivity. The length of time that viruses can survive at sea has been shown to be extended on biofouled plastic, with more than half still detectable after 10 days (Wang et al. 2024) so we use this period for the duration of the drifts and focus on the spring season for which the model was run and with the spring bloom should represent the largest impact from biofouling.

Simulations with the coupled hydrodynamic/plastics dispersion Hardanger model were used to:

- 1) Identify plastics dispersion patterns and potential accumulation hotspots for aquaculture derived plastics in a fjord system.
- 2) Investigate the interaction of plastics with marine organisms and its effect in their distribution.
- 3) Identify where there were interconnections between aquaculture sites where plastics might act as vectors of infection, and if this alters with the inclusion of biofouling.
- 4) Conduct OSSE experiments assimilating synthetic hydrodynamic data from the NR to assess the impact on the distribution of plastics.

### III. SIMULATIONS RESULTS

#### MEDITERRANEAN

The dispersion patterns of microplastics and macroplastics in the Mediterranean Sea were derived from the high-resolution particle drift model MED20 and validated against recent field measurements. In Figure 4, the mean (2010-2013) surface (0-10 m) distribution of microplastics (>300 $\mu\text{m}$ ) and macroplastics (>20 cm) distribution is shown. These are strongly related to the distribution of sources (see Figure 2), being higher in areas with important riverine inputs (Algerian coast, Albanian coast in the Southern Adriatic, Turkish coasts in the Eastern Aegean and Levantine, see also Figure 1) and major river mouths (e.g. River Po/Adriatic, Nile/Levantine, Axios/Aegean)), as well as close to metropolitan cities (e.g. Barcelona, Rome, Athens etc.) and highly populated coastal areas. Large (>300 $\mu\text{m}$ ) microplastics, which are assumed to be totally removed, when some type of wastewater treatment is applied, appear more abundant in coastal areas with relatively high untreated wastewater, along the coasts of Italy, Greece, Turkey and Eastern Levantine, as well as near major North African cities (Cairo, Alexandria, Tunis, Tripoli etc.). The micro- and macroplastics distributions are also affected by near surface circulation (see Deliverable D8.6), which is particularly noticeable in the off-shore advection of floating particles from coastal source regions, as in the case of the northward current branching from the Algerian coastal jet or the dispersion of particles from the Asia Minor current towards the South Aegean. Increased concentration patches may be also noticed in some areas characterized by anticyclonic circulation (e.g. Gulf of Syrte, Ierapetra gyre) which favors the convergence/accumulation of floating particles.

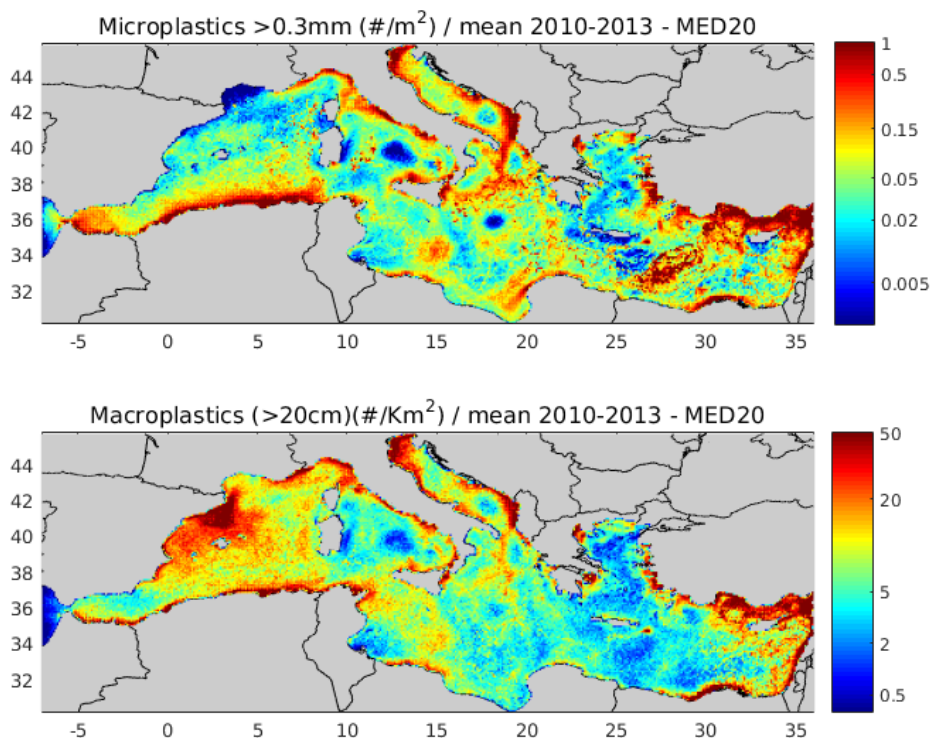


Figure 4 - Mean (2010-2013) distribution of macroplastics>20 cm (bottom, items/km<sup>2</sup>) and microplastics>300  $\mu\text{m}$  (top, items/m<sup>2</sup>) concentration in the Mediterranean Sea, as derived from the 4-year simulation of the NR (~ 5 km resolution, MED20).

In Figure 5, the mean (2010-2013) micro- and macroplastics distribution, simulated with MED20 model (i.e. Nature Run) is compared against available in situ data. A reasonable agreement was found, both in terms of magnitude and horizontal variability, capturing most

of the observed patterns, such as the increase of microplastics in the Ligurian Sea and North Adriatic coastal areas or the relatively lower concentration in the Gulf of Lion. The main model deviation for microplastics is the underestimated concentration in the Balearic Sea and the relatively overestimated/underestimated concentration along the Ligurian Sea coast and the Gulf of Lion (see also Tsiaras et al., 2021).

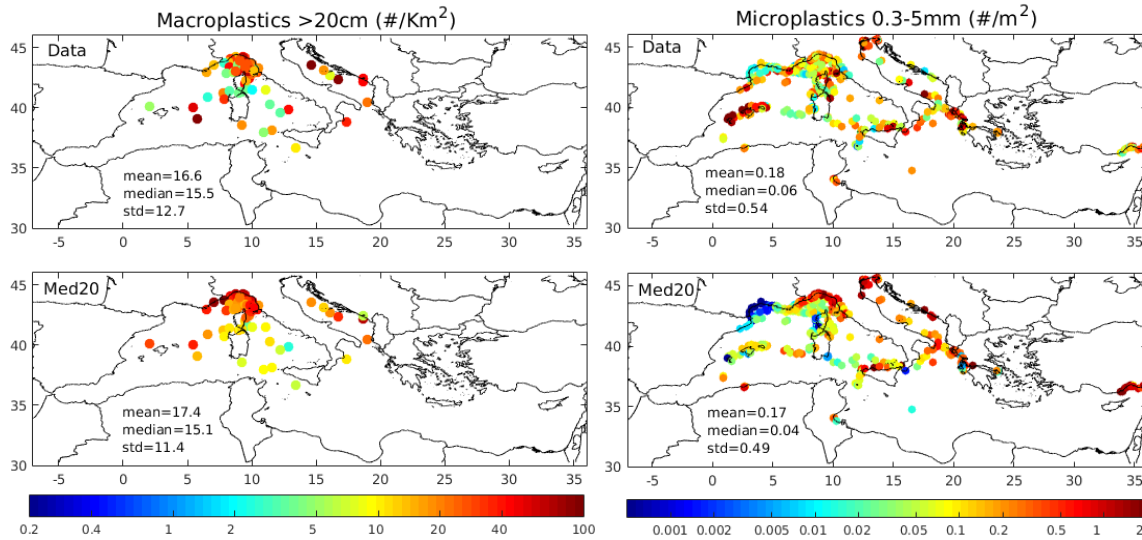


Figure 5 - Mean (2010-2013) macroplastics>20cm (left, items/km<sup>2</sup>) and microplastics>300  $\mu$ m (right, items/m<sup>2</sup>) concentration, simulated with the NR model (~ 5 km resolution, MED20), against available in situ data (see Tsiaras et al., 2021).

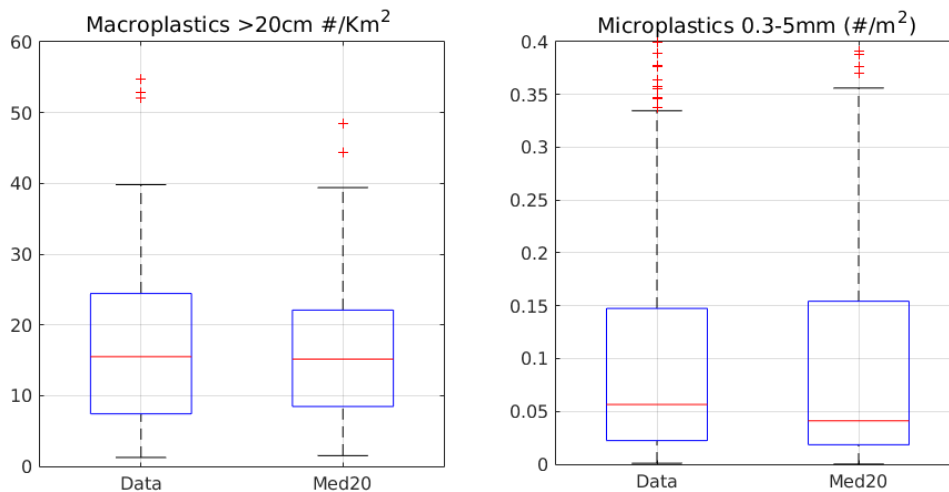


Figure 6 - Box plots, indicating the range, median and 25<sup>th</sup>/75<sup>th</sup> percentiles, of mean (2010-2013) simulated macroplastics>20cm (left, items/km<sup>2</sup>) and microplastics >0.3mm (items/m<sup>2</sup>) concentration, against in-situ data (see Figure 5).

Concerning the microplastics interaction with marine organisms, a simplified parameterization of biofilm growth has been included in the model, as a function of bacterial abundance (obtained from the biogeochemical model) that is considered as a proxy for the biofouling community. Based on the adopted formulation, smaller size microplastics (e.g. 350 $\mu$ m, 500 $\mu$ m) are gradually sinking due to the buoyancy loss resulting from the attachment of heavier biofilm, while the decrease of bacteria/algae below the euphotic zone results in the microplastics gradual defouling and relaxation at depths, where they acquire neutral

buoyancy (see Tsiaras et al., 2021 for more details). Given the dependence of biofouling on bacterial abundance, sinking is relatively faster in more productive areas. In these areas, the relaxation depth of microplastics is also found relatively deeper in the water column, given the slower defouling. As shown in Figure 7, the microplastics subsurface maximum depth is relatively higher in the Western Mediterranean, which is characterized by increased bacterial biomass, as compared to the Eastern Mediterranean, particularly the Levantine basin. In relatively shallow productive coastal areas, such as the Adriatic or the N. Aegean, microplastics may accumulate in the ocean floor (not shown).

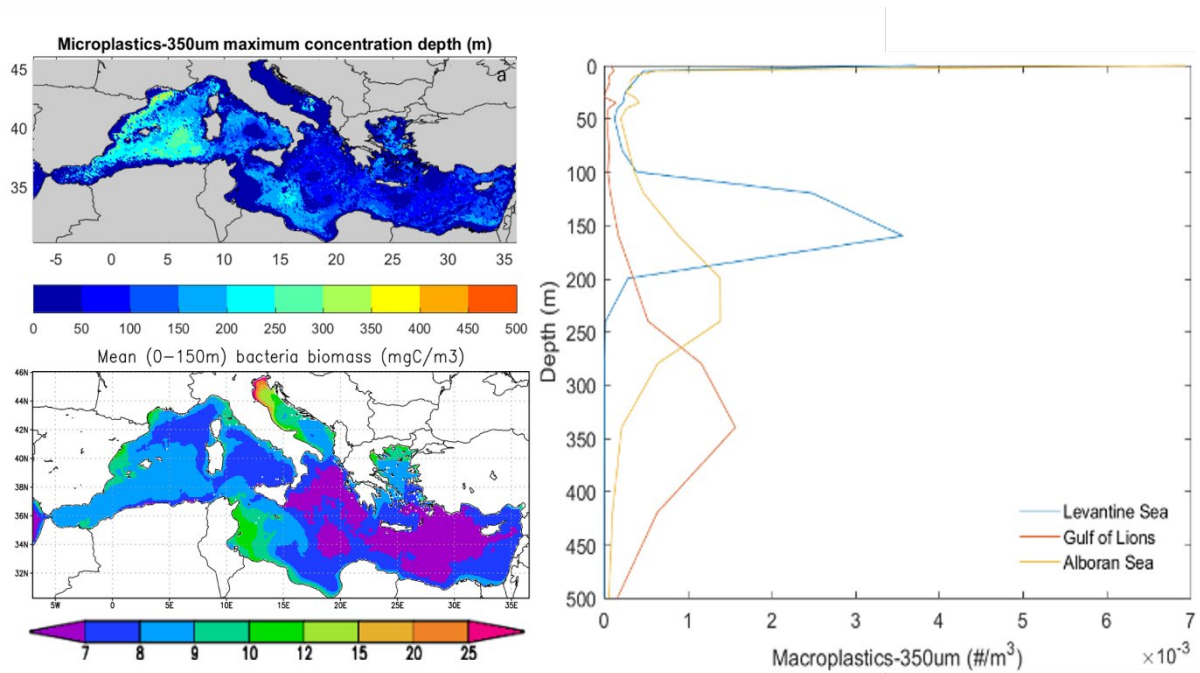


Figure 7 - Simulated annual mean (0-150m) bacterial biomass (mgC/m<sup>3</sup>) (left bottom), deep maximum depth (m) of microplastics (350 μm) (left top) and vertical distribution of microplastics (350 μm) concentration (items/m<sup>3</sup>), averaged in the Levantine basin (blue line), Gulf of Lions (orange line) and Alboran Sea (right).

To identify plastic pollution hotspots in protected areas and conservation-priority regions of the Mediterranean Sea, the simulated mean distribution of micro- and macroplastics (see Figure 4) was overlaid with key ecological habitats (see Figure 8). These include Cetacean Critical Habitats (CCH), Marine Protected Areas (MPAs), and significant seafood production sites (e.g., finfish and shellfish aquaculture), to assess areas potentially at risk from plastic pollution.

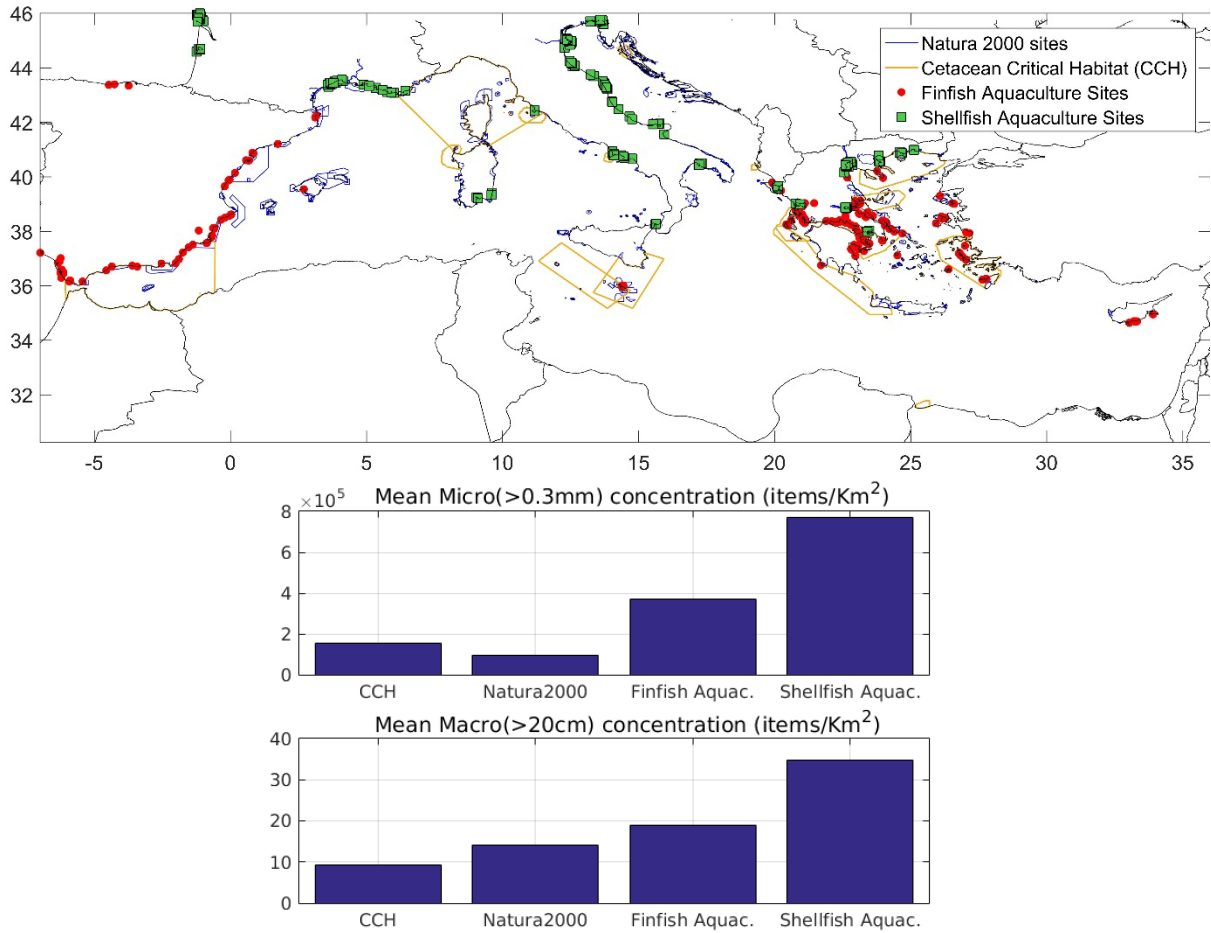


Figure 8 - Important ecological habitats (Cetacean Critical Habitats, Natura2000 sites) and aquaculture (finfish, shellfish) sites in the Mediterranean (top) and mean simulated microplastics>0.3mm and macroplastics>20cm concentrations (items/km<sup>2</sup>, bottom), averaged over different ecosystems layers (CCH, Natura2000, finfish/shellfish aquaculture).

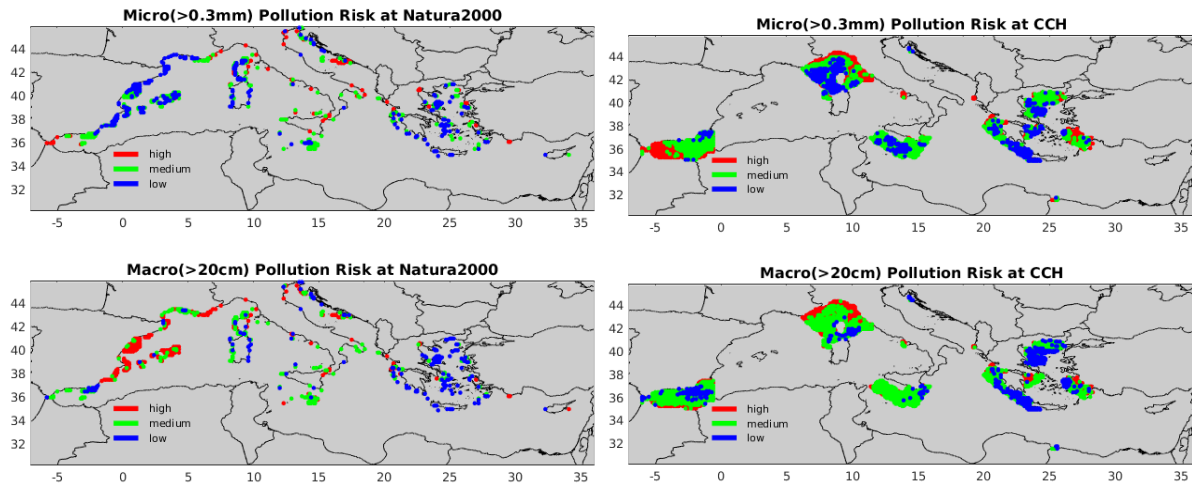


Figure 9 - Cetacean Critical Habitats (CCH, right) and Natura2000 (left) areas, classified with low (blue dots), medium (green dots) and high (red dots) pollution risk from microplastics>0.3mm (top) and macroplastics>20cm (bottom). The risk index is calculated based on the averaged area plastics concentration (C<sub>av</sub>), being lower or higher from the 25<sup>th</sup> (C<sub>25</sub>) and 75<sup>th</sup> (C<sub>75</sub>) basin-scale (see Figure 4 percentiles (i.e. low: C<sub>av</sub><C<sub>25</sub>, medium: C<sub>25</sub><C<sub>av</sub><C<sub>75</sub>, high: C<sub>av</sub>>C<sub>75</sub>).

As shown in Figure 8, the average concentration for both micro- and macroplastics is relatively higher at aquaculture sites, which are generally located in coastal and more polluted areas. This is particularly the case for shellfish aquaculture, which are mostly found in more productive river influenced areas (e.g. Adriatic, N. Aegean), where riverine inputs of plastics contribute to even higher concentrations (see also Figure 4). In Figure 9, CCH and Natura2000 sites are classified, based on their average plastics concentration, as being lower or higher when compared to the 25<sup>th</sup>/75<sup>th</sup> percentiles, calculated from the basin-scale plastics distribution (see Figure 4). As regards to microplastics, relatively more polluted Natura2000 sites are found in the Ligurian, Tyrrhenian and Adriatic Sea regions, with sites in the Spanish coast and Balearic Islands being also classified as highly polluted regarding larger macroplastics. We should note that the plastics distribution and respective pollution index may largely vary depending on the size and type of plastics, following their sources distribution. As regards to CCH, more polluted areas are found in the Ligurian/Alboran Seas and Southeastern Aegean (Dodecanese Islands).

A series of OSSE simulations were performed with the coarser resolution (MED10) forecast model to evaluate the benefit from assimilating NAUTILOS-like “synthetic” observations (temperature/salinity profiles and sea surface height/temperature) in the plastic dispersion model skill. The “synthetic” observations were obtained from the fine resolution (MED20) hydrodynamic model simulation representing the nature run, over 2010 (see Deliverable D9.1 for more details).

Three simulations were performed with the forecast model:

- a) Free model run without any data assimilation applied,
- b) Assimilation of 78 randomly selected TEM/SAL profiles (Assim78, see also Figure 10), corresponding to the pre-NAUTILOS ocean observation status, and
- c) Assimilation of 110 randomly selected TEM/SAL profiles (Assim110, see also Figure 10), corresponding to the post-NAUTILOS ocean observations implying a 40% increase in the ocean observations.

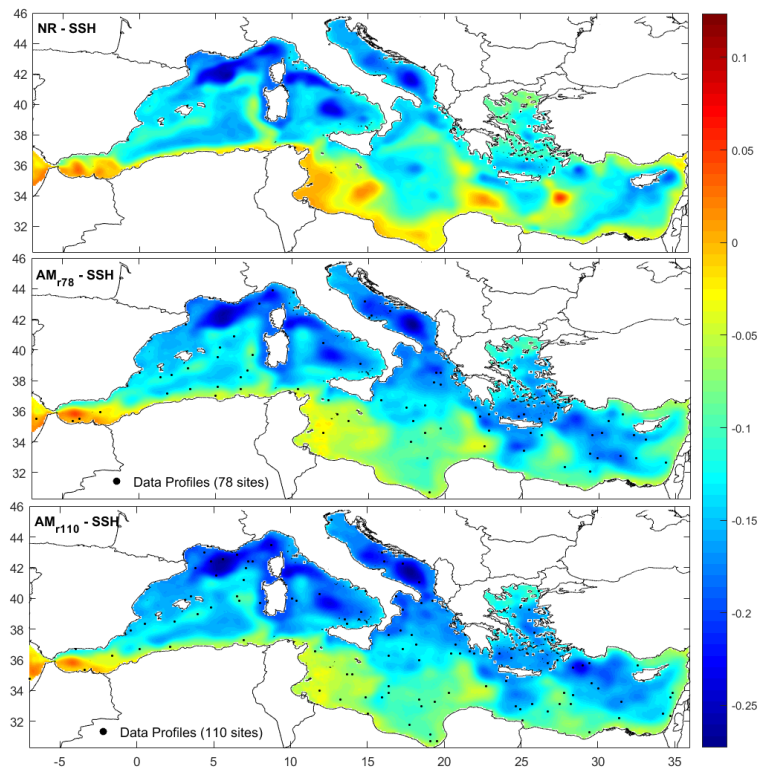


Figure 10 - Annual mean sea surface height (SSH, m), simulated with MED20 Nature Run (NR, top) and MED10, assimilating 78 ( $AM_{r78}$ ) and 110 ( $AM_{r110}$ ) randomly selected TEM/SAL profiles, along with SSH/SST surface data. Randomly selected TEM/SAL profiles are indicated.

The simulated distribution of plastics with MED10 model is then evaluated against MED20 distributions, being considered as the “truth”. In Figure 11, boxplot and Taylor diagrams are shown for micro- and macroplastics, simulated with the MED10 forecast model, against the nature run (MED20). For both micro- and macroplastics, MED10 simulated concentrations appear slightly lower, as compared with MED20 (see Figure X.9 boxplot). This may be largely attributed to the coarser resolution of MED10, resulting in relatively more frequent beaching of plastics particles, given the less fine representation of the coastline and coastal circulation, as well as the relatively stronger horizontal mixing. The latter process affects the stochastic (random) movement in the horizontal, which is mainly responsible for the beaching of lagrangian particles, along with wind/waves cross-shore transport. Comparing the different MED10 simulations, in the case of macroplastics, one may notice a slight increase in the model skill (i.e. decrease of RMS error and increase of correlation), when assimilating the relatively higher amount of post-NAUTILOS ocean observations (Assim110, see Figure 11 Taylor diagram), as compared to the pre-NAUTILOS experiment (Assim78) and the Free run (without any data assimilation). In the case of microplastics, the three experiments show a quite similar skill (see Figure 11 Taylor diagram), suggesting that the simulated microplastics distribution is less affected by circulation and thus the number of assimilated observations from the nature run. This might be related to the microplastics distribution, being more directly related to the land sources distribution, as biofouling induced sinking results in a relatively shorter period of floating at sea, as compared with larger macroplastics that may retain their buoyancy for a longer period and thus travel long distances in the open sea (see e.g. Fazey and Ryan, 2016).

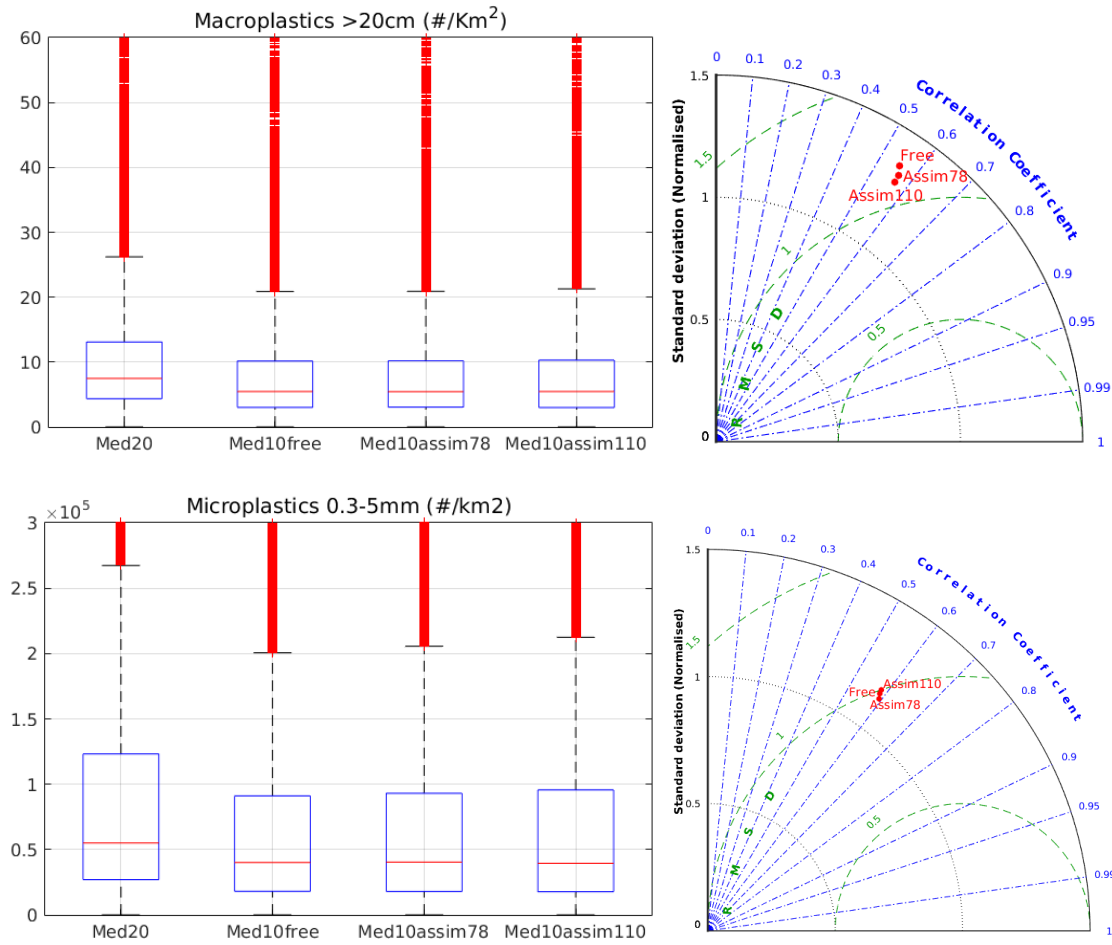


Figure 11 - Box plots (left) and Taylor diagrams (right) of macroplastics >20 cm (top) and microplastics >30  $\mu$ m (bottom) assimilation experiments (Assim78, Assim110) against free run (Med10free) and Nature Run (Med20).

### HARDANGER FJORD SYSTEM

The distribution and potential hotspots for aquaculture derived microplastics was modelled, and the resulting distribution is shown when using currents from the nature run (see Figure 12) and with coarser resolution model assimilating pre- and post-NAUTILOS observations (see Figure 13). The general pattern shows that transport is contained within the main fjord systems, with some particles reaching the coastal current and being transported northwards.

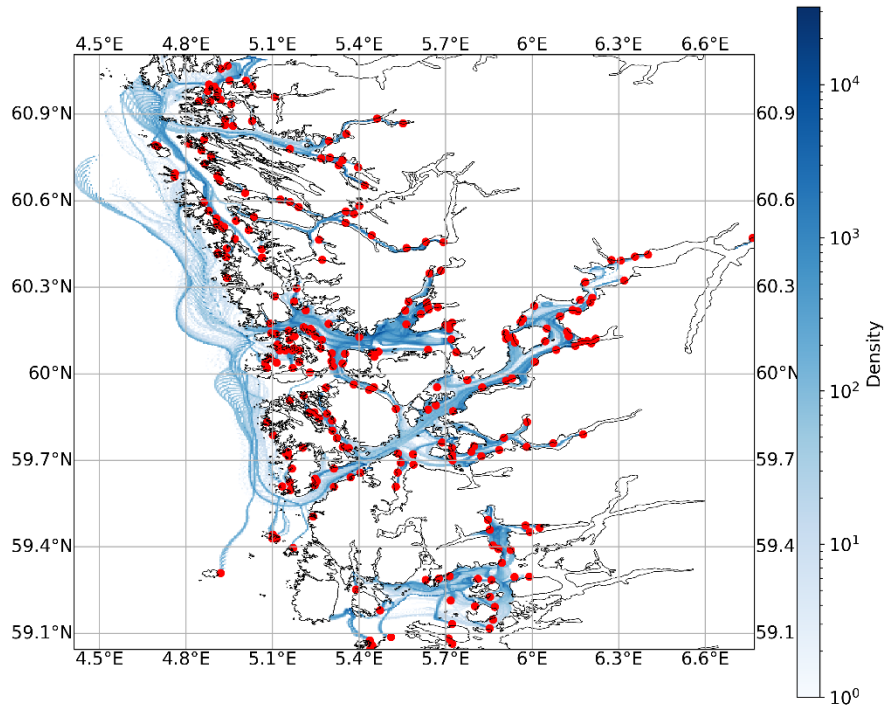


Figure 12 - Concentration of microplastics (particles per  $m^2$ ) in the nature run with non-biofouling particles. The concentrations should be taken to show relative impact rather than absolute numbers as they will scale with the input (here 10,000 particles per aquaculture site).

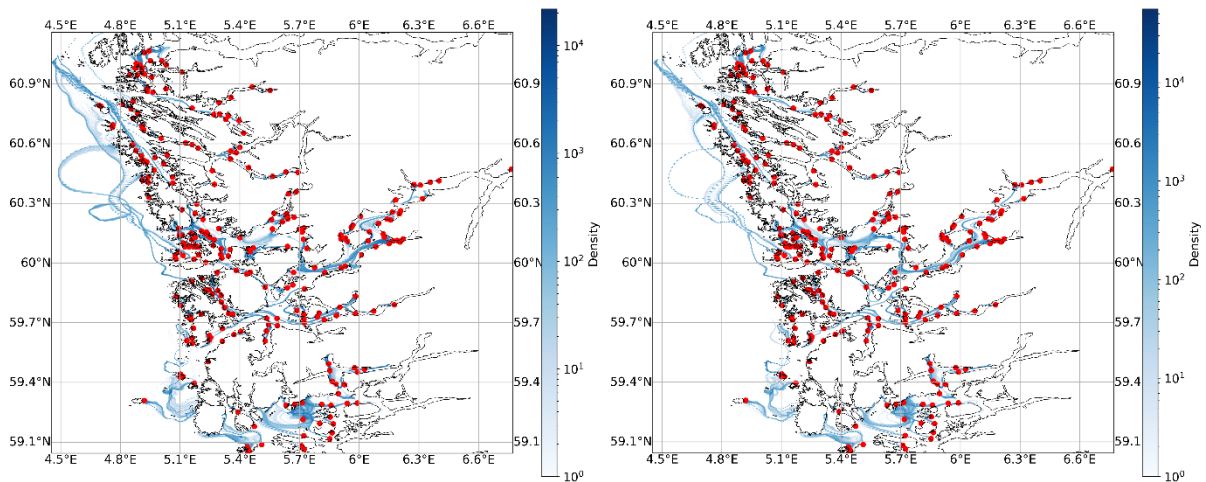


Figure 13 - Concentration of microplastics (particles per  $m^2$ ) simulated with the coarse resolution model, assimilating pre-NAUTILOS (left) and post-NAUTILOS (right) observations.

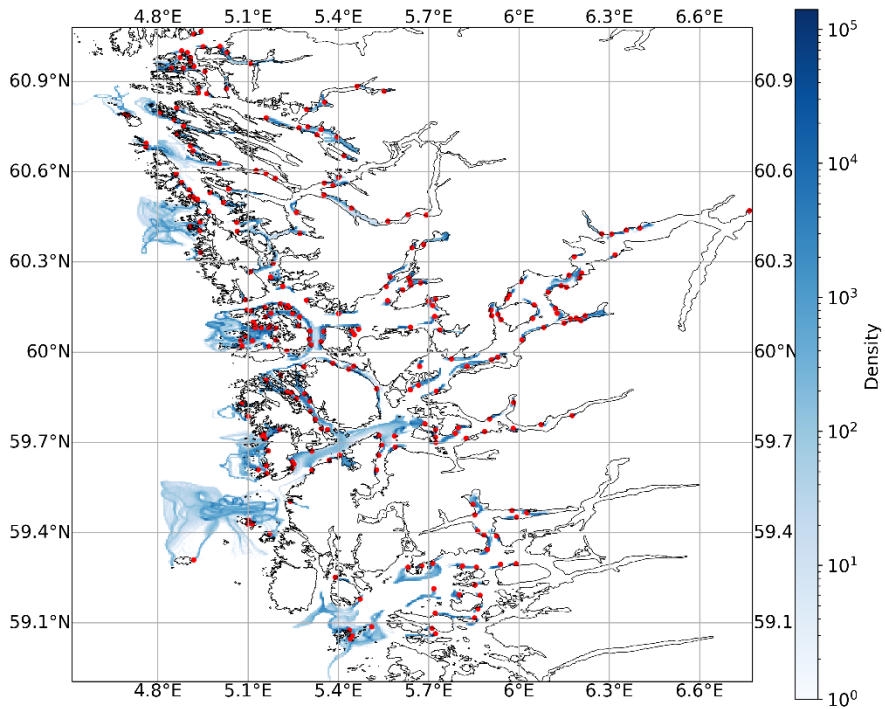


Figure 14 - Concentration of microplastics (particles per m<sup>2</sup>) in the nature run using biofouling particles.

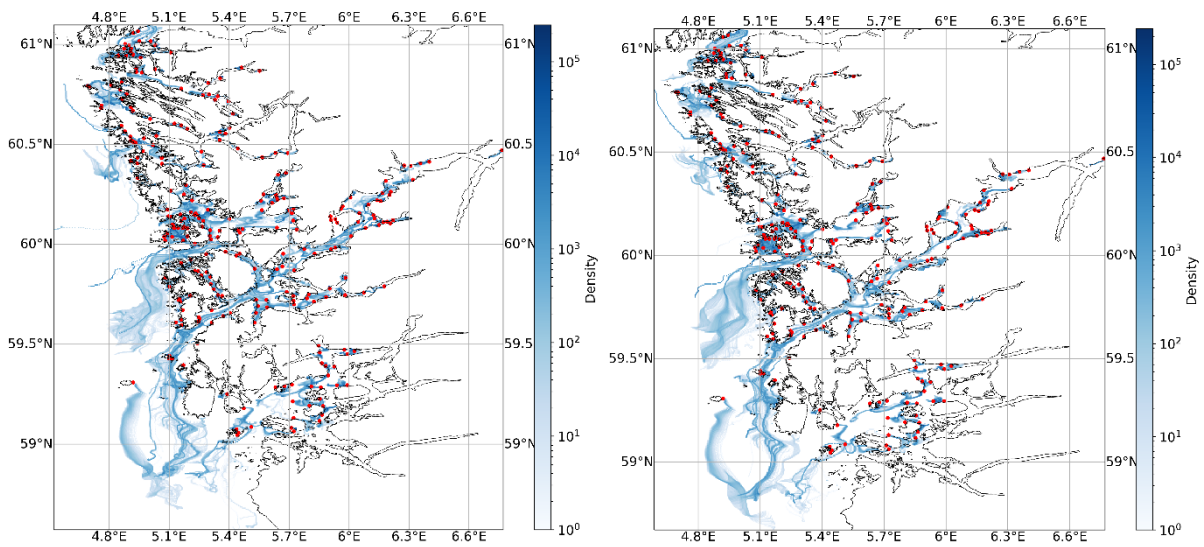


Figure 15 - Concentration of microplastics (particles per m<sup>2</sup>) in the pre-NAUTILOS (left) and post-NAUTILOS (right) driven run when using biofouling.

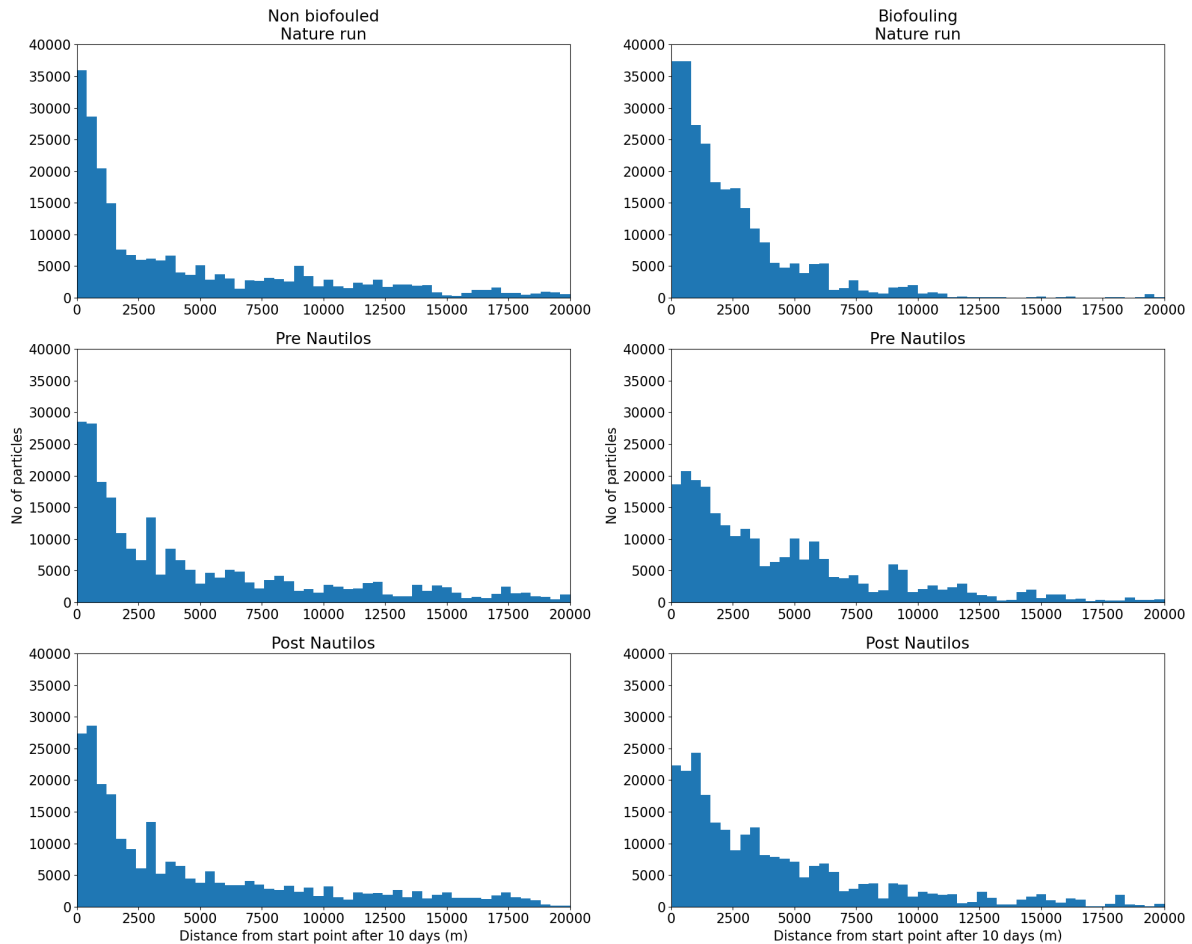


Figure 16 - The distance the particles travelled from their start point to the end of the model run for the nature run (top), pre-NAUTILOS (middle) and post-NAUTILOS (bottom) forcing and using the non-biofouling (left column) and biofouling (right column) models.

We see that when including biofouling in the nature run the travel distances are reduced with many particles staying near the coast (see Figure 14 and 15), especially very few travel more than 5km from the start point and remain mostly within 2.5 km of the start location (see Figure 16). This is expected as the particles sink with biofouling and generally currents at depth are weaker than those near the surface. In the pre- and post-NAUTILOS runs however we see a more complex result. Whilst very long transport (> 10 km) is reduced, the average distance travelled increases (see Figure 16).

This is likely related to the coastal stranding scheme used in the model. Particles held at the surface encounter stronger (and more wind affected) currents, the stranding scheme in OpenDrift stops particles which hit the coastline. Whilst the currents in the forcing model should not take particles onshore two factors – the timestep used in the particle model, and the mismatch between the realistic coastline and the model grid - can result in particles reaching the coast regardless. This is especially pronounced in the coarser resolution model, where the mismatch in coastline is greater and there are fewer grid cells to resolve the current aligning with the coast nearshore making the timestep more critical.

As a concern from aquaculture derived plastics is the possibility to act as a vector for infection the connectivity between the sites under the different runs was examined (see Figure 17). Connectivity was defined as if the particles came within a set distance (200 m) of a farm other

than its origin. The depth of the particle was not considered, so those with biofouling may be at depth when in the vicinity of a neighbouring farm.

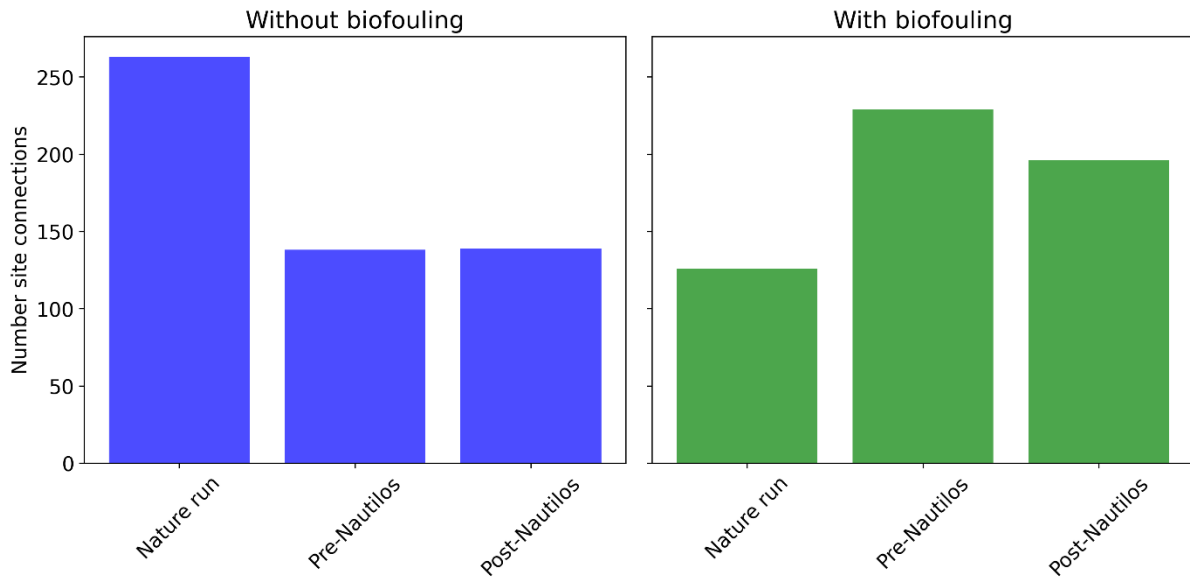


Figure 17 - Number of site connections.

When studying non-biofouling particles, the nature run demonstrates a connectivity rate twice that of the coarser model. This reflects both the slightly longer distances travelled and the currents remain more constrained to the coasts, and therefore the farms, with the higher resolution forcing. More surprising is that the inclusion of biofouling increases the connectivity of coarser model run whilst having the opposite effect on the nature run. Overall the number of farms with connectivity to at least one other farm was 56% - 71% across all runs, demonstrating the risk of plastics as a disease vector in this region.

Comparing the pre- to post-NAUTILOS simulations shows small differences with the connectivity in post-NAUTILOS being very slightly closer to the nature run, however the change is considerably smaller than the differences driven by the change of model resolution. The assimilation scheme also only includes temperature and salinity, this will not impact tidal currents which likely contribute in particular to the longer distances travelled by some particles within the fjord system.

## IV. DISCUSSION

### MEDITERRANEAN

---

The simulated distributions of micro- and macroplastics were strongly related to the distribution of included land-based sources, being higher in areas with important riverine inputs and highly populated coastal areas. These distributions were also affected by near surface circulation, which was mostly noticed in the off-shore advection of floating particles from coastal source regions and relatively higher concentration patches in areas characterized by anti-cyclonic circulation. The simulated distributions were found in reasonable agreement with available in situ data, both in terms of magnitude and horizontal variability. We should note that the included sources of plastics are characterized by significant uncertainty, in both their amount and distribution. Riverine inputs were based on a global empirical model (Lebreton et al., 2017), using only one Mediterranean River, while a uniform microplastics concentration of (influent) wastewater was considered for the entire Mediterranean, in the absence of available data from different countries. The simulated distribution of micro- and macroplastics was overlaid with key ecological habitats, such as Cetacean Critical Habitats and Natura2000 sites to assess the potential risk from plastic pollution.

A series of OSSE simulations (see also Deliverable D9.1) were performed with the coarser resolution (MED10) forecast model to evaluate the benefit from assimilating NAUTILOS-like “synthetic” observations (temperature/salinity profiles and sea surface height/temperature) in the plastic dispersion model skill. For both micro- and macroplastics, MED10 simulated concentrations were slightly lower, as compared with the fine-resolution model, which is likely attributed to the coarser resolution of MED10, resulting in relatively more frequent beaching of plastics particles, given the less fine representation of the coastline and coastal circulation. In the case of macroplastics, assimilating a relatively higher amount (+40%) of post-NAUTILOS ocean observations resulted in a slightly increased model skill (see Table 1) in reproducing the Nature Run macroplastics distribution, as compared to the pre-NAUTILOS experiment and the Free run. In the case of microplastics, the model skill in pre- and post-NAUTILOS assimilation experiments was quite similar to the free run, showing no improvement from additional post-NAUTILOS ocean observations (see Table 1). This outcome was attributed to the microplastics distribution being less affected by circulation, but more strongly related with the land sources distribution, as biofouling induced sinking results in a relatively shorter residence time, as compared with larger macroplastics that may travel long distances floating in the open sea. Furthermore, both micro- and macroplastics distributions are mainly affected by near surface circulation. Given that NAUTILOS-like ocean observations mainly refer to temperature/salinity profiles in the water column, additional post-NAUTILOS observations have a limited impact on near surface circulation, as suggested by the small improvement of sea surface height (Figure 18, see also Deliverable D9.1). We should note that both macro- and microplastics particles are also subject to stochastic (i.e. random) movement, which results in a not entirely predictable distribution, under small changes in the circulation field.

Table 1 - Relative RMSD (RRMSD) decrease (%) in assimilation runs (Assim78, Assim110) compared to the free run ((AM/FR-1)\*100) for micro- and macroplastics.

RRMSD (%) (AM/FR-1)*100	Microplastics	Macroplastics
Assim78	-1.6	-2.7
Assim110	+0.9	-5.0

**Taylor diagram of SSH (Med. Sea)**

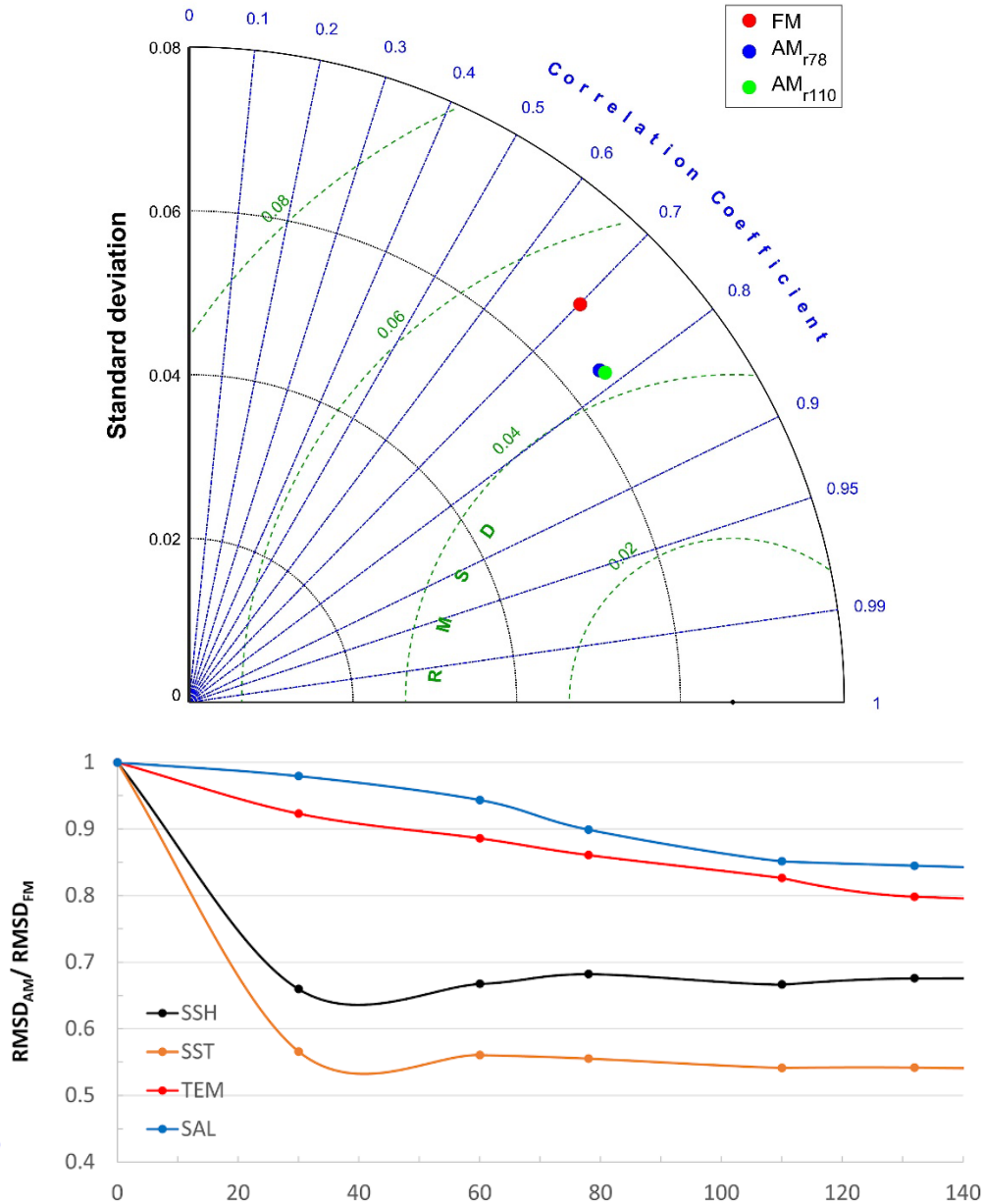


Figure 18 - Taylor diagram of sea surface height (SSH) (top) and relative RMSD for SSH, SST, TEM and SAL (bottom) of the assimilation models (AM) compared to the free model run (FM) for the selected variables, computed over the entire model domain, as a function of the number of uniformly distributed assimilation points (up to the first 140 locations).

## HARDANGER FJORD SYSTEM

---

The distribution of plastics between aquaculture sites in the Hardanger fjord system was investigated in several model runs. The runs were setup to investigate the possibility of particles as vectors of virus transport. It was therefore chosen to represent plastic derived from aquaculture ropes (which is buoyant and therefore likely to transport further) and use a time window of 10 days corresponding to virus survival.

The largest difference in results between model runs when using floating particles (with biofouling turned off) is driven by the grid resolution. This is consistent with other studies on particle dispersal (Nooteboom et al., 2020). The higher resolution nature run represents strong current jets more accurately and transport along coastlines. As aquaculture sites are concentrated in the nearshore and in areas with strong currents (which are preferred to disperse waste) this results in a much higher connectivity between farms in the nature run than the coarser resolution pre- and post-NAUTILOS runs.

The inclusion of the new biofouling model also has a significant impact, reducing the distances travelled in the nature run and also halving the connectivity between sites. This reflects that the biofilm growth on the particles increases their density, causing them to sink to a depth where currents are lower, or to the seabed where they are caught till resuspending. The biofouling module includes the growth and dynamic change of biofilm on the particles based on modelled phytoplankton concentrations. It does not include ingestion by zooplankton which can lead to faster sinking times in the fecal pellets (Berezina et al., 2021). Paradoxically, when implemented in the coarser resolution model, the biofouling led to an increase in distances travelled and connectivity. This may be a result of the numerics of the handling of coastlines in OpenDrift, where weaker sub-surface currents may lead to decreased beaching, and highlights the importance of considering all aspects of a model setup when implementing new features.

The OSSE experiment showed relatively small differences in the distribution compared to either the grid resolution or the inclusion of biofouling. Whilst the assimilation of temperature and salinity profiles will improve the representation of the vertical structure of the water column, and subsequently the currents, the primary drivers such as winds and tides will not be affected. In a fjordic environment the vertical structure might play a large role in the biological activity, but short distance transport (stranding) will be influenced predominantly by the wind at the surface and long distance transport by the energetic tidal straits where the vertical structure is relatively homogenous, neither of these will be greatly influenced by the assimilation.

Unfortunately, there is no validation data available for this region, so whilst the study highlights a potential impact, it does not give quantitative particle density information. A follow up using the microplastic sensors developed with NAUTILOS to quantify the impact, combined with these density maps would be highly valuable. The current model setup treats all farms identically and does not include other plastic sources, which are areas for possible improvement in the setup.

## V. IMPACT OF NAUTILOS-LIKE OBSERVATIONS ON PARTICLES ADVECTION DIFFUSION OCEAN FORECASTING

A series of OSSE simulations were performed to evaluate the impact of improved hydrodynamics from assimilating NAUTILOS-like “synthetic” observations (temperature/salinity profiles) in the simulated distribution of plastics. Two Lagrangian particle drift models, coupled with hydrodynamic/biogeochemical models, were implemented, covering two different marine environments and scales (Mediterranean basin-scale, Hardangerfjord coastal scale).

In the Mediterranean, assimilating a relatively higher amount (+40%) of post-NAUTILOS ocean observations resulted in a small but noticeable improvement in the skill of the simulated macroplastics, as compared to the pre-NAUTILOS experiment and the Free run. In the case of microplastics, no improvement from additional post-NAUTILOS ocean observations was found, with the model skill in pre- and post-NAUTILOS assimilation experiments being quite similar with the free run. This relatively weaker effect of improved near surface circulation on microplastics distribution might be attributed to biofouling induced sinking, which results in a relatively short residence time at surface, as compared with larger macroplastics that may travel long distances floating in the open sea. Moreover, given that NAUTILOS-like ocean observations mainly refer to temperature/salinity profiles in the water column, the improvement on near surface circulation, which primarily affects both micro- and macroplastics distributions, was relatively small.

In the Hardangerfjord, the OSSE experiments showed that the assimilation of a higher amount of post-NAUTILOS ocean observations (temperature and salinity profiles) resulted in relatively small differences in the microplastics distribution. While the assimilation of temperature and salinity profiles improved the representation of the vertical structure in the water column (see Deliverable D9.1), this did not affect the microplastics transport. In a fjordic environment, short distance transport (stranding) is predominantly affected by near surface currents, which are mostly influenced by wind, while long distance transport is mostly controlled by energetic tidal straits. These two primary drivers for microplastics transport were not significantly influenced by the assimilation of additional temperature and salinity profiles. On the other hand, considering the quite complex bathymetry of the Hardangerfjord area, the model resolution and time step, affecting the successful representation of the coastline (i.e. beaching) and current jets, had an important impact on microplastics transport. Given the limited availability of in situ observations of microplastics in this region, a follow up using the microplastic sensors developed with NAUTILOS would be highly valuable to quantify the potential impact and validate the simulated microplastics distributions.

In both Mediterranean and Hardangerfjord, the adopted parameterization for biofouling induced sinking is characterized by significant uncertainty, given the lack of sufficient experimental data on this process. Moreover, existing observations on the microplastics vertical distribution in the water column are currently very limited (no such observations in the Mediterranean or Hardanger), due to the large sample volume that is required. Thus, the SCT microplastic sampler (SuNaMiPS), developed within NAUTILOS, is expected to provide cost-effective underwater measurements that would be highly valuable to provide evidence on the microplastics vertical distribution and evaluate the model parameterizations.



## VI. CONCLUSIONS AND RECOMMENDATIONS

The results obtained in Task 9.3 and presented above in this report provided useful insight on the effect of various factors (model resolution, biofouling, ocean circulation) on the distribution of plastics in two different areas (Mediterranean, Hardangerfjord) and potential impacts on ecological habitats and aquaculture sites. The performed OSSE simulations indicated that microplastics distributions were less sensitive to the improved hydrodynamics from assimilating additional post-NAUTILOS ocean observations (temperature/salinity profiles). However, the macroplastics (Mediterranean) forecast skill presented a small but noticeable improvement, which suggests a stronger impact of circulation on floating litter with relatively higher residence time at sea. Thus, the assimilation of available satellite and in situ hydrodynamic data is expected to further improve the forecast skill of modelling tools for the assessment of marine litter pollution. Despite this, the existing knowledge on the sources of plastics is still fragmented and characterized by important uncertainty, in both their amount and distribution. For instance, the adopted riverine inputs in the Mediterranean were based on a global empirical model (Lebreton et al., 2017), using only one Mediterranean River, while a uniform microplastics concentration of (influent) wastewater was considered for the entire Mediterranean, in the absence of available data from different countries. While there are efforts to better quantify land-based inputs of plastics (e.g. González-Fernández et al., 2021), there is a need for more systematic monitoring for both river and wastewater inputs, particularly for microplastics. Similarly no observations of microplastics existed in the Hardanger fjord and the quantity released from aquaculture sites is an open question. Even though monitoring of plastics in the marine environment has been significantly enhanced over the last decade, the data coverage is still poor in some areas (e.g. Eastern Mediterranean), while available in situ data are still not sufficient to resolve the seasonal variability of plastics abundance. The use of cost-efficient new sensors for microplastics, developed within NAUTILOS, is expected to significantly contribute to cover such gaps. Moreover, given that existing observations on microplastics in the water column are currently scarce, the SCT microplastic sampler, also developed within NAUTILOS, is expected to provide cost-effective underwater measurements that would be highly valuable to provide evidence on the microplastics vertical distribution and evaluate model parameterization on biofouling induced sinking.

## VII. REFERENCES

- Baretta, J.W., Ebenhöh, W., Ruardij, P., 1995. The European regional seas ecosystem model, a complex marine ecosystem model. *Netherlands Journal of Sea Research*, 33, 233–246.
- Berezina, A., Yakushev, E., Savchuk, O., Vogelsang, C., & Staalstrom, A. (2021). Modelling the influence from biota and organic matter on the transport dynamics of microplastics in the water column and bottom sediments in the Oslo fjord. *Water*, 13(19), 2690.
- Blumberg, A. F., Mellor, G.L., 1983. Diagnostic and prognostic numerical circulation studies of the South Atlantic Bight. *Journal of Geophysical Research*, 88, 4579–4592.
- Butenschön, M., Clark, J., Aldridge, J. N., Allen, J. I., Artioli, Y., Blackford, J., et al. 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. *Geoscientific Model Development*, 9(4), 1293-1339.
- Cholewińska, P., Moniuszko, H., Wojnarowski, K., Pokorny, P., Szeligowska, N., Dobicki, W., ... & Górniak, W., 2022. The occurrence of microplastics and the formation of biofilms by pathogenic and opportunistic bacteria as threats in aquaculture. *International Journal of Environmental Research and Public Health*, 19(13), 8137.
- Cózar, A., Echevarría, F., González-Gordillo, J. I., Irigoien, X., Úbeda, B., Hernández-León, S., et al. 2014. Plastic debris in the open ocean. *Proc. Natl. Acad. Sci. U.S.A.*, 111, 10239–10244. doi: 10.1073/pnas.1314705111
- Dagestad, K.-F., Röhrs, J., Breivik, Ø., and Ådlandsvik, B., 2018. OpenDrift v1.0: a generic framework for trajectory modelling, *Geosci. Model Dev.*, 11, 1405-1420. doi: 10.5194/gmd-11-1405-2018.
- Fazey, F. M. C., and Ryan, P. G., 2016. Debris size and buoyancy influence the dispersal distance of stranded litter. *Mar. Pollut. Bull.* 110, 371–377. doi:10.1016/j.marpolbul.2016.06.039
- Gomiero, A., Haave, M., Kögel, T., Bjorøy, Ø., Gjessing, M., Lea, T. B., et al. 2020. TRACKing of PLASTtic emissions from aquaculture industry (TrackPlast).
- González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., et al. 2021. Floating macrolitter leaked from Europe into the ocean. *Nat. Sustainabil.*, 4, 474–483.
- Gunther, H., Behrens, A., 2012. The WAM model. Validation document Version 4.5.4, Institute of Coastal Research Helmholtz-Zentrum Geesthach (HZG).
- Kalaroni, S., Tsiaras, K., Petihakis, Economou-Amilli, A., Triantafyllou, G., 2020a. Modelling the Mediterranean Pelagic Ecosystem using the POSEIDON ecological model. Part I: Nutrients and Chlorophyll-a dynamics. *Deep-Sea Research*, PT II, 104647.
- Kalaroni, S., Tsiaras, K., Petihakis, G., Economou-Amilli, A., Triantafyllou, G., 2020b. Modelling the Mediterranean Pelagic Ecosystem using the POSEIDON ecological model. Part II: Biological dynamics, *Deep-Sea Research*, PT II, 171, 104711.

Kjørboe, T., Tang, K., Grossart, H.-P. and Ploug, H., 2003. Dynamics of microbial communities on marine snow aggregates: colonization, growth, detachment, and grazing mortality of attached bacteria. *Appl. Environ. Microbiol.* 69, 3036–3047. doi: <https://journals.asm.org/doi/10.1128/AEM.69.6.3036-3047.2003>.

Kooi, M., Nes, E. H. V., Scheffer, M., Koelmans, A.A., 2017. Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. *Environmental Science & Technology*, 51(14), 7963-7971.

Korres, G., Hoteit, I., Triantafyllou, G., 2007. Data assimilation into a Princeton Ocean Model of the Mediterranean Sea using advanced Kalman filters. *Journal of Marine Systems*, 65, 84–104.

Lebreton, L. C. M., Greer, S. D., Borrero, J. C., 2012. Numerical modelling of floating debris in the world's oceans. *Mar. Pollut. Bull.*, 64, 653–661. doi:10.1016/j.marpolbul.2011.10.027.

Lebreton, L., van der Zwet, J., Damsteeg, J., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. *Nat. Commun.*, 8, 15611. doi: 10.1038/ncomms15611.

Mohsen, M., Lin, C., Hamouda, H.I., Al-Zayat, A.M., Yang, H., 2022. Plastic-associated microbial communities in aquaculture areas. *Frontiers in Marine Science*, 9, 895611.

Nooteboom, P. D., Delandmeter, P., van Sebille, E., Bijl, P. K., Dijkstra, H. A., & von der Heydt, A. S. (2020). Resolution dependency of sinking Lagrangian particles in ocean general circulation models. *PloS one*, 15(9), e0238650.

PlasticEurope, 2020. *Plastics – the Facts 2020 An analysis of European plastics production, demand and waste data*. Bruxelles: Plastics Europe.

Pollani, A., Triantafyllou, G., Petihakis, G., Konstantinos, N., Dounias, K., Koutitas, C., 2001. The Poseidon operational tool for the prediction of floating pollutant transport. *Marine Pollution Bulletin*, 43, 270–278.

Ravdas, M., Zacharioudaki, A., Korres, G., 2018. Implementation and validation of a new operational wave forecasting system of the mediterranean monitoring and forecasting centre in the framework of the copernicus marine environment monitoring service. *Nat. Hazards Earth Syst. Sci.*, 18, 2675–2695. doi: 10.5194/nhess-18-2675-2018.

Scheffer, M., Baveco, J.M., DeAngelis, D.L., Rose, K.A., van Nes, E.H., 1995. Super-individuals a simple solution for modelling large populations on an individual basis. *Ecological Modelling*, 80(2–3), 161-170.

Tsiaras, K., Costa, E., Morgana, S., Gambardella, C., Piazza, V., Faimali, M., Minetti, R., Zeri, C., Thyssen, M., Ben, I.S., Hatzonikolakis, Y., Kalaroni, S., Garaventa, F., 2022. Microplastics in the Mediterranean: Variability from Observations and Model Analysis. *Frontiers in Marine Science*, 9, 784937.

Tsiaras, K., Hatzonikolakis, Y., Kalaroni, S., Pollani, A., Triantafyllou, G., 2021. Modeling the pathways and accumulation patterns of micro- and macro-plastics in the Mediterranean. *Frontiers in Marine Science*, 8, 743117.

Wu, H., Hou, J., Wang, X., 2023. A review of microplastic pollution in aquaculture: Sources, effects, removal strategies and prospects. *Ecotoxicology and Environmental Safety*, 252, 114567.