NET4mPLASTIC PROJECT

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Implementation of the numerical model and first results obtained with a a 3D transport model calibrated for microplastics

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1 Introduction

Numerical models, aided with *in situ* and remote observations, are a powerful tool for the identification of potential sources of microplastics in the marine environment, their dispersion pathways and to highlight areas potentially at risk of impacts due to floating marine litter (both macro- and microplastics). Numerical models are commonly used to describe the 3D dynamics of coastal areas and of open seas, and in the last decades the Adriatic Sea has proven to be an ideal location for the implementation of several numerical models both in coupled and uncoupled configurations (Bajo et al., 2007, Benetazzo et al., 2013, Carniel et al., 2016, Skiric et al., 2013). The Po River Delta, from a modeling point of view, is an area of high interest due to its complex morphology and the strong influences of the river discharges. Apart from one recent work (Maicu et al, 2018), this river-sea systems is generally represented in numerical models in an uncoupled way using by freshwater sources located over the river mouths as boundary conditions to ocean hydrodynamical models (Falcieri et al., 2014).

In the framework of NET4mPLASTIC a dedicated numerical simulation of the Po delta (NET4mPLASTIC's Pilot Site 1, figure 1) was implemented using the Regional Ocean

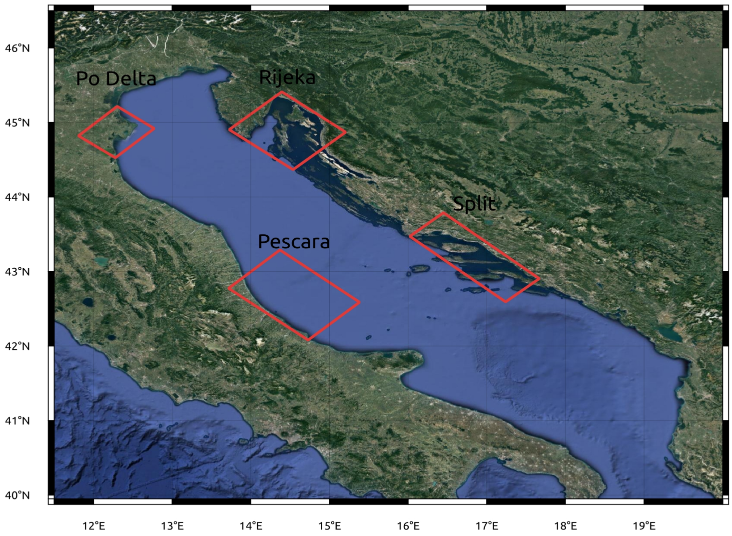

Figure 1: The NET4mPLASTIC four pilot sites in the Adriatic Se

Modelling System (Haidvogel et al., 2000; Marchesiello et al., 2003; Peliz et al., 2003; Di Lorenzo, 2007; Dinniman et al., 2003; Budgell, 2005; Warner et al., 2005, b; Wilkin et al., 2005). The resulting 3D temperature, salinity and current fields has been used as forcings for a Lagrangian model (ICHTHYOP, Lett et al., 2008) that will simulate the microplastic dispersion pathways and potential accumulation sites. Lagrangian models have been previously used to track micro- and macro- plastic debris in the Adriatic Sea. Most of the available applications in literature (Carlson et al., 2017, Liubartseva et al., 2016, Atwood et al., 2019) cover short time periods or focus on specific events/processes. In NET4mPLASTIC we aim to run for each Pilot Site (PS1 – Po Delta, PS2 – Pescara coast, PS3 – Rijeka and PS4 – Split) a 4 years long simulation so that the resulting potential distribution maps will cover a period of time sufficient to give a statistical relevance. The location and size of the pilot sites have been identified with the collaboration of all of the project partners with the aim to cover the project sampling locations.

In this deliverable the overall implementation of the hydrodynamical model and of the the Lagrangian simulation will be described in details. Pilot Site 1 will be used as an example. The implementation discussed will be the same used for the other NET4mPLASTIC pilot sites.

2 Hydrodynamical model set up

The Regional Ocean Modelling System (ROMS) is widely used numerical model based on a community developed code. The model's source code is freely available at (www.myroms.org) under the "MIT/X License" (http://www.opensource.org/licenses/mitlicenses.php). ROMS was initially developed and is currently maintained at Rutgers University (NJ, USA) in the early 1990's and has since become one of the most widely used hydrodinamic model in oceanographical applications. ROMS is a free surface ocean model with primitive equation that solves the Reynolds averaged form of the Navier-Stokes equations using the hydrostaic approximation. The horizontal grid is a curvilinear orthogonal Arakawa C gird (Arakawa and Lamb, 1997) while the vertical layers follow a stretched terrain following coordinates. ROMS is build with a modular

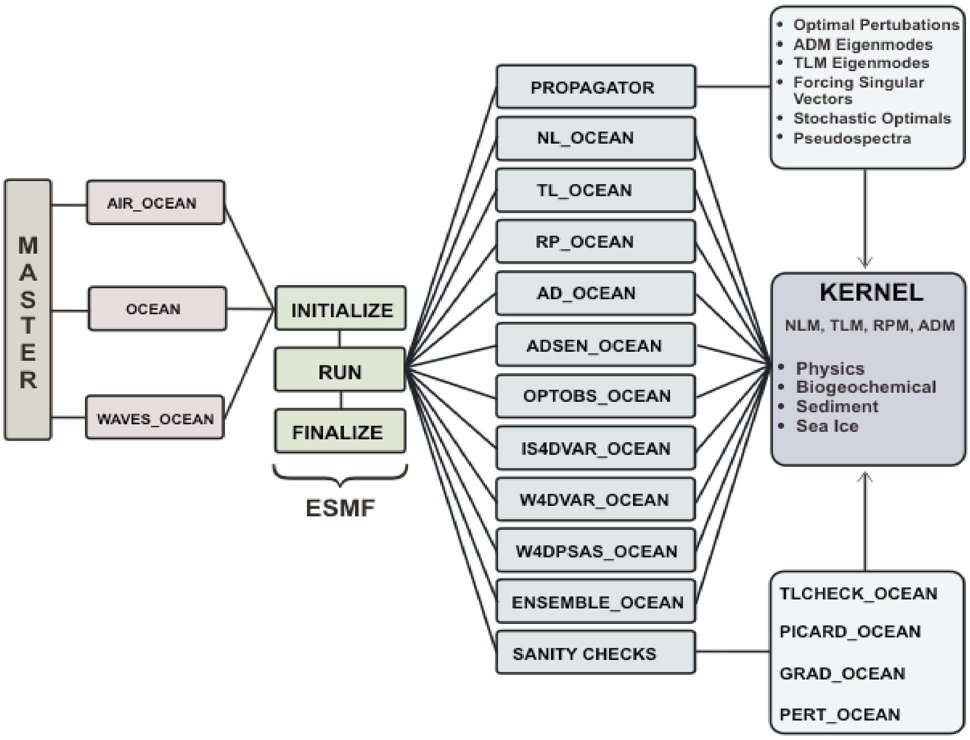

Figure 2: ROMS general structure. All the possible coupling pathways (air, ocean and waves) plus the sediment, biological and ice models are shown (www.myroms.org).

structure (figure 2) so to allow to adapt the physical and numerical set up to the environment and processes that are going to be simulated. ROMS can be coupled with a series of sub-model to simulate ocean-athmosphere fluxes, sediments, sediment's transport, biogeochemical cycles, sea-ice interaction and wave processes. Moreover the air-water interface fluxes are based on the bulk parametrization of Fairall et al. (1996, 2003); this at is an adaptation of the COARE (Coupled Ocean-Atmosphere Response Experiment) algorithm for the computation of surface fluxes of momentum, sensible heat, and latent heat. The details of the model numerics are described in Shchepetkin and McWilliams (2005) and in Haidvogle et al. 2008.

The model implementation is composed of several consequential steps:

1. Definition of the model code set up and of the physical processed that need to be included to simulate correctly the study area dynamics;
2. Grid creation and testing
3. Definition of run parameters and coefficients
4. Atmospherical forcing
5. Identification and application of boundary conditions
6. Riverine inputs

2.1 Simulation set up

For the NET4mPLASTIC implementation the latest release of ROMS was used (ROMS 3.8, svn revision 1046). The simulation set up is composed of a list of modules that are used to compile the ROMS source code. Each module represents a specific part of the code that adds a process or a parametrization to the final executable file. The activated modules selected in for the NET4mPLASTIC implementation are coherent with previous successful implementation of ROMS in the Adriatic Sea.

In table 1 all the modules used in the NET4mPLASTIC implementation are listed.

Module	**Description**
Momentum equations	
UV_ADV	Horizontal and vertical advection of momentum
UV_COR	Coriolis therm in the momentum equations
UV_VIS2	Harmonic horizontal mixing
UV_QDRAG	Quadratic bottom friction
SPLINES_VVISC	Splines reconstruction of vertical viscosity
Tracers equations	
TS_MPDATA	Recursive MPDATA 3D advection
TS_DIF2	Harmonic horizontal mixing for tracers
NONLIN_EOS	Non-linear equation of state
SALINITY	Include salinity in the equation of state
SOLAR_SOURCE	Include solar radiation term
SPLINES_VDIFF	Spline reconstruction of vertical viscosity for tracers
Pressure gradient algorithm	
DJ_GRADPS	Spline density Jacobian (Shchepetkin, 2003)
Surface fluxes	
BULK_FLUXES	To activate the bulk fluxes COARE parametrization (Fairall et al, 1996, 2003)
ATM_PRESS	Atmospheric pressure therm
COOL_SKIN	Cool skin correction
LONGWAVE	Compute net long-wave radiation
EMINSUP	Compute evaporation – precipitation

Model configuration options	
SOLVE3D	Solve the 3D primitive equations
CRUVGRID	Use a curvilinear grid
MASKING	Use grid masking
AVERAGES	Compute time averaged data in outputs
Analytica conditions	
ANA_BSFLUX	Analytical salinity flux at bottom (set to 0)
ANA_BTFLUX	Analytical temperature flux at bottom (set to 0)
Horizontal mixing	
MIX_GEO_TS	Mixing of tracers on geopotential surfaces
MIX_S_UV	Mixing of momentum along S−surfaces
Vertical mixing	
GLS_MIXING	Genericl Length Scale mixing
CHARNOCK	Charnock surface roughness
CRAIG_BANNER	Craig and Banner wave breaking surface flux
KANTHA_CLAYSON	Kantha and Clayson stability function (Kantha and Clayson,1999)
N2S2_HORAVG	Horizontal smoothing of buoyancy sheer
RI_SPLINES	Splines reconstruction for vertical sheer
Boundary Conditions	
Free surface	Chapman

Ubar/Vbar	Flather
U/V	Radiation/Nudging
TKE	Gradient
Temp/Salt	Radiation/Nudging

Table 1 ROMS modules activated in the NET4mPLASTIC implementation

2.2 Grid creation and testing

To correctly represent the coastal and plume dynamics in a delta area high horizontal resolutions are needed; in the case of the Po delta a 100 m horizontal resolution can be considered sufficient to provide a good representation of the main coastal currents (due to the grid generation process the actual horizontal resolution in the PS1 implementation is 104 m). The Pilot Site 1 grid (i.e. child grid, figure 3) was derived from the grid of the Oil Spill operational model implemented at Regione Marche (i.e. the parent model) by increasing it resolution from 1 km to 100 m while keeping the same grid rotation. A ROMS grid can be rotated so to cover the whole modelling domain with the smallest possible number of nodes; this way the computational time is optimized. In the Adriatic Sea this is generally achieved by using a 45°E rotation of the grid, roughly the basin's main axis. The same approach was used for PS1 grid for two reasons:

- this rotation allows to cover the whole delta area and at the same time to reduce to the minimum the land area covered by the mask (i.e. the grid dimensions are kept as small as possible);

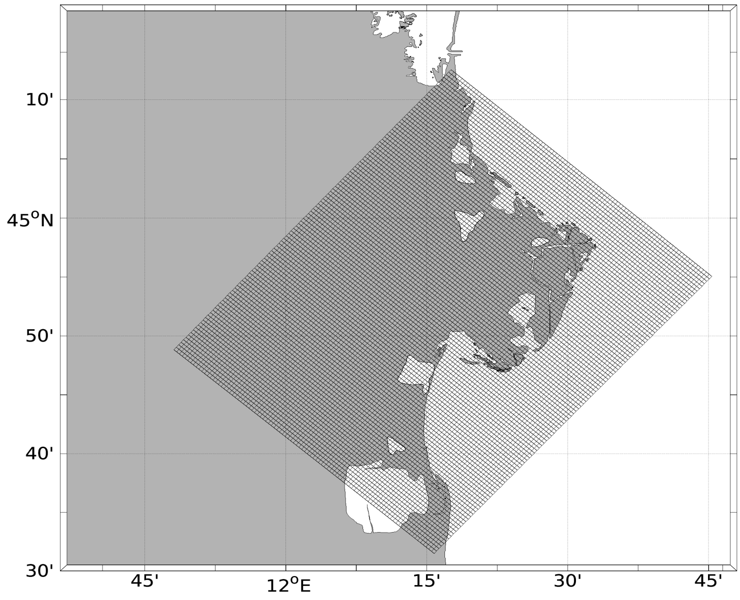

Figure 3: The PS1 ROMS grid (just one in five nodes are shown for clarity).

- the model initial and boundary conditions are derived from the Regione Marche Oil Spill operational model results this way the parent and child grids share some nodes and the same rotations, hence the interpolation errors are reduced to a minimum.

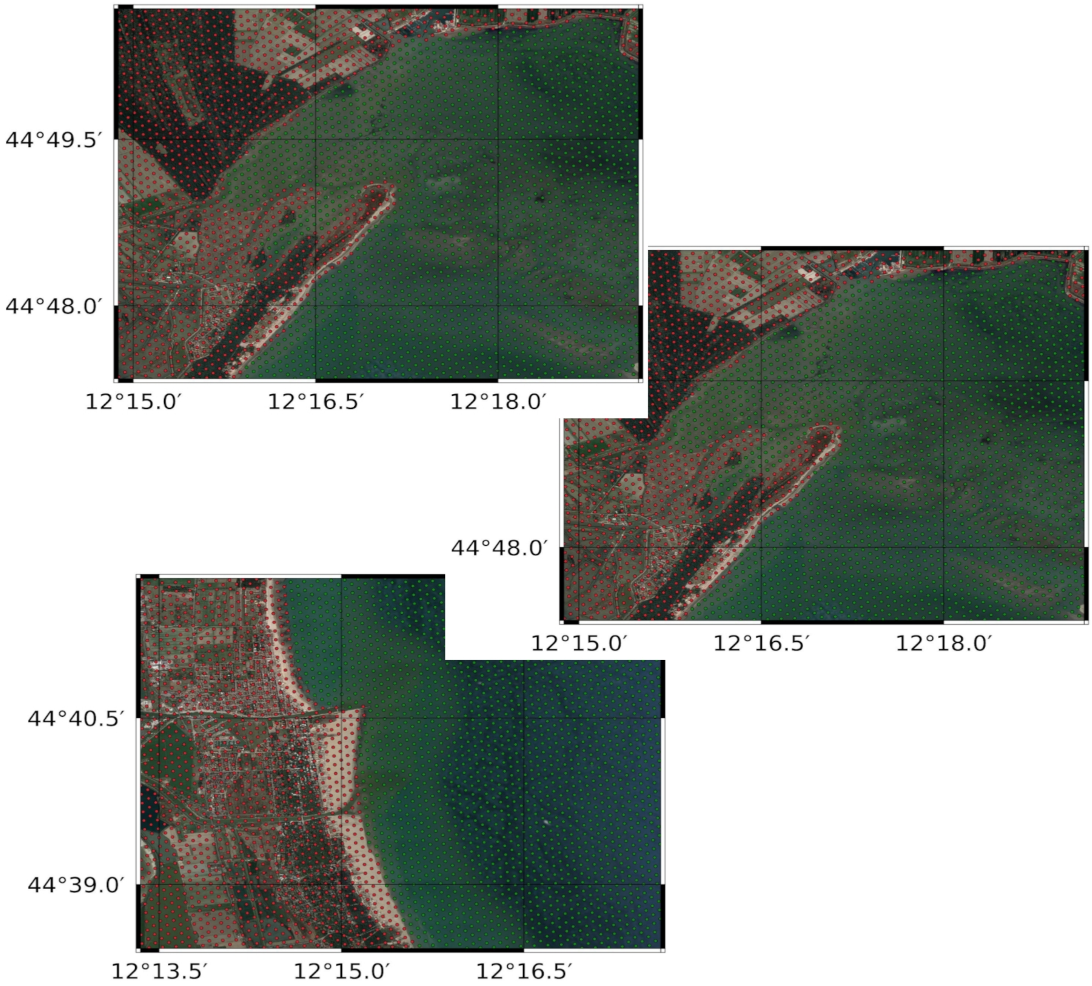

Figure 4: Three examples of the model land see mask (green dots over represent sea nodes, red dots represent land nodes).

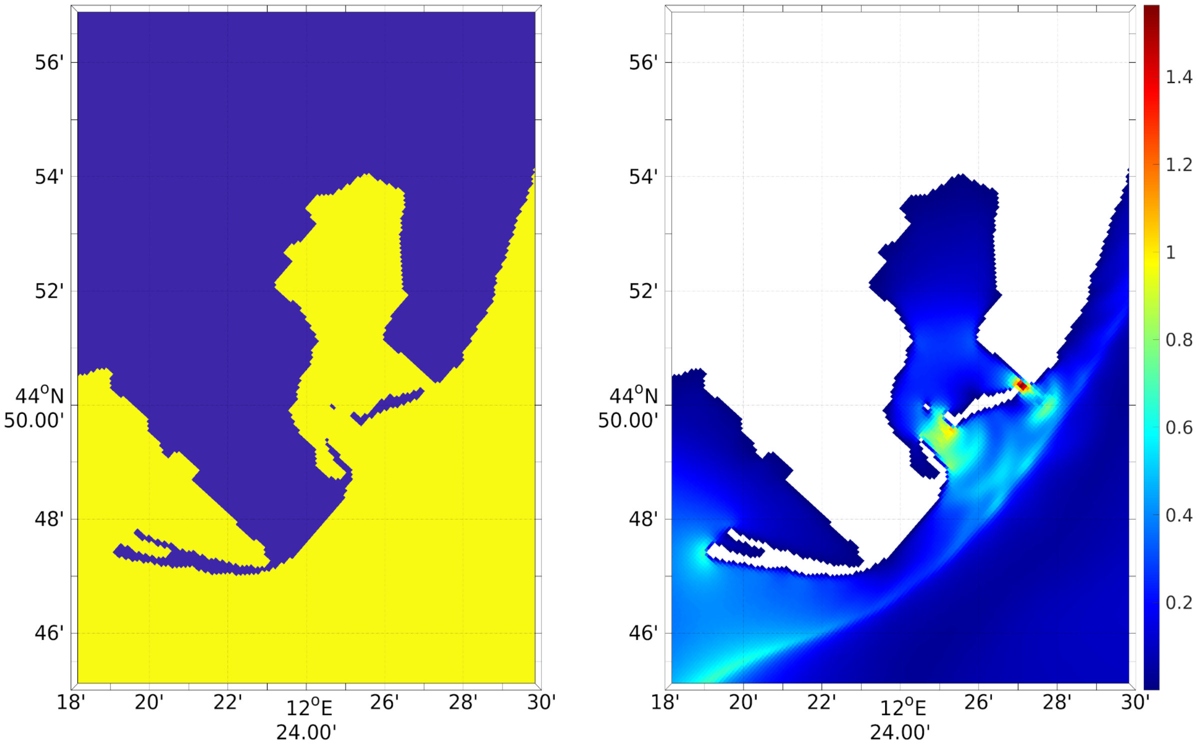

Figure 5: left panel: the land-sea mask over the Scardovari lagoon in one of the test runs use to verify the suitability on adding coastal lagoons with a 100m resolution; right panel: the module of the surface current after 2 days of simulation. It is possible to not e how the current reach values over 1.5 m/s that eventually lead to a model blow up.

Once the grid is created the land/sea mask have to be defined. This is done buy checking weather a grid node is on sea or land and assigning the specific value (i.e. 1 for sea and 0 for land, figure 4). In this phase several makss were tested to check the feasibility of including the Po Delta coastal lagoons in the PS1 simulations (several different land-sea mask were created to represent different coastline shapes and sizes of the lagoon inlets). After extensive testing it was found that with a 100 m resolution the inclusion of coastal lagoons causes the insurgence of very strong currents at the lagoons inlets that result in an unrealistic simulation and eventually leads to a model blow up (figure 5). It was hence decided not to include the coastal lagoons in the NET4mPLASTIC PS1 model set up. This will not be an issue for the scope of the project since we can assume that the Po Delta coastal lagoons do not act as a

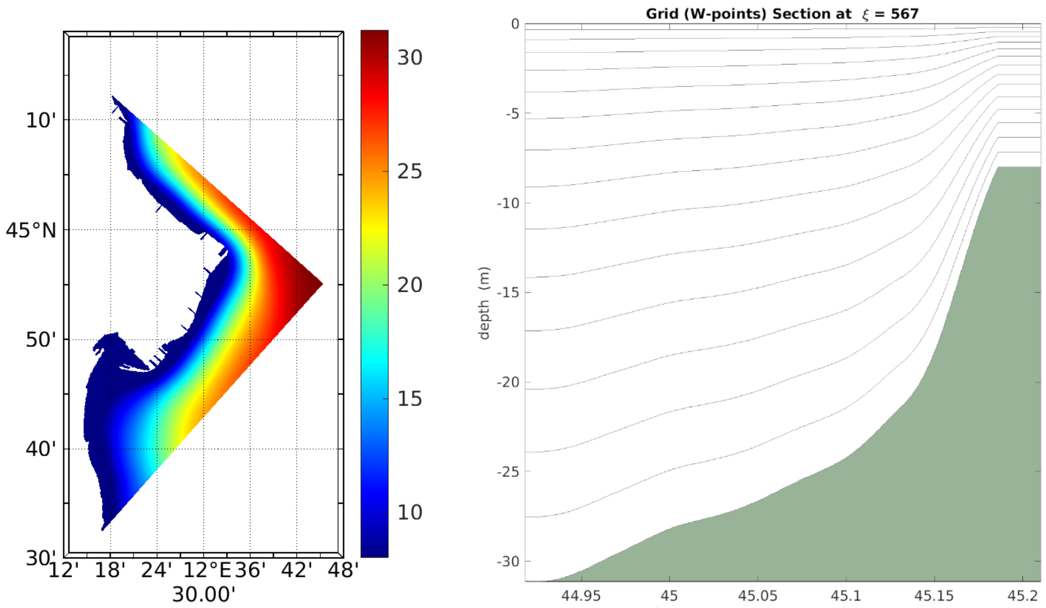

Figure 6: left panel: the NET4mPLASTIC Pilot Site 1 bathymetry; right panel: the s-coordinate 15 vertical layers along the eastern boundary of the model domain.

significant input of micorplastic (since there are no direct inputs in the lagoons themselves) and, as simulation results show, they are generally not close to accumulation sites.

The numerical domain area is a relatively shallow continental coastal area that presents maximum depths reaching less than 32 m (in the easternmost corner of the model domain, figure 6). In order to have an optimal representation of the surface layer (i.e. the part of the water column where most of the microplastic particles can be found) a 15 vertical layers of terrain following sigma coordinates set up was choose (figure 6). The stretching parameters and algorithms are reported in table 1 and were choose so to increase the vertical resolution near the sea surface (a detailed description of the sigma coordinate system and of the stretching algorithms can be found in Shchepetkin and McWilliams 2005.

Table 2: the s−coordinates layer stretching parameters used in the the PS1 grid.

Parameter	**Value**
V− Transform	2

V – Stretching	4
Theta_S	3
Theta_B	1.1
Tcline	4

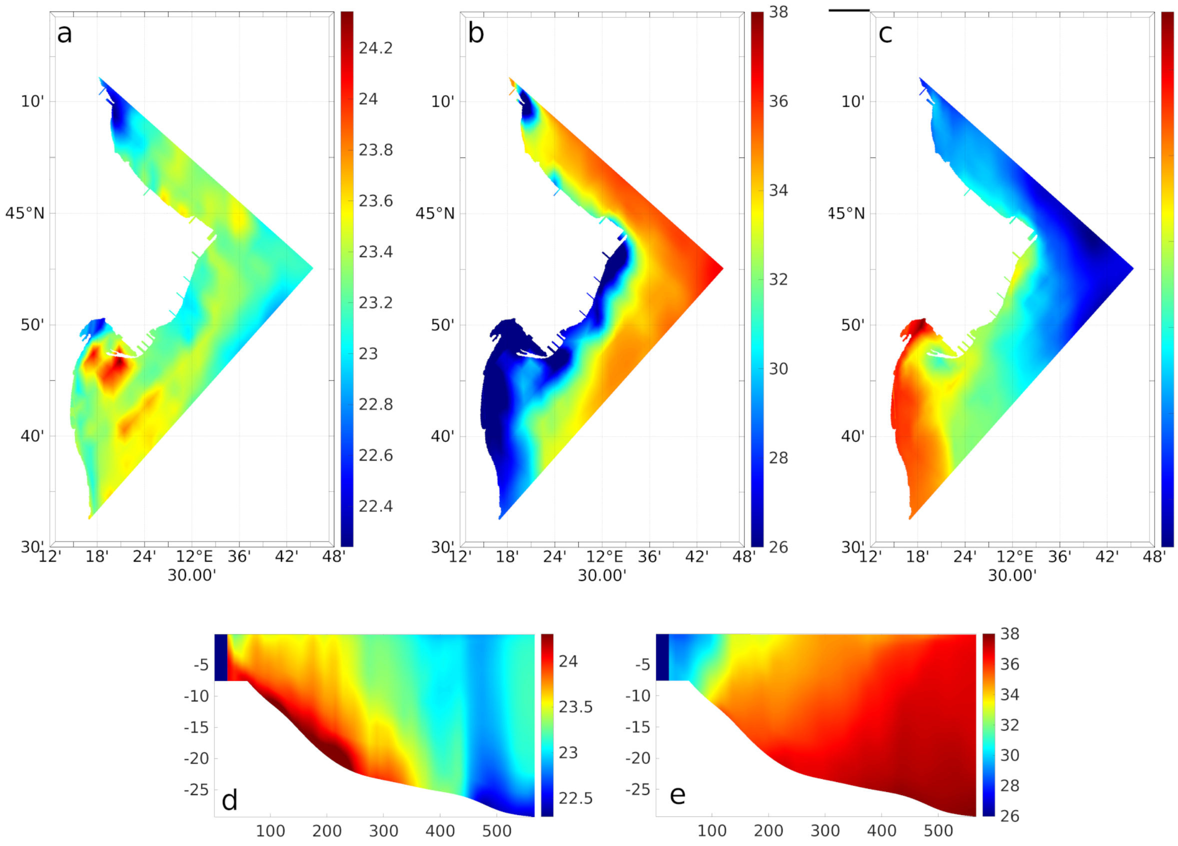

Figure 7: PS1 initial conditions for surface values (panel a temperature, panel b salinity and panel c free surface elevation) and at boundaries (panel d temperature and panel e salinity)

2.3 Initial and boundary condition

The model initial conditions were directly derived from those used in the Regione Marche Oil Spill Model by interpolating the temperature, salinity, free surface elevation, zonal and meridional current components over the PS1 grid. In figure 7 the surface values (temperature, salinity and free surface elevation) and the eastern boundary (temperature and salinity) are shown as a general description of the 3D fields used for initialization. The model initialization was set on September 1st 2014 and run for 4 months (up to December 31st 2014) for startup.

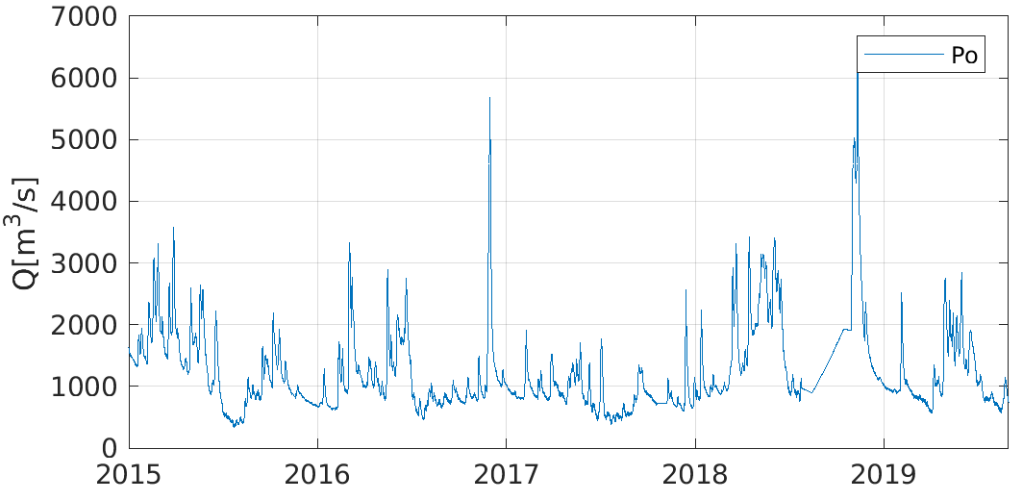

Figure 8: Po river streameflow hourly data at Pontelagoscuro

River mouth name	Position [Lon, Lat]	Number of model nodes	Percentage of Po water
Brenta	12.3154, 45.1843	2	N/A
Adige	12.3325, 45.1614	4	N/A
Po di Maistra	12.4102, 45.0360	2	5%
Po di Tramontana	12.5065, 49.9941	2	10%
Po di Dritta	12.5466, 44.9699	7	30%
Po di Scirocco	12.5142, 44.9330	3	8%
Po di Tolle 1	12.4943, 44.8976	2	14%
Po di Tolle 2	12.4817, 44.8720	2	
Po di Tolle 3	12.4651,44.8461	2	
Po di Gnocca 1	12.4182 ,44.8104	3	17%
Po di Gnocca 2	12.4079, 44.7994	3	
Po di Goro	12.3989, 44.7921	4	16%

Table 3: Distribution of PO river discharges between the major mouths.

2.4 Model forcing

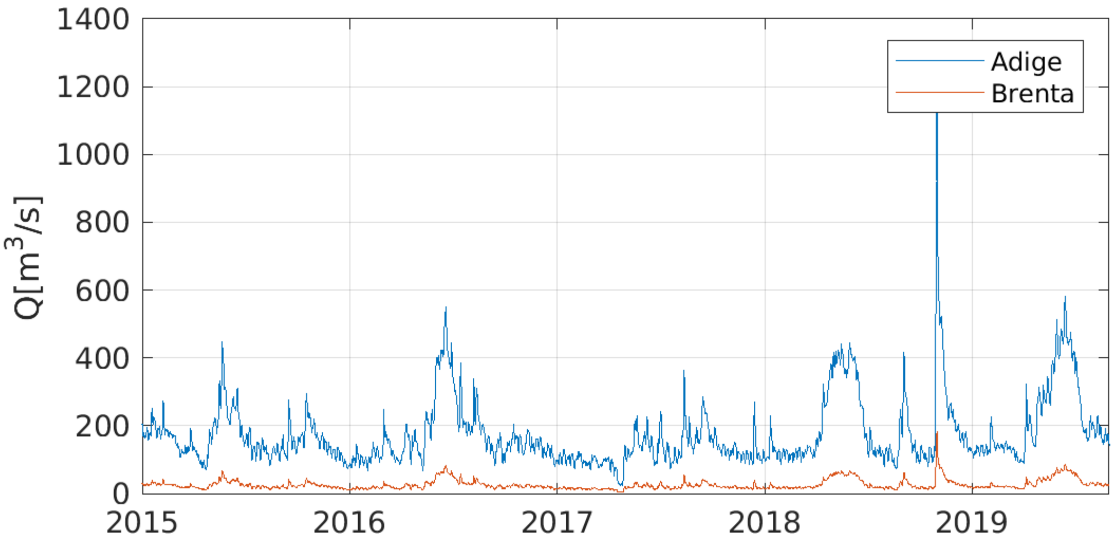

Figure 9: Adige and Brenta rivers streamflow

In the configuration chosen for the NET4mPLASTIC ROMS implementation the model needs external atmospherical forcing to compute the sea-atmosphere fluxes. To be consistent with the Oil Spill model the same forcing was used, specifically hourly data from the ARPA Emilia Romagna SIMC – COSMO implementation with an horizontal resolution of 2.2 km and a temporal time step of 1 hour.

It was not necessary to directly include tides in the Pilot Site 1 model implementation since the tidal forcing was already included in the Regione Marche Oil Spill model used to derive boundary conditions.

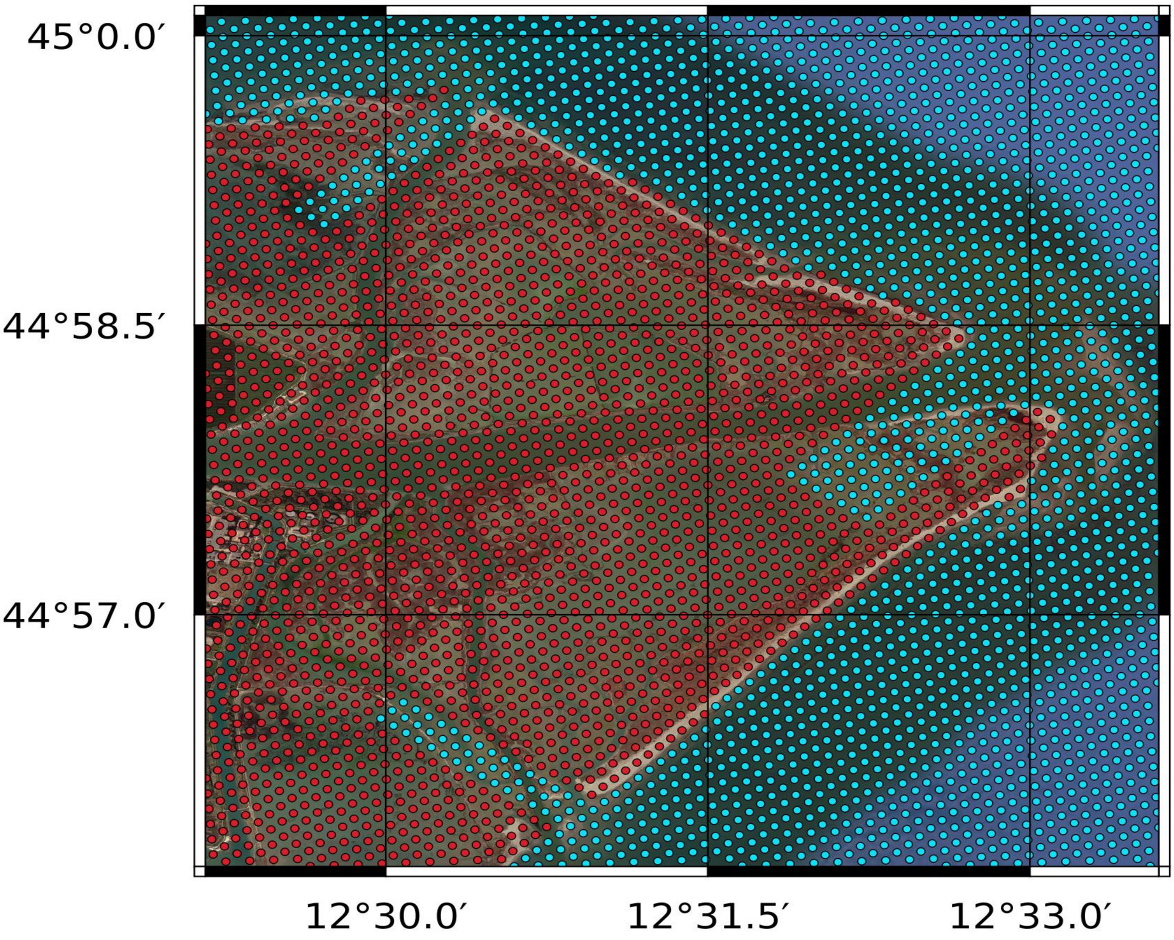

Figure 10: The land-sea mask in the Po di Dritta area(red dots show land nodes, cyan dots mark the sea nods.). The mask shows the channel used as river mouths.

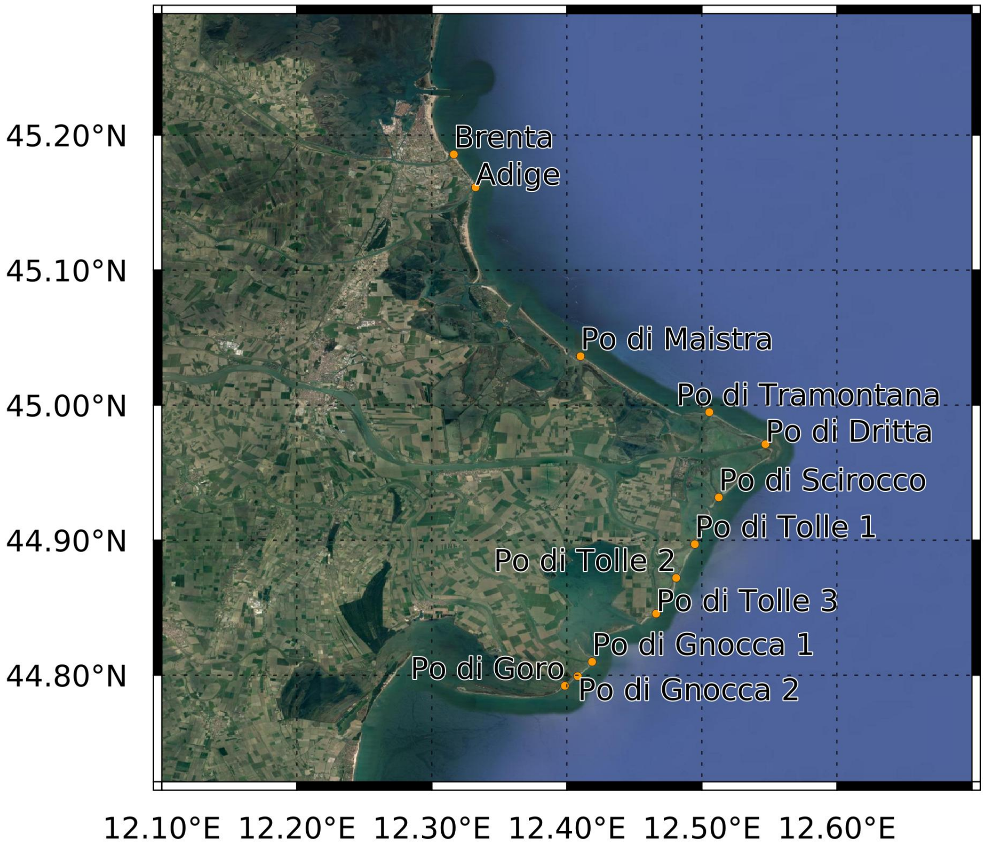

Figure 11: Location of each of the river mouths used in the model implementation.

2.5 Riverine inputs

The Pilot Site 1 area is strongly influenced by riverine inputs from the Po river (and partially from the Adige and Brenta rivers). From the point of view of microplastic inputs the rivers are the major source and hence they play a fundamental role in the model implementation. Discharge data for the Po River (figure 8) were obtained for the Pontelagoscuro station (about 40 km inland from the Po di Dritta river mouth) from ARPA Emilia Romagna. The Po data set shows a gap between July and October 2018, to cover this period a monthly climatology computed over the 1981-2020 period was used. The total Po discharge observed at Pontelagoscuro was divided between each of it branches following Maicu et al 2018. The percentage of each branch is shown in the 4th column of table. Data for Adige river were collected from the daily averages produce by ARPA Veneto (figure 9). The Brenta river discharge was computer as a fraction (15%) of the Adige's streamflow.

In the hydrodynamical model rivers are generally represented as a point source of momentum characterized by an imposed temperature and salinity. If those sources are placed directly on the model coastline numerical issues can develop resulting in instabilities, especially in the temperature and salinity fields. In order to avoid this the riverine sources were placed 15 nodes inland and connected to the coast by a channel. This not only prevent numerical instabilities but also helps in representing a realistic river-sea plume dynamics with the formation of a more salt intrusions and variations of the free surface elevation at the river mouth (figure 10). A total of 12 river mouths (1 for the Adige and Brenta each, and 10 for the various Po branches) were used; figure 11 shows the location of each mouth and table 1 reports their positions.

2.6 Simulation set up

The simulation for Pilot Site 1 was initialized on September 1st 2014; a 4 months start up period was defined to let the model dynamics stabilized after initialization.

The model numerical time step was set to 15 seconds and the internal time step to 1s. Those a very short time steps that resulted in a longer computational time were necessary in order to have a stable simulation with the 100 m horizontal resolution grid.

Model outputs were saved every two hours a average fields and stored in daily files.

3 ICHTHYOP

To study the dispersal patterns, pathways and potential accumulation zones of MP released by the Po, Adige and Brenta rivers the Individual Based Model ICHTHYOP (Lett et al., 2008) was implemented over PS1. ICHTHYOP is a 3D Lagrangian model developed to study eggs and larval dispersion in marine environment under the influence of currents and thermohaline water properties; it includes several biological features (i.e. larval growth, recruitment of juveniles, diurnal vertical migrations, lethal temperature and mortality) that in this implementation were not activated. In the model the virtual MP particles behave just as a Lagrangian drifter under the effect of horizontal/vertical advection, dispersion and of a buoyancy force due to the difference between particle and environment water densities, added to the vertical current velocities.

3.1 Simulation set up

In the Po delta several potential sourced of microplatic particles can be found (i.e. industrial plants, waste water treatment plants, ports and so on) but all of those are several order of magnitude smaller than the potential inputs form the Po, _Adige and Brenta rivers; hence those were the only ones considered in this implementation. It can be assumed that the concentration of MP particles in the Po river waters is almost constant during the year, previous studies showed values in the order of 10 particles per m^3. In the implementation for NET4mPLASTIC that value was used to set the number of particles release each day proportional to the river discharge.

MP particles were released on a straight line located in front of each river mouth to mimic a direct discharge form the river itself. The Po delta presents 7 main mouths (figure 11) from north to south: Maistra, Tramontana, Dritta, Scirocco, Tolle (divided into three branches), Gnocca (divided into two branches) and Goro.

ICHTHYOP was used in a full 3D configuration and mircoplastic particles released at the sea surface and let free to move in the water column depending on the currents and n the balance between their buoyancy and the vertical currents. The 3D outputs of the ROMS hydrodynamical simulations (i.e. 3D current field, water column temperature and salinity) from January 1st 2015 to August 12 2019 were used to force the Lagrangian simulations running ICHTHYOP off line. For each time step the individual displacement of particles was computed with a Runge-Kutta 4 integration scheme; horizontal dispersion was included with a turbulent dissipation rate of $\epsilon=10^{-7}$; a value in agreement with turbulent kinetic energy observations in the Adriatic Sea.

For each day between January 1st 2015 and August 11th 2016, virtual microplastic particles were released every two hours at each of the river mouths and followed for the subsequent 15 days. The position of each particle was recorded every two hours. As an example of the outputs of the Lagrangian simulations figures 12, 13 and 14 show the track of the particle released on the first time step of January 1st 2015 fro each of the 12 river mouths.

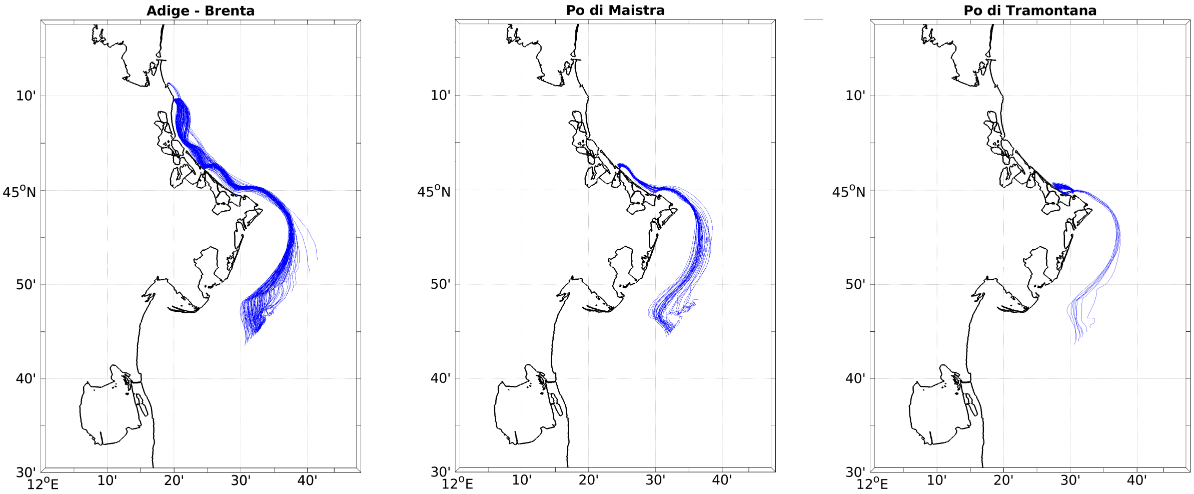

Figure 12: Microplastics particle track for the release on January 1st 2015 at 01:00 for the Adige - Brenta (left panel), Po di Maistra (central panel) and Po di Tramontana (right panel)

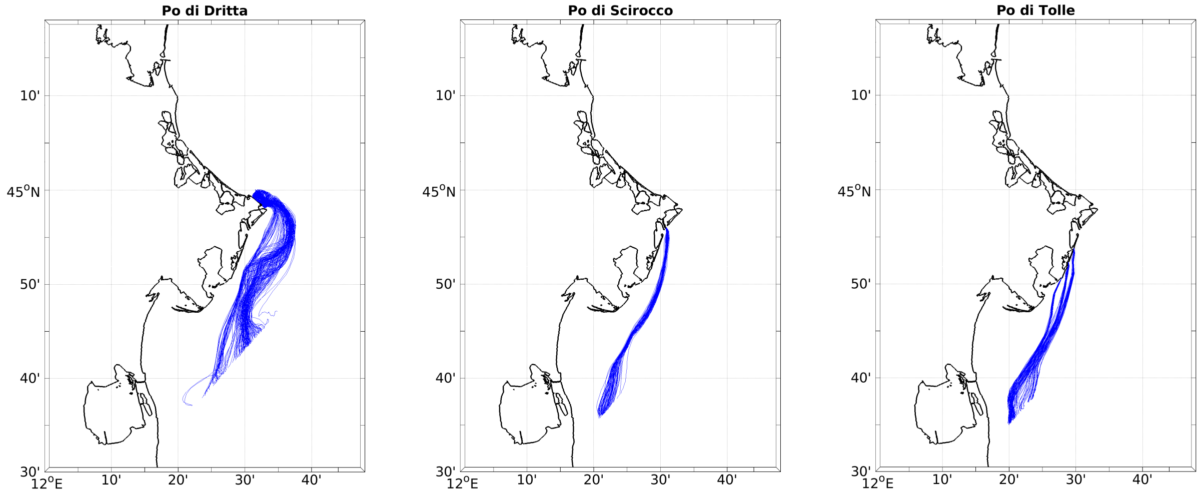

Figure 13: Microplastics particle track for the release on January 1st 2015 at 01:00 for the Po di Dritta (left panel), Po di Scirocco(central panel) and Po di Tolle (right panel)

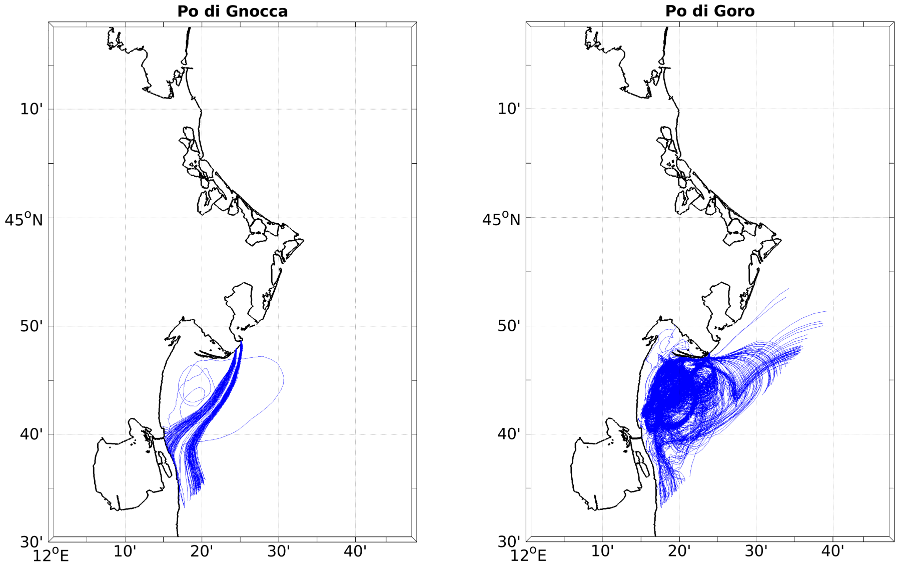

Figure 14: Figure 12: Microplastics particle track for the release on January 1st 2015 at 01:00 for the Po di Gnocca (left panel) and Po di Goro (right panel)

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