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## Executive summary

This document explains in detail the set-up and implementation of two numerical high-resolution models for the test cases of Taranto and Barcelona, as expected in the EuroSea workplan. Both models are state of the art and have been carefully validated. The operating services resulting will be in the core of OSPAC product, the main deliverable of WP5.2.

The third pilot involved in the project, Alexandría, does not have models ready, since this port, quite unexpectedly, failed to obtain the internally required permits to work in the project. Nevertheless, this is not a concerning delay, since all methodologies are developed, and we will proceed to the modelling work once the substitute port is designated. At this moment, locations in Colombia or Madagascar are being studied. Contacts with local authorities are established and a final decision will be made before the end of 2021.

## 1. Introduction

The ocean is an essential part of the planet that plays a crucial role in the global life system and provides vital resources for humanity. Coastal zones are the most affected areas by direct anthropic pressures, and their management is very complex due to the multiple interconnected processes that occur there. Therefore, understanding the physical behavior of coastal zones is vital to managing the main problems related to impacts and resource exploitation activities (Liste et al., 2021). In this coastal setting, ports and adjacent cities are one of the main anthropic infrastructures that generate economic wealth. The increase in maritime traffic has resulted in rapid growth in port activity. As ports and cities are affected by met-ocean conditions, especially extreme events, personalized real-time and forecast information on environmental conditions is needed to manage their growth. Wind, waves, and sea level are traditionally the most critical met-ocean parameters.

Supporting port and city activities require accurate ocean forecasting systems. In response to this growing demand for continuous and updated met-ocean information, high-resolution models are being implemented in coastal areas, combined with in situ observations, that allow for a better understanding and characterization of the main hydrodynamic characteristics of these areas. As a result, the operational physical oceanography is maturing quickly, and ocean modelling circulation as an operational capability is now a fact.

In the framework of the EuroSea Project, the WP5 team has been working on developing a 3D hydrodynamic operational tool with enough resolution to solve the dynamics of restricted domains such as Barcelona's and Taranto's local coastal waters, harbors, and beaches. This deliverable provides a complete description of the CMEMS downscaled circulation operational forecast systems in Barcelona's and Taranto's local coastal waters.

The report is organized as follows: Section 2 describes the study site. Section 3 describes the 3D modeling systems and setups. Finally, section 4 presents validations and results.

## 2. Areas of Interest

### 2.1. Taranto

The area of interest is focused on the Southern Adriatic and Northern Ionian seas of Mediterranean basin, with special zoom in the Gulf of Taranto (hereafter GT) and particularly in the Mar Grande and Mar Piccolo where the port of Taranto is located.

The southern Adriatic Sea extends approximately southward along the latitude of 42°N to the threshold of the Strait of Otranto and has a maximum depth of 1270 m. An exchange of waters with the Ionian Sea occurs at the Strait of Otranto at approximately 40°N. The northern Ionian Sea extends south of 38°N and has a steeper continental slope than the Adriatic basin. The offshore maximum depth is 3500–3700 m.

The GT (Figure 1a) is situated in the northwestern Ionian Sea and is approximately delimited in open sea by the line connecting Apulia and Calabria (Gulf of Taranto – Boundary Section, GT-BS in Figure 1a). It is a deep, semi-enclosed ocean area in southern Italy encircled by two peninsulas, Apulia and Basilicata/Calabria (Figure 1a). It is open to the northern Ionian Sea, and a deep trench of more than 2000 m connects it to the eastern Mediterranean Sea. The continental shelf area, considered as the area from the coasts to the 200 m depth contour, occupies only 10 % of the total Gulf area (Pinardi et al., 2016) with the shelf wider on the Apulia than the Calabria side.

A complex water mass circulation (Sellschopp and Álvarez, 2003) with high seasonal variability (Milligan and Cattaneo, 2007) characterizes the GT basin. Oceanographic studies (Poulain, 2001; Bignami et al., 2007; Turchetto et al., 2007; Grauel and Bernasconi, 2010; Oddo and Guarnieri, 2011) describe two main GT surface circulation structures: (i) a cyclonic gyre encompassing the Western Adriatic Coastal Current (WACC) flowing around Apulia into the GT from the northern Adriatic Sea, and (ii) an anticyclonic circulation connected to the Ionian Surface Waters (ISW) flow entering from the central Ionian Sea. In addition, studies on the coastal current in the inner part of the GT (De Serio and Mossa, 2015) show a coastal flow supporting the anticyclonic gyre structure.

Other studies in the GT based on observations (Pinardi et al., 2016) showed that in the Gulf (i) a mixed layer thickness extending down to 30m; (ii) an intermediate water salinity maximum - indicative of Modified Levantine Intermediate Waters - in the deep part of the Gulf; and (iii) low salinity values at the surface indicating surface waters of Adriatic or Atlantic origin. Federico et al. (2017) simulated the basin-scale circulation of the GT showing the circulation structure affected by the WACC position and strength (Artegiani et al., 1997a; Artegiani et al. 1997b; Cushman-Roisin et al., 2001; Ciancia et al., 2018). The WACC normally flows southwestward out of the Adriatic Sea, entering the GT from the surface down to 100m. In some cases the WACC could be weak and a reversed northeastward coastal current could be present in Gulf along the Apulia coasts, exiting the GT-BS. On the basis of a long-term modelling reanalysis, Pinardi et al. (2016) hint on a possible reversal of the large-scale anticyclonic gyre of the GT, connecting this feature to the inflow-outflow system of the GT-BS.

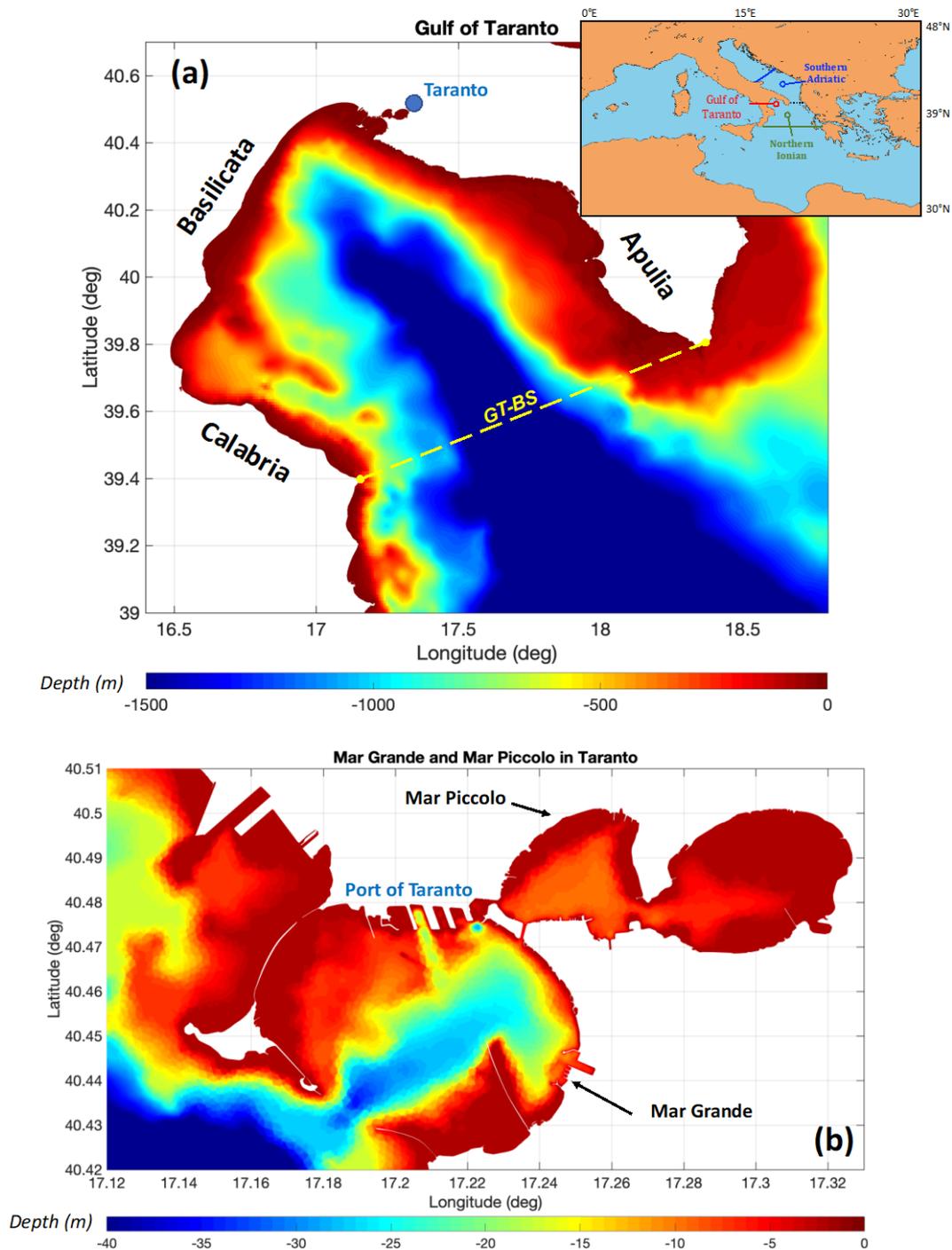


Figure 1. Area of interest: bathymetry and coastline of Gulf of Taranto (a) and Mar Grande (southwestern part of domain, where port of Taranto is located) and Mar Piccolo (northeastern part of domain) of Taranto (b)

A 7.5 km wide sheltered elliptical embayment, called the Mar Grande – Mar Piccolo system of Taranto (Figure 1b), hereafter named MG-MP, opens in the northeastern part of the GT. The MG-MP is a marine system that experienced over the last few decades strong biochemical pollution and environmental degradation, and it is considered a hotspot study site for economic, ecological and scientific reasons. In the MG-MP the circulation consists of along-shore currents, which follow the direction of the wind and are modulated by

tidal forcing (Scroccaro et al., 2004) with a tidal range of about 20 cm (Umgiesser et al., 2014). In Umgiesser et al. (2014) and Ferrarin et al. (2014), a 3D, annual and baroclinic model simulation of the Taranto basin was performed, focusing on mixing capacity and comparison with other Mediterranean lagoons. De Pascalis et al. (2016) described the averaged fields of MG-MP, showing that the basin is dominated by estuarine dynamics, but it could be that the Gulf would switch between the two opposite vertical circulations during the year (Federico et al., 2017).

## 2.2. Barcelona

In the following, the focus is on the local coastal waters of Barcelona's city, in the Northwestern Mediterranean (Figure 2).

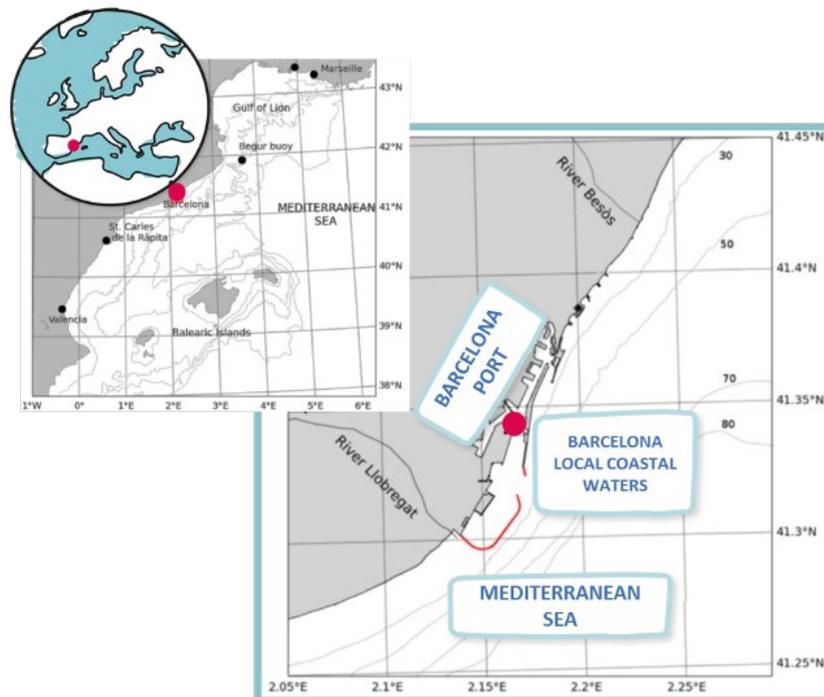


Figure 2. (Left corner) Extended study area comprising the NW Mediterranean. Focus is placed around the Barcelona local coastal waters and port area. Isobaths are drawn up to 80m.

On the northmost Spanish Mediterranean coast where Barcelona is located, the general circulation pattern presents a relatively complex pattern primarily determined by the bottom bathymetry (Sánchez-Arcilla and Simpson, 2002). Essential are the characteristics of the continental shelf and the slope. The shelf is broad in the north (about 70 km), narrows to less than 20 km in the central stretch of the coast (in front of Barcelona city), and then widens again abruptly to about 60 km further south. The end of the shelf is marked by a reasonably steep slope, with a mean value of about 0.01 km (Mestres et al., 2016). Due to the microtidal character of the Mediterranean Sea, tidal perturbations to the currents are not significant in this area (Poulain et al., 2013; Tsimplis et al., 1995).

## 3. Methodology

### 3.1. Numerical models

#### Taranto

The modelling system is based on the SHYFEM model, which is a 3-D finite element hydrodynamic model (Umgiesser et al., 2004) solving the Navier–Stokes equations by applying hydrostatic and Boussinesq approximations. The unstructured grid is Arakawa B with triangular meshes (Bellafiore and Umgiesser, 2010; Ferrarin et al., 2013), which provides an accurate description of irregular coastal boundaries. The scalars are computed at grid nodes, whereas velocity vectors are calculated at the center of each element. Vertically a  $z$  layer discretization is applied and most variables are computed in the center of each layer, whereas stress terms and vertical velocities are solved at the layer interfaces (Bellafiore and Umgiesser, 2010). The peculiarity of unstructured meshes is the ability of representing several scales in a seamless fashion, reaching higher resolution where necessary.

The model uses a semi-implicit algorithm for integration over time, which has the advantage of being unconditionally stable with respect to gravity waves, bottom friction and Coriolis terms, and allows transport variables to be solved explicitly. The Coriolis term and pressure gradient in the momentum equation, and the divergence terms in the continuity equation are treated semi-implicitly. Bottom friction and vertical eddy viscosity are treated fully implicitly for stability reasons, while the remaining terms (advective and horizontal diffusion terms in the momentum equation) are treated explicitly. A more detailed description of the model equations and of the discretization method is given in Umgiesser et al. (2004) and Ferrarin et al. (2017).

The model has been already applied to simulate hydrodynamics of several systems in many regions of world, proving its quality and accuracy. Exploiting the variable mesh approach, the model has been successfully applied to several scales, from the open sea (e.g., Mediterranean Sea, Black Sea, Gulf of Mexico) to the coastal seas and estuaries (e.g., coastal areas of Adriatic Ionian and Western Mediterranean Seas in Italy, Kotor Bay in Montenegro, Danube Delta in Romania) to open-sea islands (e.g., Malta) to the fjords (e.g., Roskilde, Denmark, Oslo) to the lagoons (e.g., Venice, Menor in Spain, Nador in Morocco, Dalyan in Turkey, Curonian in Lithuania, Tam Giang in Vietnam) to the ports (e.g., Apulian ports in Italy) to the rivers (e.g., Po river in Italy, Savannah river in Georgia, US) to the lakes (e.g., Geneva in Switzerland, Garda in Italy).

The modelling approach is based on the downscaling of CMEMS Marine products released at the regional scale of Mediterranean Sea. The current Med-CMEMS implementation is based on NEMO (Nucleus for European Modelling of the Ocean; Madec, 2008) finite-difference code with a horizontal resolution of  $1/24$  of a degree (4–5 km approximately) and 141 unevenly spaced vertical levels. The system is provided by a data assimilation system based on the 3D-VAR scheme developed by Dobricic and Pinardi (2008).

#### Barcelona

The 3D hydrodynamic tools described in this deliverable are based on the COAWST Modelling System (Warner et al., 2010), a three-dimensional hydrodynamic model integrating atmosphere and ocean circulation, surface waves, and sediment transport components.

COAWST framework system is used to develop two ocean circulation model configurations. The first one, called OSPAC V1, is now operational using the ocean circulation model and fields. The second one, called OSPAC V2, is now ready to be implemented in operational but, for now, is only running offline using the coupling circulation and waves models and fields. Based on the Model Coupling Toolkit, COAWST enables the exchange of information among numerical models representing different processes of the oceanic system,

thus allowing an explicit description of their interactions. We used the latest available version of the COAWST modelling system (version 3.7), as of the date of publication of this deliverable. However, complete model details are available on the COAWST website<sup>1</sup> for detailed checks and future improvements.

Both model configurations are described in detail below:

#### OSPAC V1:

In the OSPAC V1 configuration, high-resolution simulations have been performed by circulation fields using the Regional Ocean Modelling System (ROMS Model). ROMS is a three-dimensional, free-surface, topography-following numerical model that solves finite difference approximations of Reynolds Averaged Navier Stokes (RANS) equations using hydrostatic and Boussinesq approximations with a split-explicit time-stepping algorithm (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008; Shchepetkin and McWilliams, 2009). In addition, ROMS includes options for various model components such as different advection schemes (second, third, and fourth-order), turbulence closure models (e.g., Generic Length Scale mixing, Mellor-Yamada, Brunt-Väisälä frequency mixing, user-provided analytical expressions, K-profile parameterization), and several options for boundary conditions.

OSPAC V1 used the latest available version of the ROMS model (version 3.9) as of the date of publication of this deliverable. However, numerical details and a complete model description, user documentation, and source code are available at the ROMS website<sup>2</sup> for future checks and improvements.

#### OSPAC V2:

In the OSPAC V2 configuration, high-resolution simulations have been performed by coupling circulation and waves fields, ocean circulation using the ROMS Model (described above), and surface waves using the Simulating Waves Nearshore Model (SWAN Model). SWAN is a spectral wave model that solves the transport of wave action density and includes source terms from wind and sinks terms to include wave energy dissipation due to white capping, breaking, and bottom friction (Booij et al., 1999). The simulations are based on a two-way coupling between ROMS and SWAN running on the same computational grid.

OSPAC V2 used the latest available versions of the ROMS model (version 3.9) and the SWAN Model (version 41.31) as of the date of publication of this deliverable. However, all model details are available at the ROMS website<sup>2</sup> and SWAN website<sup>3</sup> for future checks and improvements.

### 3.2. Bathymetry and grid generation

#### Taranto

Starting from the experience of the first implementation of the Southern Adriatic Northern Ionian coastal Forecasting System (Federico et al., 2017), here in EuroSea we have developed a specific and higher-resolution configuration for Taranto Seas. The new system covers only the GT with a horizontal resolution from 3km in open-sea to 100m in the coastal waters to 20m in the port of Taranto. Figure 3 shows the grid and bathymetry in GT and MG-MP. A single open boundary is created connecting Calabria and Apulia coasts through the GT-BS (Figure 1a). This configuration has been created to perform specific process studies and long-term hindcast simulations, due to the reduced density meshes in respect with the first one. The new horizontal grid has

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<sup>1</sup> <https://www.usgs.gov/software/coupled-ocean-atmosphere-wave-sediment-transport-coawst-modeling-system>

<sup>2</sup> <http://www.myroms.org/>

<sup>3</sup> <https://swanmodel.sourceforge.io/>

been be created adopting advanced and customized tools (mainly python-based) of meshing based on GMSH<sup>4</sup> and BLENDER<sup>5</sup> software.

The bathymetry was derived from the EMODnet<sup>6</sup> product at resolution of  $1/8 \times 1/8$  arc-minutes (circa 230 x 230 meter) resolution for open sea and coastal waters and integrated with higher-resolution bathymetry (resolutions of order of meter) for coastal areas in MG-MP and Taranto Port area provided by the Italian Navy Hydrographic Institute. The vertical discretization is based on z-layers approach. The vertical spacing is 2 m until 90 m from the sea surface, the resolution is then progressively (stepwise) increased down to the bottom with a maximum layer thickness of 200 m. This is appropriate for solving the field both in coastal and open-sea areas.

### Barcelona

Bathymetries are built using a combination of bathymetric data from EMODnet<sup>6</sup> and specific high-resolution sources provided by local Port Authorities. An updated and higher resolution bathymetry is also applied to adjust the open boundary to the coastal bathymetries in the port domains. Finally, the bathymetry information interpolated at the mesh is smoothed using a Shapiro filter with an r-factor criterion below 0.25.

The bottom boundary layer was parameterized with a logarithmic profile using a characteristic bottom roughness height of 0.002 m. The turbulence closure scheme for the vertical mixing is the generic length scale (GLS) tuned to behave as k-epsilon (Warner et al., 2005). Horizontal harmonic mixing of momentum is defined with constant values of  $5 \text{ m}^2\text{s}^{-1}$ .

### 3.3. Boundary conditions

#### Taranto

The modelling system is three-dimensionally downscaled from Med-CMEMS both in terms of initialization and open boundaries. The scalar fields from Med-CMEMS (non-tidal sea surface height, temperature and salinity) are treated at the boundary nodes of nested system through a clamped boundary condition. The velocity fields are imposed as nudged boundary condition from parent model in the barycentre of the triangular elements using a relaxation time of 3600 s. The tidal elevations derived from the OTPS (Oregon State University Tidal Prediction Software, Egbert and Erofeeva, 2002) tidal model with  $1/30$  horizontal resolution are added at the Med-CMEMS sea surface height and prescribed at each boundary node. Eight of the most significant constituents are considered for astronomical tidal model: M2, S2, N2, K2, K1, O1, P1, Q1.

Three basic surface boundary conditions are used:

- a) For temperature, the air-sea heat flux is parameterized by bulk formulas described in Pettenuzzo et al. (2010).
- b) For momentum, surface stress is computed with the wind drag coefficient according to Hellermann and Rosenstein (1983).
- c) For the vertical velocity and the salinity, the salt flux boundary condition is adopted and the water flux advected through the air-sea interface is given by precipitation minus evaporation.

For the atmospheric fields, well-consolidated products from ECMWF (6.5 km resolution and 3h frequency) are adopted as forcing. The atmospheric fields are corrected by land-contaminated points following Kara et

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<sup>4</sup> <http://gmsh.info/>

<sup>5</sup> <https://www.blender.org/>

<sup>6</sup> <https://www.emodnet-bathymetry.eu/>

al. (2007) and horizontally interpolated at each ocean grid node by means of Cressman's interpolation technique (Cressman, 1959).

The atmospheric variables used for the parametrization are 2 m air temperature (T2M), 2 m dew point temperature (D2M), total cloud cover (TCC), mean sea level atmospheric pressure (MSL), and meridional and zonal 10 m wind components (U10M and V10M) and total precipitation (TP).

Rivers and wastewater inputs are treated as clamped boundary condition imposing the discharge, salinity and temperature.

In GT, five main rivers (Bradano, Basento, Agri, Sinni and Crati, as reported in Figure 3) discharge from the western coastline with a relatively low annual mean runoff ( $\sim 75 \text{ m}^3/\text{s}$ , Verri et al., 2018). Due to a lack of available observations, river inflow surface salinity is fixed to a constant value of 0.1 at the river boundaries.

In MG-MP, we implemented the fresh water sources reported in De Pascalis et al. (2016), collecting the final report of the SPICAMAR projects (2003 and 2009) as detailed in Caroppo et al. (2011). The submarine springs (*citri*) have been introduced in the modelling system again starting from the dataset reported in De Pascalis et al. (2016), collecting the studies of Stefanon and Cotecchia (1969), Scroccaro et al. (2004), Cerruti (1948), Spizzico and Tinelli (1986). The salinity values reported by the authors were around 5 psu due to the water seepage through the underwater karst rocks.

Water temperature at the river, freshwater and spring source boundaries adapts to the environmental inner value inside the basin.

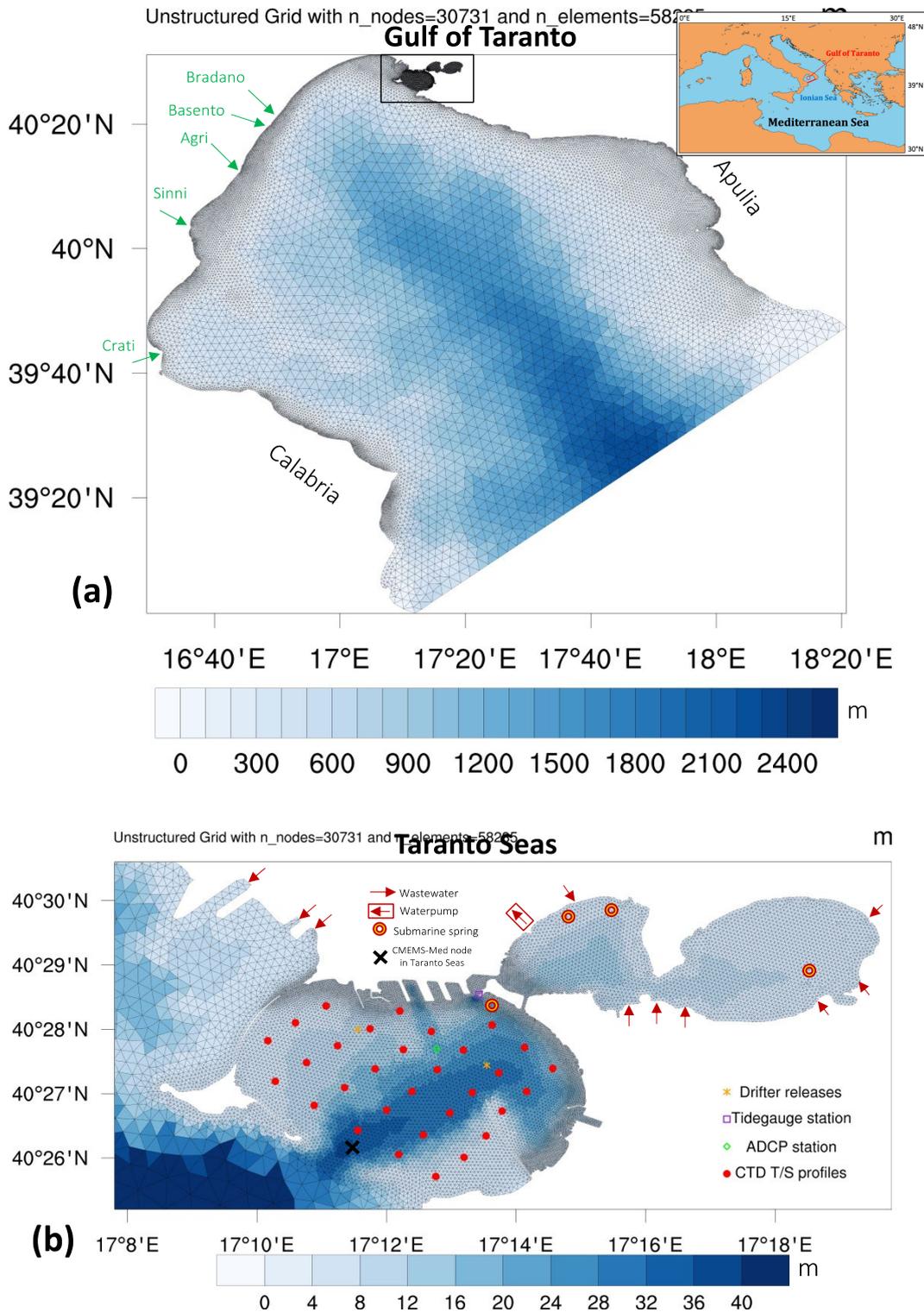


Figure 3. (a) Horizontal grid with bathymetry overlapped for Gulf of Taranto system; green arrows indicate rivers discharging in Gulf of Taranto. (b) Horizontal grid with bathymetry overlapped in the MG-MP. Symbols indicate wastewater discharge, waterpump and submarine springs (as reported in De Pascalis et al., 2016), and observed data used for validation.

## Barcelona

Grid refinement is used to nest down to the study zone along with the entire domain (Figure 4). Both OSPAC V1 and V2 model applications consist of 2 nested regular grids with a spatial resolution of  $\sim 350$  m and  $\sim 70$  m for the coastal waters (CSTBCN grid) and port domain (PRTBCN grid), respectively (see Figure 5 for examples of domains and bathymetries). The nesting ratio ( $\sim 5$ ) between coastal and port domains is defined to get enough resolution to reproduce the circulation due to the inner shape of the port considering the mesoscale dynamics of the coastal domain. The chosen vertical discretization consists of 20 sigma levels for the coastal water domain (CSTBCN grid) and 15 levels for the Barcelona port domain (PRTBCN grid).

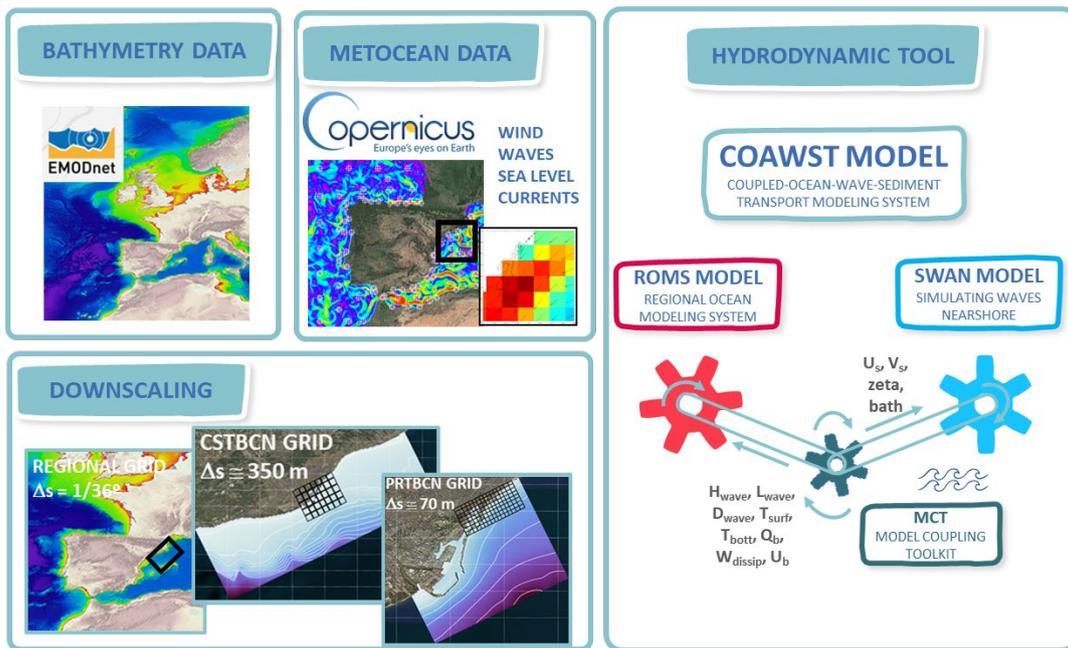


Figure 4. Hydrodynamic tool and setup overview scheme

Both OSPAC V1 and V2 models are nested into the daily updated regional ocean forecast products delivered by CMEMS- IBI (Sotillo et al., 2015). At the sea surface, the models are driven by high frequency (hourly) wind stress, atmospheric pressure, and fluxes of water and surface heat derived from the Spanish Meteorological Agency (AEMET) forecast services, based on two operational applications of the HIRLAM (High-Resolution Limited Area Model): One, the HNR ( $0.05^\circ$  resolution and a forecast horizon of + 36 h), covering the Spanish territory and another covering the more extended regional euro-Atlantic ONR application ( $0.16^\circ$  resolution and a forecast horizon of + 72 h). Further detailed information on this methodology can be found in Sotillo et al. (2019).

The HNR and ONR fields are jointly used according to the best available basis and pre-processed to obtain wind surface stress, surface net heat, and salinity fluxes. Hourly barotropic water currents and sea level are provided by CMEMS-IBI and consistently applied as Open Boundary Conditions (OBC) with Chapman and Flather algorithms (Carter and Merrifield, 2007). Moreover, daily average values of CMEMS-IBI currents, temperature, and salinity are imposed through the water column as clamped (Dirichlet) boundary conditions (Sotillo et al., 2019).

## 3.4. Physical and numerical setting

### Taranto

About the main numerical settings, we use a TVD (total variation diminishing) scheme for both the horizontal and vertical advection in the transport and diffusion equation for scalars, with constant diffusivity.

Horizontal advection of momentum is discretized by an upwind scheme and horizontal eddy viscosity is computed by the Smagorinsky's formulation.

For the computation of the vertical viscosities and diffusivities, a  $k-\epsilon$  turbulence scheme is used, adapted from the GOTM (General Ocean Turbulence Model) model described in Burchard et al. (1999).

The bottom drag coefficient is computed using a logarithmic formulation via bottom roughness length, set homogeneous over the whole system to a value of 0.01 m (Ferrarin et al. 2017).

### Barcelona

The numerical simulations are performed on two-nested grids configurations (Figure 5). OSPAC V2 is performed on two-nested grids configurations with two-way ocean refinement and one-way wave refinement with coupled exchanges between two grids for the fields of currents, bathymetry from the ocean to the wave, and wave dissipation, height, length, and direction, surface and bottom periods, and bottom orbital velocities from the wave to the ocean model (Figure 5).

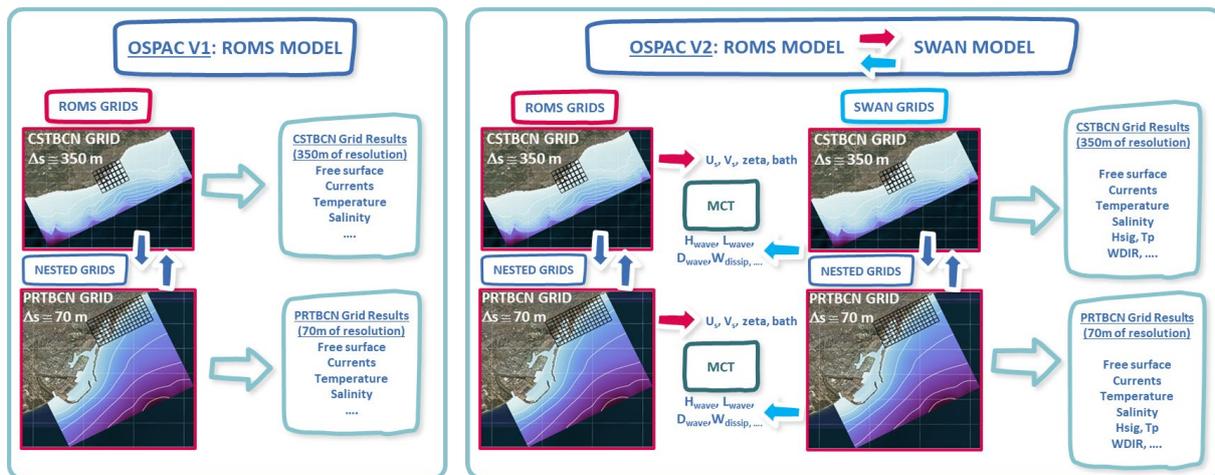


Figure 5. The left panel shows OSPAC V1 numerical configuration operational scheme. The right panel shows OSPAC V2 numerical configuration scheme.

## 4. Results

### Taranto

The GT configuration has been run in active model for a recent period (2018-2019). One month (December 2017) of spin-up is performed. Here we show results in the coastal and harbor scale of Taranto and a quantitative analysis comparing the modelling results with observations.

Figure 6 shows surface and bottom current velocity fields, averaged over the whole year in MG-MP area. The estuarine circulation and the different behavior of the two layers is immediately clear. The surface circulation (Figure 6a) is mainly flowing out from the Mar Piccolo to the Mar Grande and the Gulf of Taranto. The surface

fresh water inputs effect is well visible because this fresh water tends to remain on the surface layer due to its low density. In general, the surface current values in the Mar Piccolo are very low, varying in a range between 0 and about 10 cm/s. The averaged bottom circulation shows a quite different trend, and Figure 6b represents the last available layer in every node of the computational grid, following the bathymetry changes. The flow moves in the opposite direction going into the Mar Piccolo basin through the narrow channels with higher mean velocities. The effects submarine springs are also clearly visible as current hotspots in Figure 6b. The velocity at the bottom of the basin is, in general, lower than the surface one.

The study on the circulation in MG-MP is qualitatively in agreement with other reference studies (e.g., De Pascalis et al., 2016).

The maps of monthly mean surface temperature of MG-MP system are reported in Figure 7. It is worth to note the difference in terms of spatial distribution between the two basins. The Mar Grande is colder than Mar Piccolo during the wintertime (highlighted for Nov, Dec, Jan, Feb), while it is warmer during the other months. The signal of submarine springs and wastewater discharges are clearly evident in some months (e.g., citrus in Mar Grande close to the port of Taranto in July, wastewater discharges in northwestern part of domain outside MG-MP).

The monthly mean surface salinity in MG-MP system (Figure 8) shows always fresher fields in Mar Piccolo, with the maximum difference between the two basins in Nov and Dec. These differences could be due to (i) the presence of a larger number of fresher springs in Mar Piccolo than in Mar Grande, and (ii) the open-sea direct influence in GT in Mar Grande. Also, for the salinity fields the modeled submarine springs and wastewater are well noticeable.

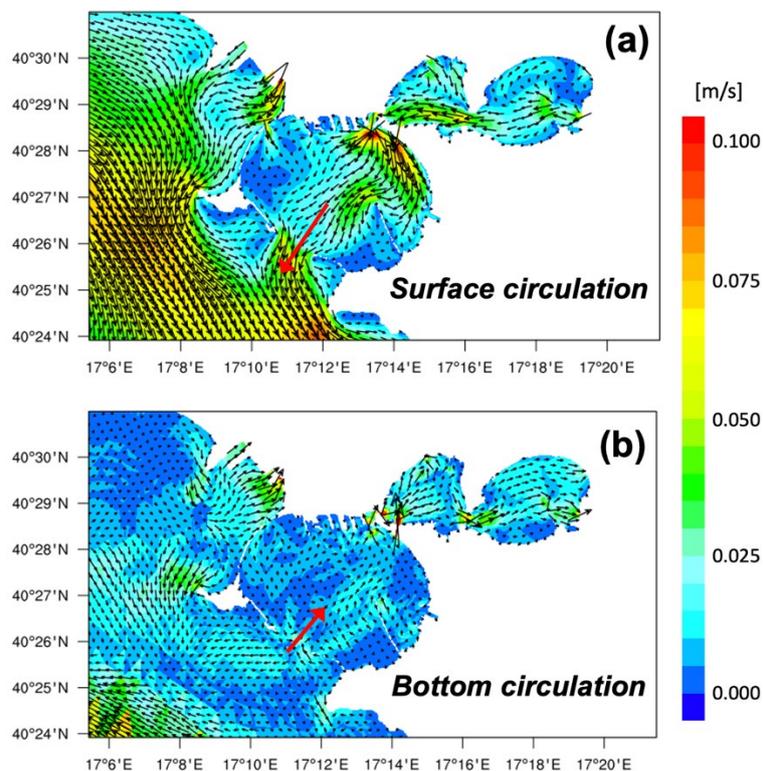


Figure 6. Yearly average (2018-2019) surface (a) and bottom (b) circulation in Mar Grande and Mar Piccolo of Taranto

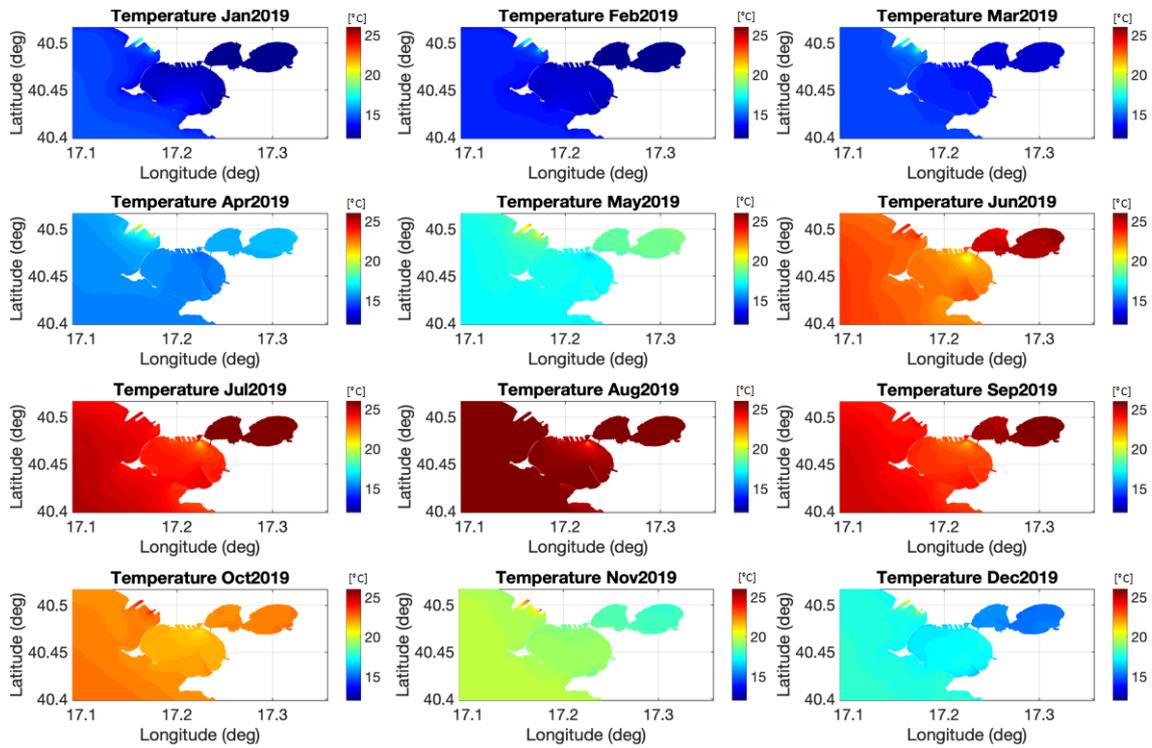


Figure 7. Monthly average (2019) surface temperature in Mar Grande and Mar Piccolo of Taranto

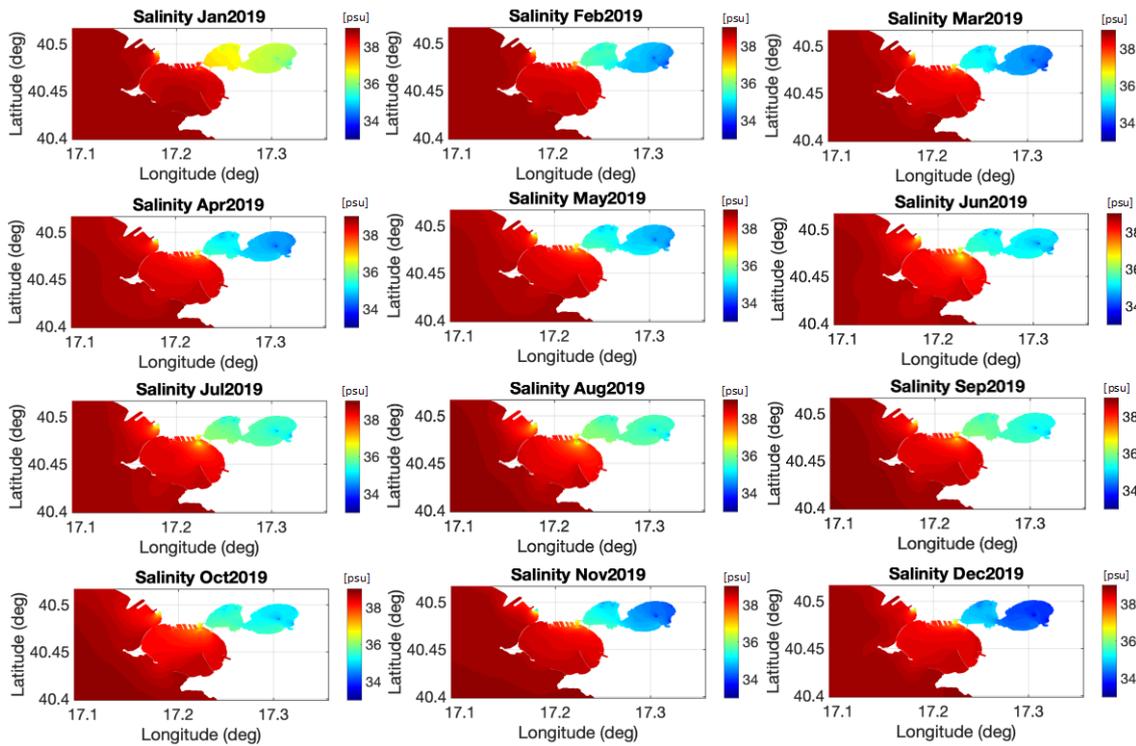


Figure 8. Monthly average (2019) surface salinity in Mar Grande and Mar Piccolo of Taranto

The modelling results have been here displayed for the tidegauges in Taranto (see Figure 3b for the location). Due to a long period unavailability of observing data by the Taranto tidegauge (from October 2016 to March 2019), we had the opportunity to compare the model with the observations only for the period 2019/03/28 – 2019/12/31. Results of sea level comparison are reported in Figure 9, where we use daily mean outputs from model, and Figure 10, where we use hourly instantaneous outputs from model. In particular, Figure 9b highlights the BIAS between model and observations at the tidegauge station in Taranto Port. Here the GT modelling system is in a good agreement with observation, with highest discrepancy are in September 2019 and December 2019 (model overestimates the observations up to 10cm). The average BIAS over the entire timeseries is 2.2 cm.

Furthermore, the sea level hourly snapshots of GT model are compared in Figure 10 with tidegauge in Taranto Port, also in terms of BIAS, for different periods: 2019/03/28 – 2019/06/05 (Figure 10a), 2019/06/05 – 2019/08/13 (Figure 10b), 2019/08/13 – 2019/10/22 (Figure 10c), 2019/10/23 – 2019/12/31 (Figure 10d). The model is qualitatively in good agreement with observation in terms of phase and with a general underestimation of amplitude. The highest differences are reported for the period 2019/09/10-2019/09/20 (Figure 10c), during the extreme event impacting Taranto on 2019/11/12 (Figure 10d) with an underestimation of 15cm by the model, and for the days of 2019/12/11-12 with model overestimation.

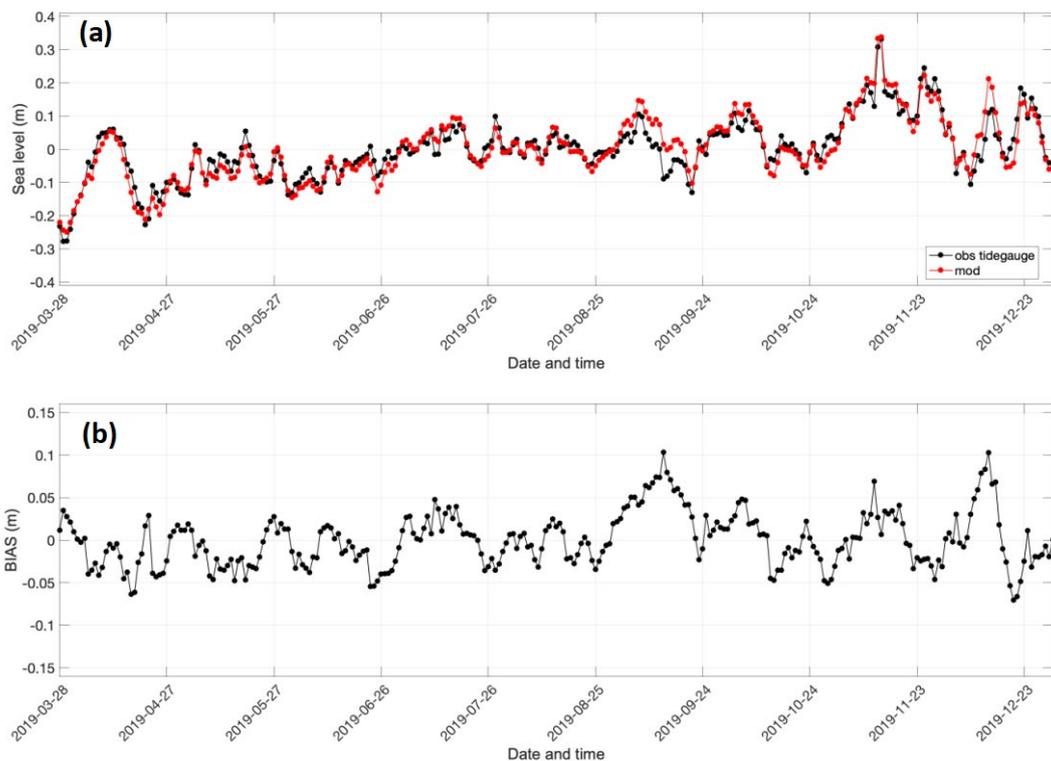


Figure 9. Sea level (daily mean) comparison of GT model with tidegauge in Taranto Port (a) and BIAS of model vs. observations (b)

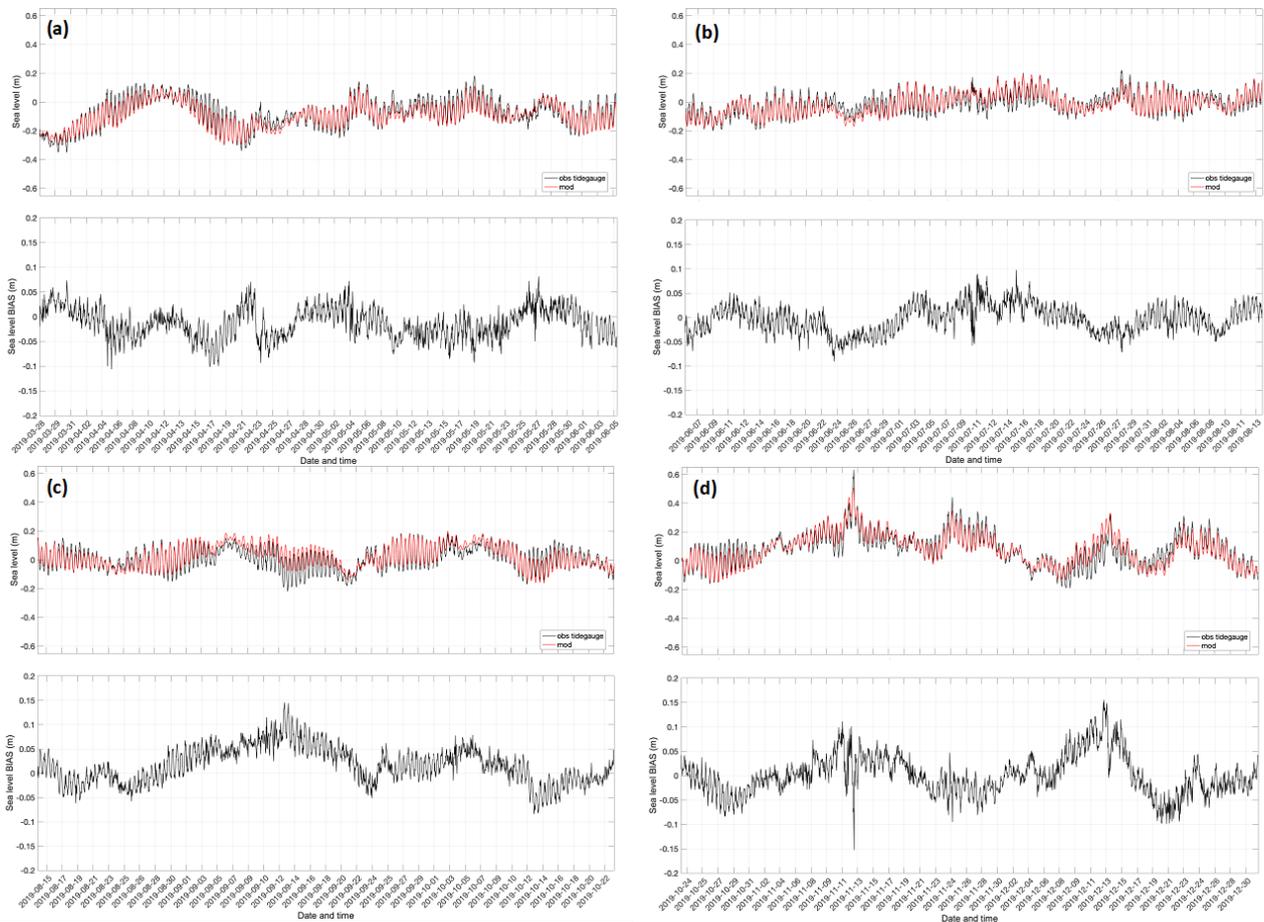


Figure 10. Sea level (hourly snapshot) comparison of GT model (red line) with tidegauge (black line) in Taranto Port for different periods (upper panels) and BIAS (lower panels): (a) 2019/03/28 – 2019/06/05, (b) 2019/06/05 – 2019/08/13, (c) 2019/08/13 – 2019/10/22, (d) 2019/10/23 – 2019/12/31.

Here follow the main outcomes of the sea surface temperature validation. The GT simulation carried out in active model for the period 2018-2019 (with one month - December 2017 - of spin-up) has been analyzed to assess the accuracy of model in comparison with satellite temperature. In particular, the temperature field at surface layer of model has been compared with satellite observation product: Mediterranean Sea Ultra High Resolution (0.01°) Sea Surface Temperature Analysis (SST\_MED\_SST\_L4\_NRT\_OBSERVATIONS\_010\_004, Buongiorno Nardelli et al., 2013). The comparison refers to the instantaneous value at 00:00 of the model surface temperature against the satellite foundation SST (~ SST at midnight). Figure 11 shows the time series (January 2018-December 2019) of daily SST BIAS and RMSE, between model and satellite observation, averaged over the whole Gulf of Taranto domain (see Figure 3a). The model is in well agreement with the observation, describing the pattern of seasonal cycle of temperature (Figure 11a). BIAS and RMSE time series are displayed in Figure 11b and Figure 11c respectively, showing a mean (over the entire domain and entire timeseries 2018-2019) BIAS of 0.17°C and a RMSE of 0.64°C. The larger discrepancy between model and observations are reported in April-May 2018, May-June 2019 and August-September 2019.

The GT system was adopted also to run a short-term period (1-11 October 2014, +5 days of spin-up) which we have the availability of different observing dataset (ADCP and CTD) collected during an oceanographic survey named MREA14 and described in Pinardi et al. (2016). The velocity fields of GT have been compared

with the observed ADCP data recorded at the surface (see the location in Figure 2) and with CMEMS-Med model in Figure 12. The comparison shows a remarkable similarity between the GT model fields and the observations, demonstrating that SURF-U is capable of propagating the tidal sea level from the lateral open boundary condition to inshore.

Figure 13 shows the mean trajectories of two groups of drifters released in the positions (yellow dots in Figure 3b), for the first 12 h after their release (5 October 2014). The observed trajectory is shown in black and is compared to those simulated by the Lagrangian model using the GT model and CMEMS model data. The CMEMS data are derived from the single grid point outside the Taranto Sea (black cross on the right panel of Figure 3b), chosen ad hoc for the simulation. For the eastern group of drifters, the GT model trajectory shows a significant improvement, while for the western group the GT model and CMEMS drifts are equivalent. This could be due to limitations in our modelling hypothesis, such as the low spatial/temporal variability of wind forcing and the neglected effects of Stokes drift. However, the inherent limited predictability of objects floating at sea can only be ameliorated by ensemble methods.

Figure 14 shows the model comparison between GT model and CMEMS and the temperature CTD data collected during the MREA14 survey. The spatial distribution of the CTD profiles (red circles on Figure 3b) is very dense (spacing between the stations is less than 1 km), due to the need to sample the coastal and local scale features. The 31 CTD temperature casts have been averaged to produce a representative profile of the Taranto Sea, as reported in the left panel of Figure 14, together with the modelled profiles. GT model is close to the observed temperature profile, showing a significant improvement in terms of the coarse resolution CMEMS analyses, as represented by a single grid point located near the entrance of the Taranto Sea (black cross in Figure 3b). The improvement is evident in the BIAS profile (Figure 14, center panel), which is  $0.13^{\circ}\text{C}$  for GT model and is  $0.3^{\circ}\text{C}$  for CMEMS. For the RMSE profile (Figure 14, right panel) values of  $0.15^{\circ}\text{C}$  and  $0.32^{\circ}\text{C}$  are obtained for GT model and CMEMS, respectively.

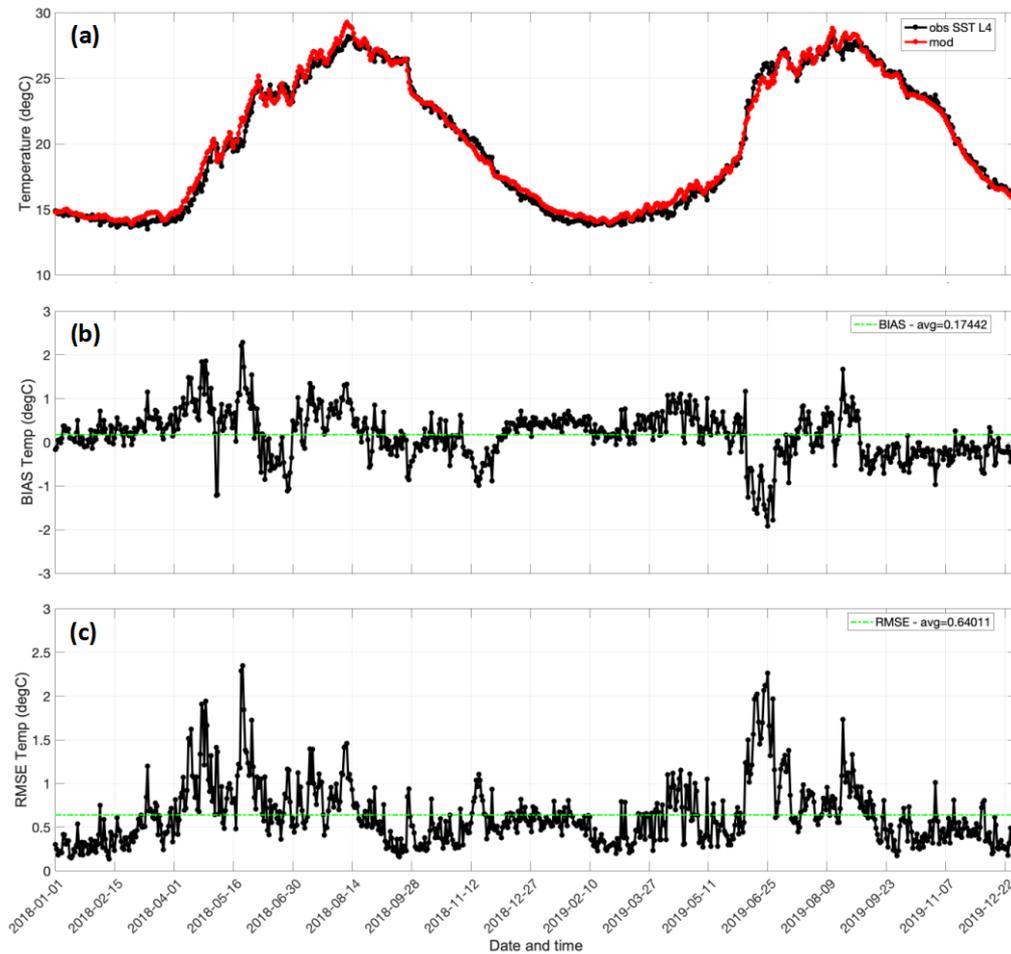


Figure 11. Time-series comparison between model surface temperature (instantaneous value at 00:00) and satellite foundation SST (~ SST at midnight), averaged over the Gulf of Taranto basin (a); BIAS (b) and RMSE (c) between model and observation (CMEMS Observation products: SST\_MED\_SST\_L4\_NRT\_OBSERVATIONS\_010\_004).

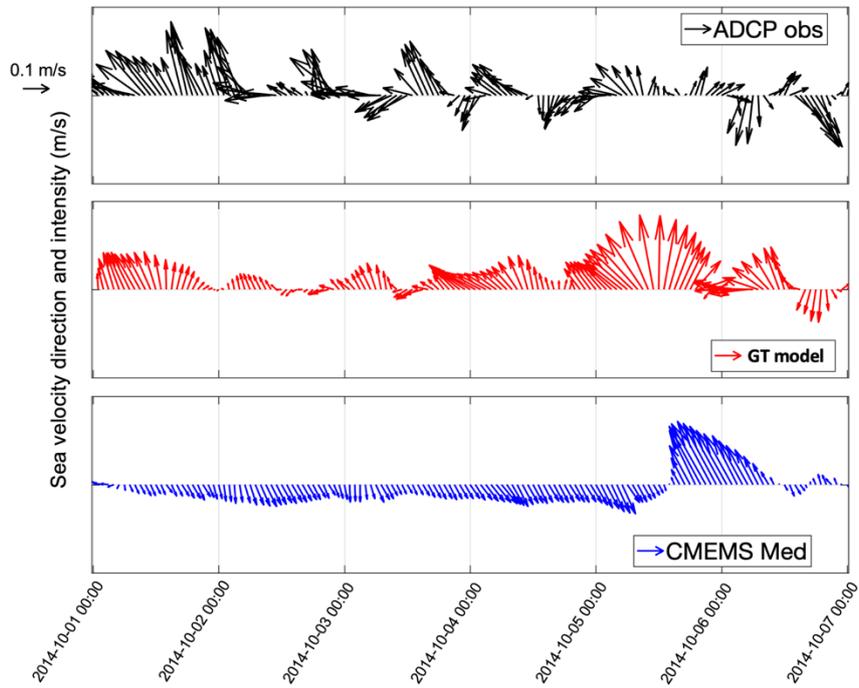


Figure 12. Time series of sea velocity direction and intensity, as measured by ADCP (black rows) and modeled by GT model (red rows) and by CMEMS Med (blue rows) (bottom panel) are given.

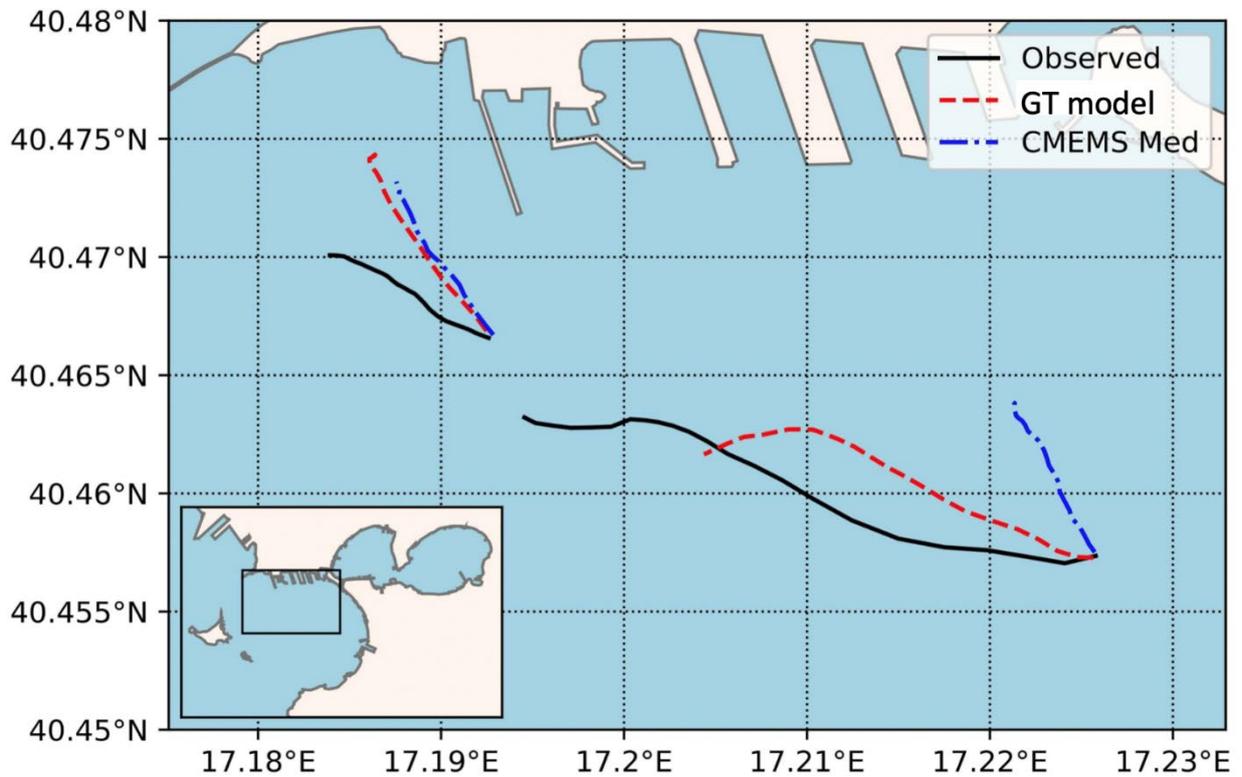


Figure 13. Mean drifter trajectories of the two drifter groups released in the Taranto Sea (black), and simulated drifter trajectories using the GT model (red) and CMEMS Med (blue).

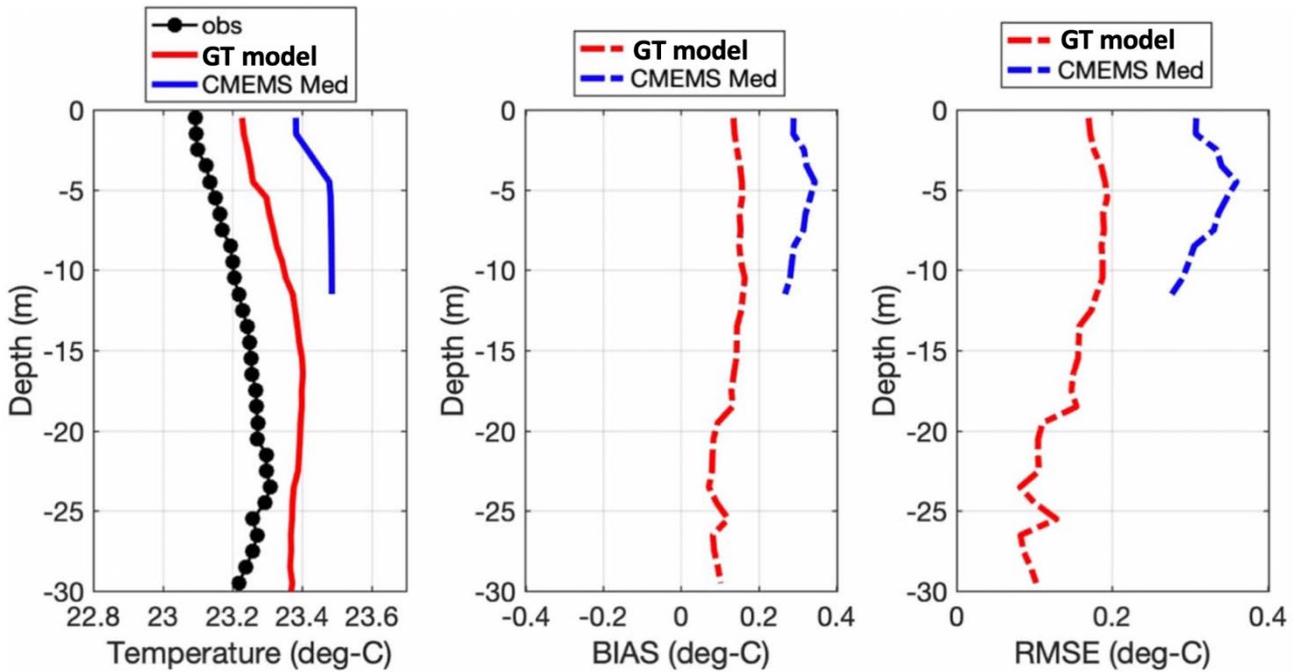


Figure 14. Comparisons between modelled (SURF-U and CMEMS Med) and observed CTD temperature profiles (left panel), with BIAS (middle panel) and RMSE (right panel). The observed temperature (black dotted line) is an average profile over the 31 CTD stations collected during the MREA14 survey in the Taranto Sea.

## Barcelona

Three-day forecasts of three-dimensional currents and other oceanographic variables, such as temperature, salinity, and sea level, are generated by the OSPAC V1 operational simulation. Product quality assessment is a crucial issue for operational forecast systems (Sotillo et al., 2019). Thus, the model outputs have been validated with in situ observations from field campaign data displaying good agreements and correlations between them, allowing us to understand better the quality and accuracy of the model forecast products. In Figure 15 we report an overview of the observations (left panel), model results (upper right panel), and validation (lower right panel) at the Barcelona local coastal waters and port.

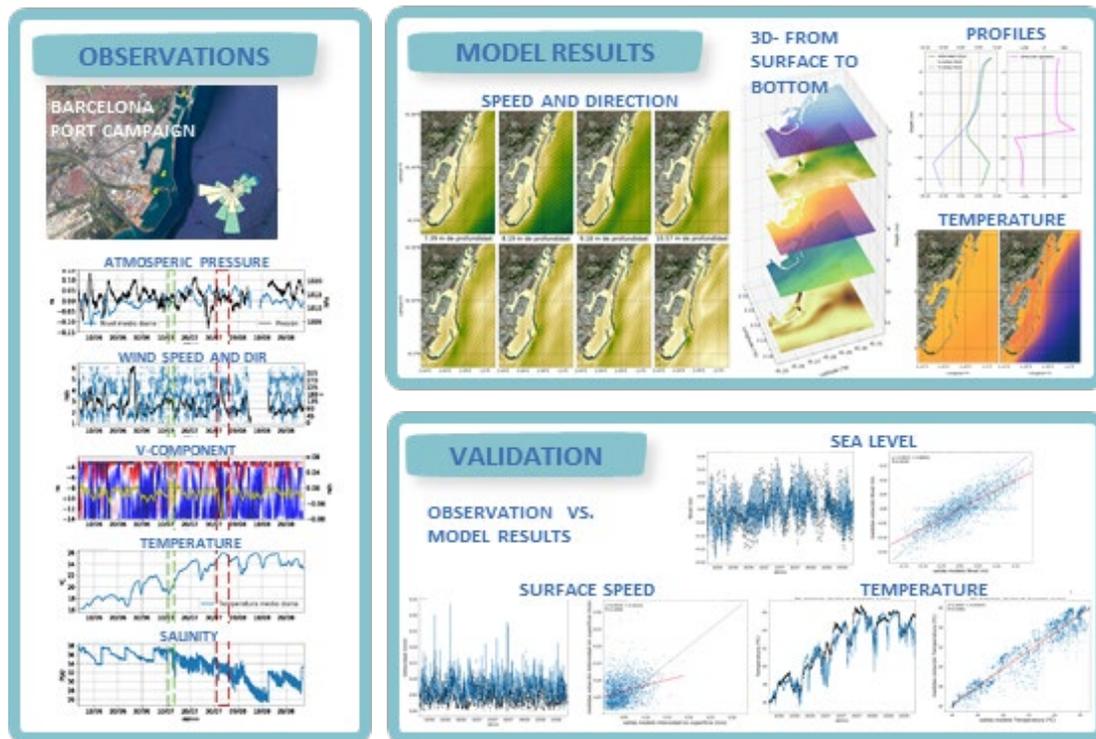


Figure 15. Overview of the observations (left panel), model results (upper right panel), and validation (lower right panel) at the Barcelona local coastal waters and port.

## 5. References

### 5.1. Taranto

Artegiani, A., Bregant, D., Paschini, E., Pinaridi, N., Raicich, F., Russo, A., (1997a). The Adriatic Sea general circulation. Part I: Air-sea interactions and water mass structure, *J. Phys. Oceanogr.*, 27, 1492–1514.

Artegiani, A., Bregant, D., Paschini, E., Pinaridi, N., Raicich, F., Russo, A. (1997b) The Adriatic Sea general circulation. Part II: Baro- clinic circulation structure, *J. Phys. Oceanogr.*, 27, 1515–1532.

Bellafiore, D., Umgiesser, G., 2010. Hydrodynamic coastal processes in the north Adriatic investigated with a 3D finite element model, *Ocean Dynam.*, 60, 255–273.

Bignami, F., Sciarra, R., Carniel, S., Santoleri, R., 2007. Variability of Adriatic Sea coastal turbid waters from SeaWiFS imagery, *J. Geophys. Res.*, 112, 3–10.

Burchard, H., Bolding, K., Villarreal, M.R., 1999. GOTM—a general ocean turbulence model. Theory, applications and test cases. Technical Report EUR 18745 EN, European Commission.

Caroppo, C., Giordano, L., Rubino, F., Palmieri, N., Bellio, G., Bisci, A., Petrocelli, A., Sclafani, P., Hopkins, T., Marsella, E., 2011. Sustainable management of the coastal environments in the framework of the SPICOSA Project: the study case of the Mar Piccolo in Taranto (Ionian, Mediterranean Sea). In *Marine Research at CNR:928–942*

- Cerruti, A., 1948. Le sorgenti sottomarine (Citri) del Mar Grande e nel Mar Piccolo di Taranto. *Annali Istituto Superiore Navale*, Napoli 7:171–196 (in Italian)
- Ciancia, E., Coviello, I., Di Polito, C., Lacava, T., Pergola, N., Satriano, V., Tramutoli, V., 2018. Investigating the chlorophyll-a variability in the Gulf of Taranto (North-western Ionian Sea) by a multi-temporal analysis of MODIS-Aqua Level 3/Level 2 data, *Continental Shelf Research*, 155, 34–44.
- Cressman, G.P., 1959. An operational objective analysis scheme, *Mon. Weather Rev.*, 87, 367–374.
- Cushman-Roisin, B., Gacic, M., Poulain, P., Artegiani, A., 2001. Physical Oceanography of the Adriatic Sea: Past, Present, and Future, Kluwer Acad., Dordrecht, the Netherlands, 304 pp.
- De Pascalis, F., Petrizzo, A., Ghezzi, M., Lorenzetti, G., Manfé, G., Alabiso, G., Zaggia, L., 2016. Estuarine circulation in the Taranto Seas, Integrated environmental characterization of the contaminated marine coastal area of Taranto, Ionian Sea (south- ern Italy), the RITMARE Project, *Environ. Sci. Pollut. R.*, 23, 12515–12534.
- De Serio, F., Mossa, M. (2015). Analysis of mean velocity and turbulence measurements with ADCPs, *Adv. Water Res.*, 81, 172–185.
- Dobricic, S., Pinardi, N., 2008. An oceanographic three-dimensional variational data assimilation scheme, *Ocean Model.*, 22, 89–105.
- Egbert, G., Erofeeva, S., 2002. Efficient inverse modeling of barotropic ocean tides, *J. Atmos. Ocean. Tech.*, 19, 183–204.
- Ferrarin, C., Roland, A., Bajo, M., Umgiesser, G., Cucco, A., Davolio, S., Buzzi, A., Malguzzi, P., Drofa, O., 2013. Tide-surge-wave modelling and forecasting in the Mediterranean Sea with focus on the Italian coast, *Ocean Model.*, 61, 38–48.
- Ferrarin, C., Bajo, M., Bellafiore, D., Cucco, A., De Pascalis, F., Ghezzi, M., Umgiesser, G., 2014. Toward homogenization of Mediterranean lagoons and their loss of hydrodiversity. *Geophys Res Lett* 41(16):5935–5941.
- Ferrarin C, Maicu F, Umgiesser G., 2017. The effect of lagoons on Adriatic Sea tidal dynamics. *Ocean Model.*, 119:57–71.
- Federico, I., Pinardi, N., Coppini, G., Oddo, P., Lecci, R., Mossa, M., 2017. Coastal ocean forecasting with an unstructured grid model in the Southern Adriatic and Northern Ionian seas, *Nat. Hazards Earth Syst. Sci.*, 17, 45–59.
- Grauel, A. L., Bernasconi, S. M., 2010. Core-top calibration of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{O}$  of *G. ruber* (white) and *U. mediterranea* along the southern Adriatic coast of Italy, *Mar. Micropaleontol.*, 77, 175– 186.
- Hellermann, S., Rosenstein, M., 1983. Normal wind stress over the world ocean with error estimates, *J. Phys. Oceanogr.*, 13, 1093–1104.
- Kara, B. A., Wallcraft, A. J., Hurlburt, H. E., 2007. A Correction for Land Contamination of Atmospheric Variables near Land–Sea Boundaries, *J. Phys. Oceanogr.*, 37, 803–818.

Madec, G. (2008). NEMO ocean engine, Note du Pole de modelisation, Institut Pierre-Simon Laplace (IPSL), France, 27, 1288–1619.

Milligan, T.G., Cattaneo, A., 2007. Sediment dynamics in the western Adriatic Sea: From transport to stratigraphy, *Cont. Shelf Res.*, 27, 287–295.

Oddo, P., Guarnieri, A., 2011. A study of the hydrographic conditions in the Adriatic Sea from numerical modelling and direct observations (2000–2008), *Ocean Sci.*, 7, 549–567.

Pettenuzzo, D., Large, W. G., and Pinardi, N., 2010. On the corrections of ERA40 surface flux products consistent with the Mediterranean heat and water budgets and the connection between basin surface total heat flux and NAO, *J. Geophys. Res.*, 115, C06022

Pinardi, N., Lyubartsev, V., Cardellicchio, N., Caporale, C., Ciliberti, S., Coppini, G., De Pascalis, F., D'Alti, L., Federico, I., Filippone, M., Grandi, A., Guideri, M., Lecci, R., Lamberti, L., Lorenzetti, G., Lusiani, P., Macripo, C. D., Maicu, F., Mossa, M., Tartarini, D., Trotta, F., Umgiesser, G., Zaggia, L., 2016. Marine Rapid Environmental Assessment in the Gulf of Taranto: a multiscale approach, *Nat. Hazards Earth Syst. Sci.*, 16, 2623–2639.

Poulain, P. M., 2001. Adriatic Sea surface circulation as derived from drifter data between 1990 and 1999, *J. Mar. Syst.* 29, 3–32.

Scroccaro, I., Matarrese, R., Umgiesser, G., 2004, Application of a finite element model to the Taranto Sea. *Chem. Ecol.*, 20:205–224, supplement 1.

Sellschopp, J., Alvarez, A., 2003. Dense low-salinity outflow from the Adriatic Sea under mild (2001) and strong (1999) winter conditions, *J. Geophys. Res.*, 108, 8104.

Spizzico, M., Tinelli, R., 1986. Hydrogeology of Galese spring, Mar Piccolo of Taranto (S. Italy). In: *Proceedings 9th Salt Water Intrusion Meeting Delft, Water Management Group*, Delft University of Technology, pp 85–97

Stefanon, A., Cotecchia, F., 1969. Prime notizie sulle caratteristiche di efflusso e sulle modalità di investigazione delle sorgenti sub-acquee ai fini di una loro captazione. *Quaderni de La Ricerca Scientifica, Istituto di Ricerca sulle Acque* 58(Rapporto n. 2): 165–195 (in Italian)

Turchetto, M., Boldrin, A., Langone, L., Misericocchi, S., Tesi, T., Foglini, F., 2007. Particle transport in the Bari Canyon (southern Adriatic Sea), *Mar. Geol.*, 246, 231–247.

Umgiesser, G., Canu, D. M., Cucco, A., Solidoro, C., 2004. A finite element model for the Venice lagoon: Development, set up, calibration and validation, *J. Marine Syst.*, 51, 123–145.

Umgiesser, G., Ferrarin, C., Cucco, A., De Pascalis, F., Bellafiore, D., Ghezzi, M., Bajo, M., 2014. Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling, *J. Geophys. Res.-Oceans*, 119, 2212–2226.

Verri, G., Pinardi, N., Oddo, P. et al., 2018. River runoff influences on the Central Mediterranean overturning circulation. *Clim. Dyn.*, 50, 1675–1703. <https://doi.org/10.1007/s00382-017-3715-9>

## 5.2. Barcelona

Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions. Part I: Model description and validation. *Journal of Geophysical Research* 104 (C4), 7649–7666.

Buongiorno Nardelli B., Tronconi, C., Pisano, A., Santoleri, R., 2013. High and Ultra-High resolution processing of satellite Sea Surface Temperature data over Southern European Seas in the framework of MyOcean project, *Rem. Sens. Env.*, 129, 1-16, doi:10.1016/j.rse.2012.10.012.

Carter GS, Merrifield MA. 2007. Open boundary conditions for regional tidal simulations. *Ocean Model.* 18:194–209. doi:10.1016/j.ocemod.2007.04.003.

Haidvogel, D. B. , Arango, H.G., Budgell, W. P., Cornuelle, B. D., Curchitser, E., Di Lorenzo, E., Fennel, K., Geyer, W. R., Hermann, A. J., Lanerolle, L., Levin, J., McWilliams, J. C., Miller, A. J., Moore, A. M., Powell, T. M., Shchepetkin, A. F., Sherwood, C. R., Signell, R. P., Warner, J. C., Wilkin, J. (2008). Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System, *Journal of Computational Physics.* 227, 3595-3624.

Liste ,M., Mestres, M., Espino, M., Sanchez-Arcilla, A., García-León, M., Sotillo, M., and Alvarez-Fanjul, E. (2021). High-Resolution 3D Forecasting System for Barcelona's Beaches and Coastal Waters. EGU General Assembly. 19-30 April 2020. Vienna, Austria.

Mestres M, Grifoll M, Sánchez-Arcilla A. 2016. Analysis of current intensification in the Northwest Mediterranean shelf. *Cont Shelf Res.* 114:29–40. ISSN 0278-4343, doi:10.1016/j.csr.2015.12.011.

Poulain, P.-M., Bussani, A., Gerin, R., Jungwirth, R., Mauri, E., Menna, M., Notar-Stefano, G., 2013. Mediterranean surface currents measured with drifters: from basin to subinertial scales. *Oceanography* 26(1), 38–47. <http://dx.doi.org/10.5670/oceanog.2013.03>.

Sánchez-Arcilla, A. and Simpson, J., 2002. The narrow shelf concept: couplings and fluxes. *Cont. Shelf Res.* 22(2), 153–172.

Shchepetkin, A. F., McWilliams, J.C. (2005). The Regional Oceanic Modeling System: A split-explicit, free-surface, topography-following coordinate oceanic model. *Ocean Modeling* 9, 347–404 doi:10.1016/j.ocemod.2004.08.002.

Shchepetkin, A. F., McWilliams, J. C. (2009). Correction and commentary for “Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the regional ocean modeling system” by Haidvogel et al., *J. Comp. Phys.* 227, pp. 3595–3624.”. *Journal of Computational Physics.* 228, 8985-9000.

Sotillo, MG., P. Cerralbo, P. Lorente, M. Grifoll, M. Espino, A. Sanchez- Arcilla & E. Álvarez-Fanjul (2019): Coastal ocean forecasting in Spanish ports: the SAMOA operational service, *Journal of Operational Oceanography*, DOI: 10.1080/1755876X.2019.1606765

Sotillo MG, Cailleau S, Lorente P, Levier B, Aznar R, Reffray G, AmoBaladrón A, Chanut J, Benkiran M, Alvarez-Fanjul E. 2015. The MyOcean IBI ocean forecast and reanalysis systems: operational products and roadmap to the future Copernicus service. *J Oper Oceanogr.* 8(1):63–79. doi:10. 1080/1755876X.2015.1014663.

Tsimplis, M.N., Proctor, R., Flather, R.A., 1995. A two-dimensional tidal model for the Mediterranean Sea. *J. Geophys. Res.* 100 (C8), 16223–16239. <http://dx.doi.org/10.1029/95JC01671>.

Warner, J.C., Armstrong, B., He, R., and Zambon, J. (2010). Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System, *Ocean Modelling*, 35, 230-244. (<http://woodshole.er.usgs.gov/project-pages/cccp/public/COAWST.htm>).



Warner JC, Sherwood CR, Arango HG, Signell RP. 2005. Performance of four turbulence closure models implemented using a generic length scale method. *Ocean Model.* 8(1):81–113.