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Cross-scale operational oceanography in the Adriatic Sea

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ABSTRACT
The oceanographic forecast capability in coastal seas is often limited by the capacity of the numerical models in correctly reproducing the complex morphology of the coastline and the exchange processes between the shelf and the open seas. In the marginal Adriatic Sea this task is of uppermost importance due to the presence of several coastal water bodies and rivers. We present here a new operational oceanographic system, called Tiresias, based on the unstructured grid model SHYFEM and representing the whole Adriatic Sea together with the lagoons of Marano-Grado, Venice and Po Delta. The novelty of this oceanographic system resides in the very high-resolution, up to 10 m, of the numerical mesh, and in the high spatial and temporal resolution of the forcing and boundary conditions that drive the forecasts. The forecast results are evaluated against sea temperature and salinity profiles, mean circulation fields derived from a regional ocean model, tide gauges and drifter trajectory. The presented results highlighted the capacity of Tiresias in forecasting the general circulation in the Adriatic Sea, as well as several relevant coastal dynamics, such as saltwater intrusion, storm surge and riverine waters dispersion.

KEYWORDS
Adriatic Sea; Lagoons; Finite element model; Coastal dynamics

1. Introduction

Oceanographic models are applied worldwide within predictive systems to forecast the sea state with the aim of helping people to operate more effectively and safely along the coast and in the open sea. Coastal ocean forecasts are crucial for managing storm damages and flooding, fisheries and aquaculture activities, shipping, harmful algal blooms and oil spills (Chaumillon et al. 2017).

Simulation of water circulation and of the principal physical processes affecting coastal areas requires the use of both numerical models at high spatial and temporal resolution and downscaling techniques capable of reproducing mass exchange between the coastal area and the open sea (coastal-offshore interactions). This goal

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can be achieved through the implementation of numerical models based on a unique unstructured grid able to describe processes at different spatial scales (Cucco et al. 2012; Zhang et al. 2016; Ferrarin et al. 2016; Stanev et al. 2017; Federico et al. 2017; Ferrarin et al. 2018), or through nesting of models (structured and unstructured) at different resolution (Kourafalou et al. 2015; Trotta et al. 2016, 2017; Fortunato et al. 2017). The use of an unstructured grid gives the advantage of using higher resolution at the coasts while applying more modest resolution in the deep sea, an approach that has proved to be accurate for the Adriatic Sea (McKiver et al. 2016).

In addition to the appropriate model resolution and numerics, oceanographic operational systems require the integration with near real-time observations to achieve a comprehensive description of the dynamics in the coastal sea (Kourafalou et al. 2015; Wilkin et al. 2017). In operational oceanography, in-situ and remote observations are needed for the accurate initial estimates of the ocean state to be used for the initialisation of short-range forecasts (Martin et al. 2015) and to set-up the appropriate boundary conditions for the simulations. This last requirement is of particular relevance in coastal seas affected by rivers and related buoyancy-driven flows (Kourafalou et al. 2015). In these systems, the representations of the river plume dynamics is crucial to achieve reliable coastal ocean forecasts.

In the context of operational oceanography, the Adriatic Sea represents a challenge, given that it is a regional sea strongly affected by air-sea, land-sea, and coastal-offshore interactions. Indeed, the main forcings of the basin circulation are the wind (influenced by the complex local orography and small scale processes), the strong buoyancy resulting from the freshwater inputs injected by the rivers, and the tidal waves generated in the Mediterranean Sea (Orlić et al. 1992).

The Adriatic Sea is an 800 km long, 150 km wide elongated semi-enclosed basin communicating with the Mediterranean Sea through the Otranto Strait in the southern part (Fig. 1). The Adriatic Sea can be formally subdivided, based on its bathymetry, in the relative shallow northern Adriatic (north of the 100 m-isobath), a middle trench and the deep southern Adriatic Pit (with depths exceeding 1,000 m, Artegiani et al. 1997). Several shallow coastal transitional water bodies are present in the northern part of the Adriatic Sea, the main of which are the Marano-Grado Lagoon, the Venice Lagoon and the system of lagoons of the Po Delta. Such coastal environments have an average depth of 1.2 -1.5 m and are characterised by a complicated network of channels (up to 15 m deep), shallow flats (generally about 1 m deep) and marshes, that are intermittently dry and wet. It has been recently demonstrated by Ferrarin et al. (2017) that these coastal lagoons significantly influence the tidal induced circulation in the entire northern Adriatic Sea.

Several oceanographic operational systems have been implemented in the Mediterranean and the Adriatic seas during the last two decades (Napolitano et al. 2016; Coppini et al. 2017, and references therein). The SHYFEM model in barotropic version has been implemented at the Centro Previsioni e Segnalazioni Maree (`https://www.comune.venezia.it/it/content/la-previsione`, Bajo and Umgiesser 2010; Zampato et al. 2016), at the Italian Institute for Environmental Protection and Research (`http://www.isprambiente.gov.it/pre_meteo_eng/simm_eng.html`) and at the CNR-ISMAR (`http://www.ismar.cnr.it/kassandra`, Ferrarin et al. 2013) for forecasting the sea level. However, these systems do not consider the baroclinic circulation, as they are mainly focused on storm surge and wave forecasting. Full baroclinic oceanographic forecasts for the Adriatic Sea are available through the Mediterranean Forecasting System (`http://medforecast.bo.ingv.it/`, Oddo et al. 2009), the Adriatic Forecasting System (`http://www.oceanlab.cmcc.it/afs/`, Oddo

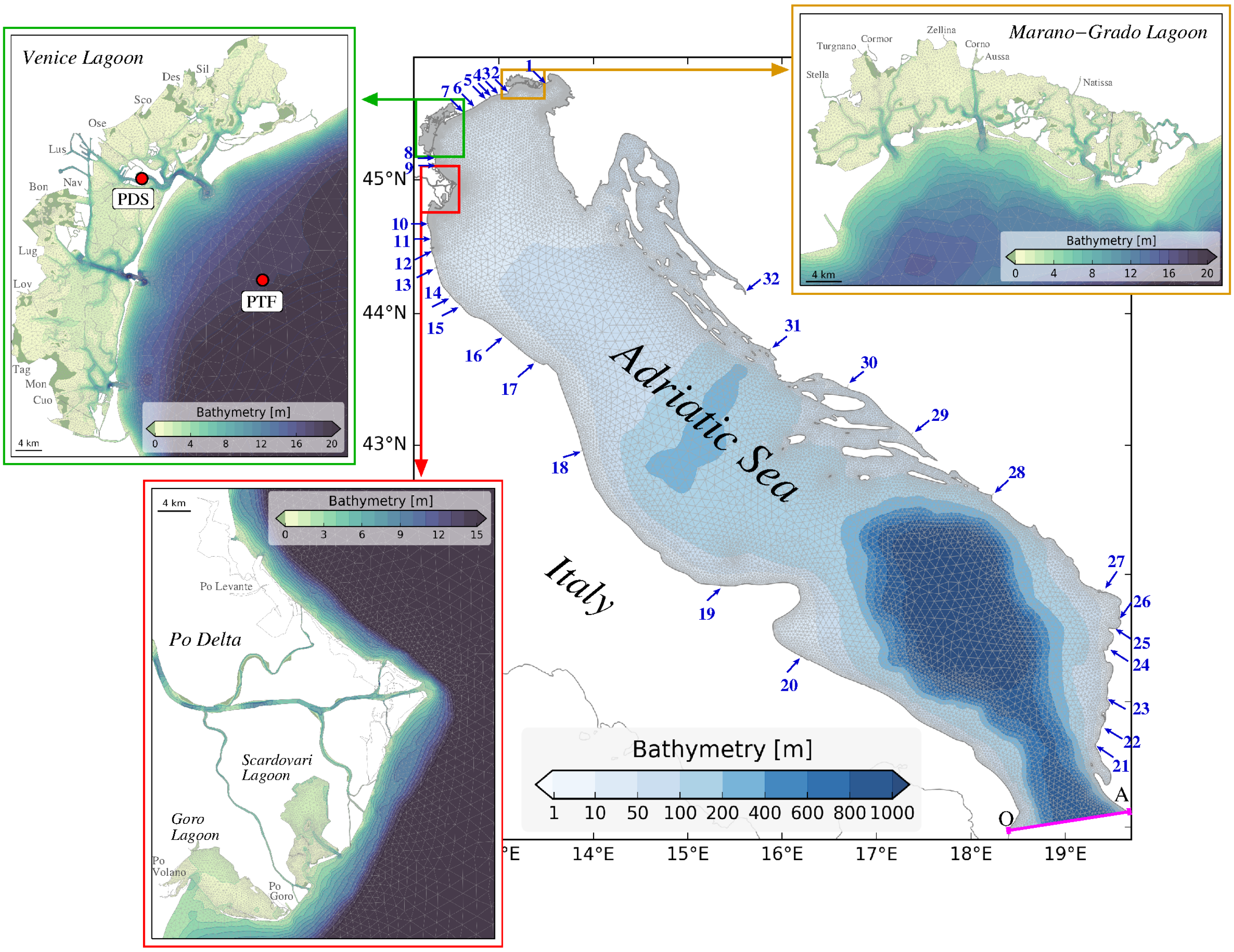

Figure 1. Bathymetry of the Adriatic Sea and of the Marano-Grado, Venice and Po Delta lagoons interpolated on the triangular numerical grid (superimposed). Arrows mark the location of the major rivers of the Adriatic Sea: 1) Isonzo, 2) Tagliamento, 3) Canale dei Lovi, 4) Lemene, 5) Livenza, 6) Piave, 7) Sile, 8) Brenta, 9) Adige, 10) Reno, 11) Lamone, 12) Fiumi Uniti, 13) Savio, 14) Uso, 15) Marecchia, 16) Metauro, 17) Esino, 18) Tronto, 19) Fortore, 20) Ofranto, 21) Vijuse, 22) Seman, 23) Shkumbi, 24) Erzen, 25) Ishm, 26) Mat, 27) Bojana, 28) Ombla, 29) Neretva, 30) Cetina, 31) Krka, 32) Zrmanja. Rivers flowing in the lagoons and in the Po Delta are labelled in the zoom panels. The purple OA line indicates the Otranto Strait boundary. The red dots in the upper-left panel indicate the tide gauges used for the storm surge validation.

et al. 2006), the BORA Adriatic Marine Forecast (`http://www.bora.gekom.hr`), the AdriaROMS Ocean Model Forecast (`https://www.arpae.it/sim/`, Chiggiato and Oddo 2008), and the southern Adriatic northern Ionian coastal Forecasting System (`http://oceanlab.cmcc.it/sanifs/`, Federico et al. 2017).

In this study we describe a novel forecasting system - called Tiresias - for the Adriatic Sea and its northern lagoons. With respect to the above cited forecasting systems, Tiresias realises a seamless transition between different spatial scales, from lagoon's tidal channels to open-sea, and adopts high spatial and temporal resolution of the forcing and boundary conditions that drive the forecasts. Tiresias is evaluated against observations in both the open sea and the coastal areas, illustrating the capability of this tool in forecasting the general circulation features in the Adriatic, as well as coastal storm surge, saltwater intrusion and particle dispersion.

2. The Tiresias forecasting system for the Adriatic Sea

2.1. The hydrodynamic model

The 3D hydrodynamic finite element model SHYFEM solves the primitive equations, vertically integrated over each layer considering tidal, atmospheric and density-driven forces. SHYFEM is open source and freely available on the web pages `http://www.ismar.cnr.it/shyfem` and `https://github.com/SHYFEM-model`. SHYFEM has been already applied to simulate hydrodynamics in the Mediterranean Sea (Cucco et al. 2012; Ferrarin et al. 2013), in the Adriatic Sea (Bellafiore and Umgiesser 2010; Federico et al. 2017; Ferrarin et al. 2016, 2017), in several coastal systems (Umgiesser et al. 2014, and references therein) and recently in the Po River-Delta-Sea system (Maicu et al. 2018).

The horizontal discretization of the state variables is carried out with the finite element method, with the subdivision of the numerical domain in triangles varying in form and size. Velocities are computed in the centre of the grid element, whereas the water levels are computed at the element vertices (nodes). Vertically the model applies Z layers with varying thickness. Most variables are computed in the center of each vertical layer, whereas stress terms and vertical velocities are solved at the interfaces between layers.

McKiver et al. (2016) pointed out the irrelevance of non-hydrostatic processes for the northern Adriatic Sea. However, non-hydrostatic processes can play a role in accurately capturing dense water cascading events in the deep Pit in the Southern Adriatic (Bellafiore et al. 2018), though including such processes comes with a high numerical cost (approx 4 times the running time of the hydrostatic case), making it impractical for operational forecasts.

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).

2.2. The model set-up

The numerical computation is performed on a spatial domain that represents the whole Adriatic Sea, the lagoon of Marano-Grado, the lagoon of Venice and the Po River Delta (including the Scardovari and Goro lagoons) by means of the unstructured grid shown in Fig. 1. The numerical domain comprises all Po River branches starting downstream the Po di Goro diversion (40 km upstream) with 9 river mouths. To adequately resolve the river-sea continuum, the unstructured grid also includes the lower part of the other major rivers flowing into the Adriatic Sea.

The use of elements of variable sizes, typical of finite element methods, is fully exploited, in order to suit the complicated geometry of the basin, the rapidly varying topographic features, and the complex bathymetry of the lagoon systems. The numerical grid of the Adriatic Sea with the lagoons consists in approximately 110,000 triangular elements with a resolution that varies from 7 km in the open-sea to few hundred meters along the coast and tens of meters in the inner lagoon channels. Recently, Ferrarin et al. (2017) showed that the inclusion of the lagoons in the simulation improved the capability of the model in reproducing tidal currents in the whole northern Adriatic Sea.

The model is able to work with wetting and drying, a feature needed in the shallow lagoons, where some areas consists of salt marshes that are intermittently dry and wet, and in the Po River floodplains.

Because of the wide area, the bathymetry of the Adriatic and the lagoons was obtained by merging several datasets, having different spatial resolution and obtained using different measurement approaches, but the same reference datum (Genoa 1942 - IGM42). The resulting bathymetry, interpolated and superimposed on the triangular mesh, is shown in Fig. 1.

In this model application, the water column is discretised in 34 vertical layers with variable thickness ranging from 1 m, in the topmost 10 m, to 100 m for the deepest layer of the Adriatic Sea. The vertical discretization of the surface layers allows one to describe the tidal propagation over the shallow tidal flats and the vertical structure of the tidal flow in the tidal channel network. 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).

For the free surface, a water flux is used containing evaporation minus precipitation and river discharge. For computing the water temperature, the air-sea heat fluxes are parameterised by the COARE (Coupled Ocean-Atmosphere Response Experiment) 3.0 bulk algorithm (Fairall et al. 2003). Also the drag coefficient for the momentum transfer of wind in the hydrodynamic model is computed according to the COARE 3.0 bulk formulae (Fairall et al. 2003).

2.3. Operational forcing and boundary conditions

Reliable forcing and boundary conditions are crucial to correctly forecast the circulation in the Adriatic Sea, which is strongly influenced by high temporal and spatial variability of the atmospheric conditions and river runoff (Orlić et al. 1992; Artegiani et al. 1997; Davolio et al. 2015; Brando et al. 2015).

2.3.1. Meteorological forcing

The weather in the Adriatic area is strongly influenced by local orography and small scale processes, and therefore for realistic oceanographic prediction an appropriate spatial resolution of the meteorological fields is required (Pasarić et al. 2009). The use of high-resolution meteorological models is essential to capture the temporal and spatial inhomogeneity of northeasterly Bora winds, characterised by topographically controlled high-speed wind jets along the eastern shore (Dorman et al. 2006; Davolio et al. 2015).

In Tiresias, the meteorological forcing is supplied by the MOLOCH limited-area, high-resolution model, developed and implemented at CNR-ISAC (National Research Council of Italy - Institute of Atmospheric Sciences and Climate) with a daily operational chain (`http://www.isac.cnr.it/dinamica/projects/forecasts`). The forecast framework comprises the hydrostatic model BOLAM (implemented over the Euro-Mediterranean region) and the non-hydrostatic model MOLOCH (implemented over Italy), nested in BOLAM (Fig. 2). The initial and boundary conditions for the BOLAM model are derived from the analyses (00 UTC) and forecasts of the GFS

(NOAA/NCEP, USA) global model (`http://www.emc.ncep.noaa.gov/GFS`).

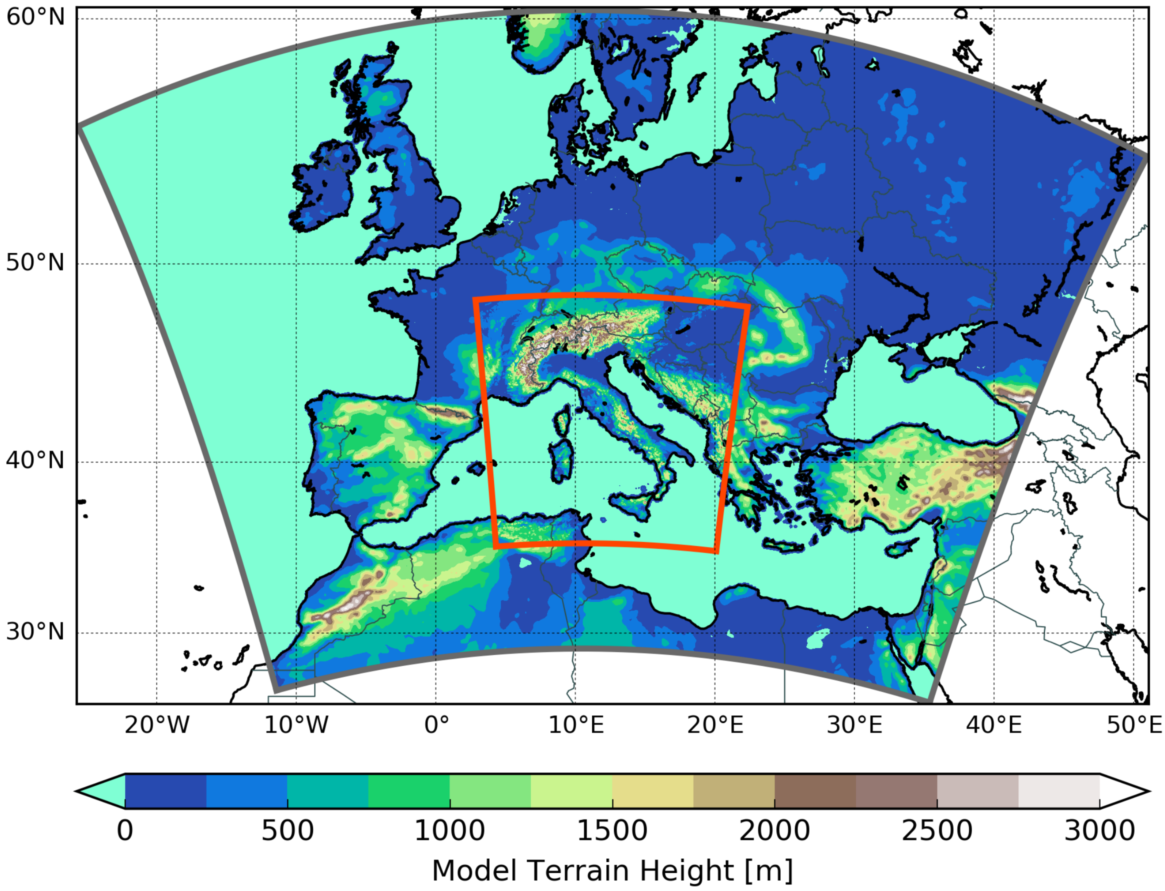

Figure 2. Integration domains of the BOLAM (gray box) and MOLOCH (red box) meteorological models.

MOLOCH is a non-hydrostatic, fully compressible, convection-permitting model. The prognostic variables, namely pressure, air temperature, specific humidity, horizontal and vertical wind velocity components, turbulent kinetic energy and five water species, are represented on a latitude-longitude rotated Arakawa C-grid. It employs a hybrid terrain-following coordinate, which relaxes to horizontal surfaces at higher elevation from the ground. Time integration is based on a time-split scheme with an implicit treatment of the vertical propagation of sound waves and a forward-backward scheme for the horizontal propagation of gravity and sound waves. Advection is computed using a second order implementation of the Godunov (1959) method, which is particularly suited to integrate in time the conservation of a scalar quantity (Toro 1992). This scheme is a total variation diminishing one, and therefore prevents the occurrence of spurious oscillations. See Malguzzi et al. (2006), Buzzi et al. (2014) and Davolio et al. (2017) for further details about the MOLOCH model physics and numerics.

The MOLOCH model is implemented with a horizontal grid spacing of 0.0113 degrees, equivalent to 1.25 km, and with 60 atmospheric levels and 7 soil levels. This model chain has already been successfully validated over the Adriatic Sea (Davolio et al. 2015, 2017; Stocchi and Davolio 2017).

MOLOCH forecasts are daily provided at hourly resolution up to 2 days. The hourly atmospheric forcing fields used from MOLOCH are: 2 m air temperature and relative humidity, total cloud cover, mean sea level atmospheric pressure, meridional and zonal 10 m wind components, total precipitation rate, and the downward short-wave radiation flux. The atmospheric forcing fields are horizontally interpolated at each ocean grid node by means of a bilinear technique.

2.3.2. River boundaries

Freshwater is discharged into the Adriatic Sea mostly from rivers along the northern and northwestern coasts. Due to the abundant freshwater inputs, the Adriatic Sea is considered a dilution basin, exporting a relatively fresh water to the adjacent Ionian Sea (Ludwig et al. 2009; Verri et al. 2018). The Po River represents the major buoyancy input with a mean discharge rate of 1500 m^3 s^{-1}, accounting for about one third of the total riverine freshwater input into the Adriatic Sea.

Even if most of the existing oceanographic forecasting systems for the Adriatic Sea adopt climatological values for the river boundaries (Chiggiato and Oddo 2008; Tonani et al. 2008; Federico et al. 2017), it is well known that freshwater discharges are generally characterised by high-frequency variations. Since freshwater strongly influences the Adriatic Sea circulation, realistic forecasts should be supplied by consistent river discharge values. The need of operational updated discharge values is made evident in the timeseries shown in Fig. 3, where the hourly freshwater discharges of the Po and Isonzo rivers for the year 2016 are plotted together with their monthly mean climatologies derived from Raicich (1996). Moreover, climate change is influencing flood regimes at the continental scale, with a shift toward later floods in the northeastern Adriatic coast (Blöschl et al. 2017).

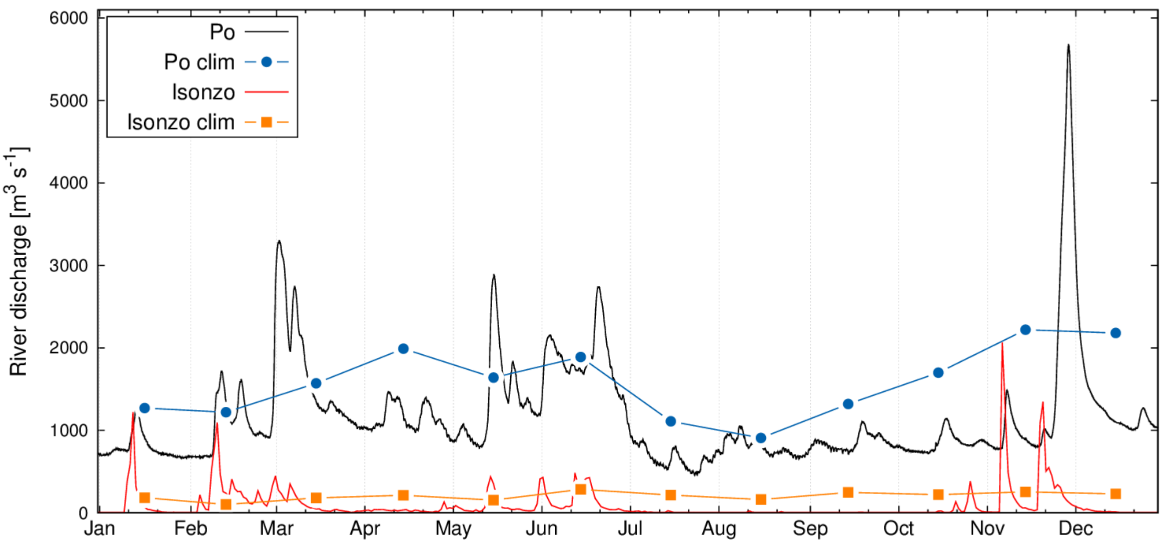

Figure 3. Po and Isonzo rivers discharges for the year 2016. Continuous lines indicate hourly values, while points-lines represent monthly mean climatologies.

In order to improve representation of the coastal freshwater discharge, in Tiresias the lower part of major rivers are included in the unstructured numerical mesh. Being aware of the strong importance of land-sea interactions in coastal forecasting (Kourafalou et al. 2015), in this study strong effort has been paid in choosing the most accurate available river discharge conditions over the Adriatic Sea. Where available, daily updated river discharge values are derived from automatic hydrometric stations nearest to river mouths, through calibrated stage–discharge relationships. This is the case of rivers Isonzo, Aussa, Corno, Zellina, Cormor, Turgnano, Stella, Lemene, Livenza, Piave, Brenta-Bacchiglione-Gorzone, Adige, Po, Reno, Lamone, Fiumi Uniti, Savio, Uso, Marecchia, Metauro, Esino and Tronto. The updated hydrographic levels are daily retrieved from the Civil Protection of Friuli Venezia Giulia and the Regional Environmental Protection Agencies of Veneto, Emilia-Romagna and Marche.

For the other rivers considered in this study (Tagliamento, Natissa, Canale dei Lovi, Sile, the tributaries of the Venice Lagoon, Po di Levante, Po di Volano, Fortore, Ofanto, Vijuse, Seman, Shkumbi, Erzen, Ishm, Mat, Bojana, Ombla, Neretva, Cetina, Krka, Zrmanja) discharges are prescribed using monthly or annual mean climatological values (Raicich 1996; Struglia et al. 2004; Ludwig et al. 2009).

Due to a lack of available observations, river inflow surface salinity is fixed to a constant value of 0.1 at the river boundaries. This value is lower than the ones (15-17) used by other authors (Simoncelli et al. 2011; Federico et al. 2017; Verri et al. 2018) and is justified by the fact that in Tiresias, by resolving the river-sea continuum, freshwater mixes with seawater before reaching the coast. Water temperature at the river boundaries adapts to the environmental value inside the basin.

2.3.3. Open sea boundary

Although it is clear that the model has to resolve the appropriate coastal scales, it is maybe less obvious that, for the open sea boundary conditions, the coastal model needs an upscaling effort to the basin scale. In this case the boundary conditions can be supplied by a model at a larger scale. The use of an unique numerical mesh limits the open sea boundaries to the Strait of Otranto at the southern end of the Adriatic Sea (section OA in Fig. 1). Each node of the Otranto open boundary is treated by defining water level, current velocity, salinity and water temperature.

The sea level and the current velocity conditions were obtained by summing the hourly tidal signal derived from the FES2012 global tidal model (Carrère et al. 2012, available at `www.aviso.altimetry.fr`) and the daily water level and baroclinic velocity predicted by the Mediterranean Forecast System (MFS, Tonani et al. 2008), available via the Copernicus Marine Environmental Monitoring Service (`http://marine.copernicus.eu/`). The total water levels are imposed to the boundary nodes, while the total current velocity are nudged using a relaxation time of 3600 s. Water temperature and salinity boundary conditions are computed using the oceanographic fields of MFS.

2.4. The operational configuration

The operational system chain consists of a daily cycle of numerical integrations. Every day a two-day forecast is produced, with the initial conditions from a hot start based on the Tiresias forecast of the previous day. The system performs a 2.5 day-long simulation with the first 12 hours as a spin-up time (the time interval in the past with respect to the target initial forecast day), allowing the model state to adjust to the updated river discharges and MFS fields.

The model is forced by the atmospheric and open sea boundary data from the MOLOCH forecasts and the MFS analysis and forecasts, respectively, for the whole simulation duration. Tiresias uses the last available river discharge data and keeps this value constant throughout the two-day forecast.

Since Tiresias in not assimilating observations, MFS 3D fields of sea temperature and salinity are nudged during the simulation. MFS runs on a structured grid having horizontal resolution of 1/24° and is operatively assimilating, through the 3DVAR scheme developed by Dobricic and Pinardi (2008), satellite sea level anomaly, satellite sea surface temperature and vertical temperature and salinity profiles from Argo floats. Nudging data are given for all nodes of the unstructured grid. The value of the relaxation coefficient is spatially varying over the model domain (as a function of the grid resolution) from 2 days in the open sea and increasing, thus diminishing the restoration contribution, toward the coast. Therefore, the nudging allows the model state to be reconciled with the assimilated MFS data in the open sea - limiting error growth in the forecast chain - and to fully compute the hydrodynamics along the coast and in the lagoons.

Tiresias runs operationally since September 2014. A two months-long simulation (July - August 2014), initialised with the MFS sea temperature and salinity fields, was performed to define the conditions for the starting state of the operational forecasting system. A similar spin-up time was used by Ferrarin et al. (2016) and McKiver et al. (2016) for simulating the Adriatic Sea hydrodynamics. The spin-up time is longer than the water renewal time in the north Adriatic lagoons (Umgiesser et al. 2014), and therefore allowed these systems to dynamically adjust after initialization from the interpolation of coarser MFS fields.

Tiresias runs on a Linux operating system. Its core is composed by a set of scripts, activated as soon as the MOLOCH atmospheric forcing is available, which prepare and launch each forecast simulation.

3. Evaluation of the modelling system

The application of the SHYFEM model to the Adriatic Sea has been validated in previous works reproducing correctly tidal propagation, storm surge, water flows at the lagoons' inlets and water temperature and salinity patterns along the northern coast (Bellafiore and Umgiesser 2010; Ferrarin et al. 2016; McKiver et al. 2016; Bajo et al. 2017; Ferrarin et al. 2017). However, because of the different model set-up and forcing conditions, an extensive validation of the Tiresias forecasts has been performed.

The validation exercises presented below aim at assessing the forecasting skills of Tiresias, but also at providing an overview of the potential applications of the numerical results, in both the open sea and the coastal areas.

3.1. Regional scale: the Adriatic Sea

In addition to the wind forcing and the strong buoyancy resulting from the freshwater inputs injected by the rivers, the circulation of the Adriatic Sea is influenced by the tide (Orlić et al. 1992). Tidal dynamics are particularly evident in the northern Adriatic Sea, where the most energetic tidal constituents - the semi-diurnal M_2 and the diurnal K_1 - reach amplitudes of 27 and 18 cm, respectively (Ferrarin et al. 2017). A reliable representation of the tidal dynamics is crucial, considering the role of tides in modulating buoyancy-driven river plumes, vertical mixing of the sea waters and dense water discharges (Orlić et al. 1992; Guarnieri et al. 2013; Benetazzo et al. 2014).

The barotropic tidal signal simulated in the Adriatic Sea using the same numerical mesh (except for some small lagoons of the Po Delta) has been recently successfully validated by Ferrarin et al. (2017). The model results were compared with the properties of the principal tidal waves and currents. Considering the tidal amplitudes and phases as vectors (or complex numbers), an overall measure of the match between a modelled and observed harmonic constituent is given by the vectorial difference, computed as distances in the complex plane (Foreman et al. 1993) The root mean square deviation of the vectorial differences, was lower than 1 cm for all constituents.

In order to assess the capability of the full baroclinic Tiresias system to properly reproduce the basin scale circulation in the Adriatic Sea, the forecast results were compared with the observations acquired within the MS16 cruise aboard R/V Minerva Uno in the period 7-17 December 2016. The main aim of this extensive field survey was to monitor the properties of the water column and sediment over the Italian side of the Adriatic Sea, from the Otranto Strait to the Gulf of Trieste. 67 water temperature and salinity profiles were acquired with a CTD SBE911plus probe.

In the validation procedure, the simulated water temperature and salinity profiles were extracted from the first day of model forecasts at the grid node nearest to the CTD station. Vertically the model results have been linearly interpolated to the observation depths. Fig. 4 maps the model performance, in terms of the difference between the average of simulated and observed values (BIAS) and the centered root mean square error (CRMSE), for the water temperature and salinity at each CTD cast.

The analysis of the results reveals that the operational model compares reasonably well with the measurements and reproduces the observed spatial variability of both water temperature and salinity. The average BIAS and CRMSE are 0.1 and 0.5 units, respectively, for both variables. The highest errors are found at two locations in the central Adriatic Sea (near Rimini and Pescara) and could be due to the use of the unrealistic climatological freshwater inputs. The model tends to overestimate the water temperature and salinity near Ancona. In the Gulf of Trieste the model overestimates the water temperature by 1^{o}C and slightly underestimates the salinity. However, due to the spatial variability of errors, it is realistic to assume that the origin of discrepancies is connected with local effects.

To investigate the model skill over the forecast of the system, the same statistical analysis was performed using the second day of model forecasts. The error analysis showed that the model uncertainty is not increasing with the forecast validity interval (average BIAS and CRMSE of 0.1 and 0.5 units, respectively, for both variables). The good performance of the system confirms the high accuracy of the MOLOCH atmospheric forecasts and demonstrates the strength of the Tiresias approach, which combines the MFS nudging in the open sea with the high-resolution calculation along the coast. It has to be considered that in the Adriatic Sea tides strongly affect coastal dynamics (Orlić et al. 1992) and the error of reproducing the tidal signal is constant during the short term forecast (Ferrarin et al. 2013).

The CTD comparison was also performed in terms of 3 representative vertical profiles, obtained averaging the CTD casts over the northern, central and southern Adriatic Sea, respectively, according to the region subdivision illustrated in Fig. 4a. The average vertical profiles of water temperature and salinity, and their statistics in terms of CRMSE and BIAS, are illustrated in Fig. 5.

In the shallow northern Adriatic Sea, the observed temperature and salinity profiles, characterised by values increasing with depth, are well reproduced by the model. For both the variables the higher discrepancies with the observations were found on the surface (upper 5 m) with a CRMSE reaching 1.6 and a BIAS of 0.8 for the salinity. Such a model overestimation could be due to the impact of atmospheric and freshwater uncertainties affecting the Tiresias results in this high dynamic areas. Indeed, the CTD observations highlights that the surface layer in the northern Adriatic Sea is

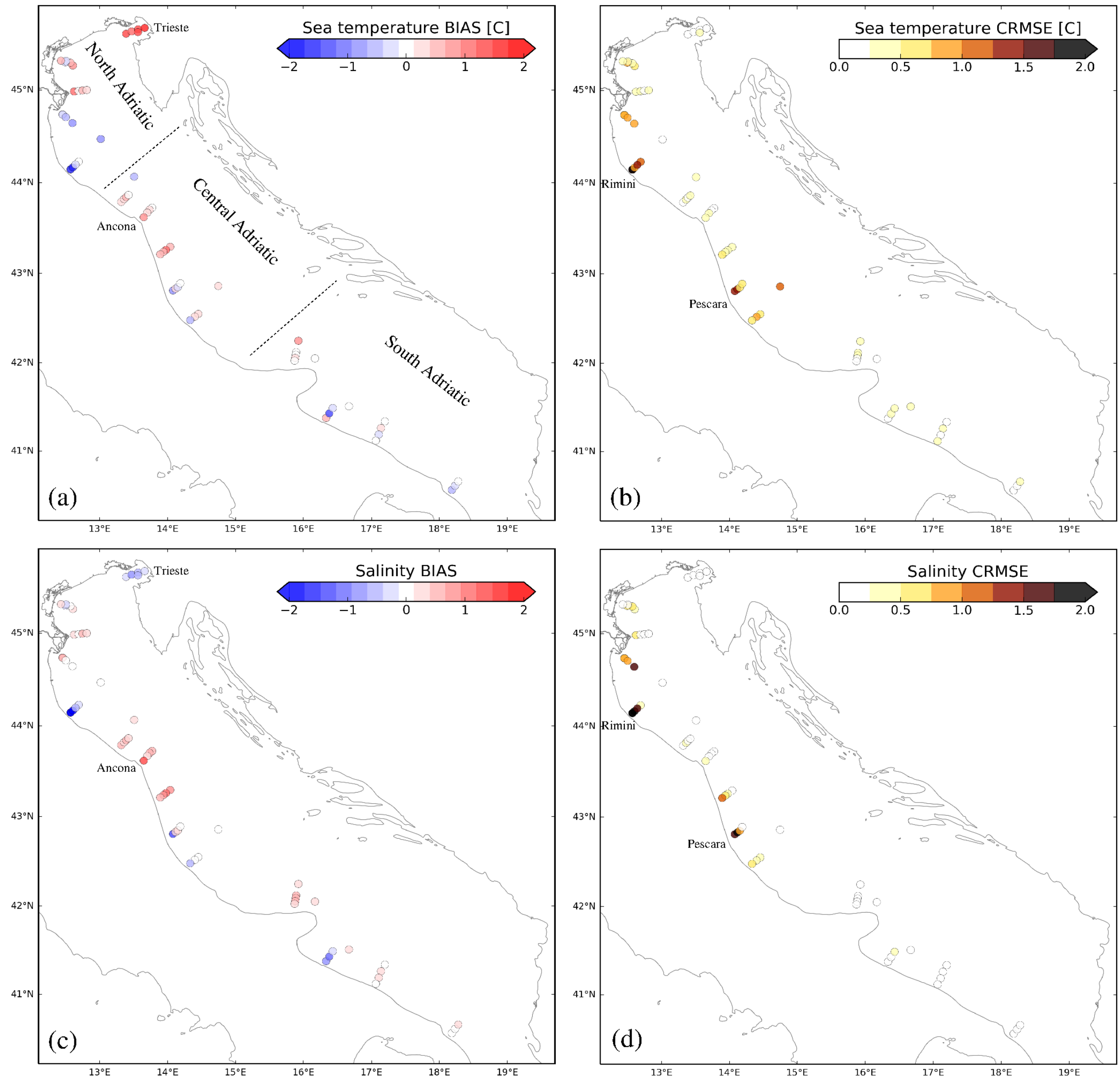

Figure 4. Results of the Tiresias validation with the observations of the MS16 survey in terms of vertical averaged BIAS and CRMSE for the water temperature (a, b) and salinity (c, d).

characterised by a standard deviation of almost 2 and 3 units for the water temperature and salinity, respectively.

In the central Adriatic Sea, the model captures the average vertical structure of the water column, characterised by colder and fresher waters in the surface. The model overestimates by 0.5 unit both the water temperature and salinity in the upper 10 m, and tends to enhance the mixing processes in the upper half of the water column.

The observed temperature profile for the southern Adriatic Sea is well reproduced by the model. The water temperature increases till 50 m and then decreases to values of about 15^{o}C at the depth of 140 m. In the southern Adriatic Sea, the vertical average Tiresias CRMSE is 0.5 ^{o}C for temperature and 0.2 for salinity. The model generally underestimates the observed salinity by about 0.2. Such a mismatch could be due to a too strong mixing of the upper coastal fresh waters flowing southward.

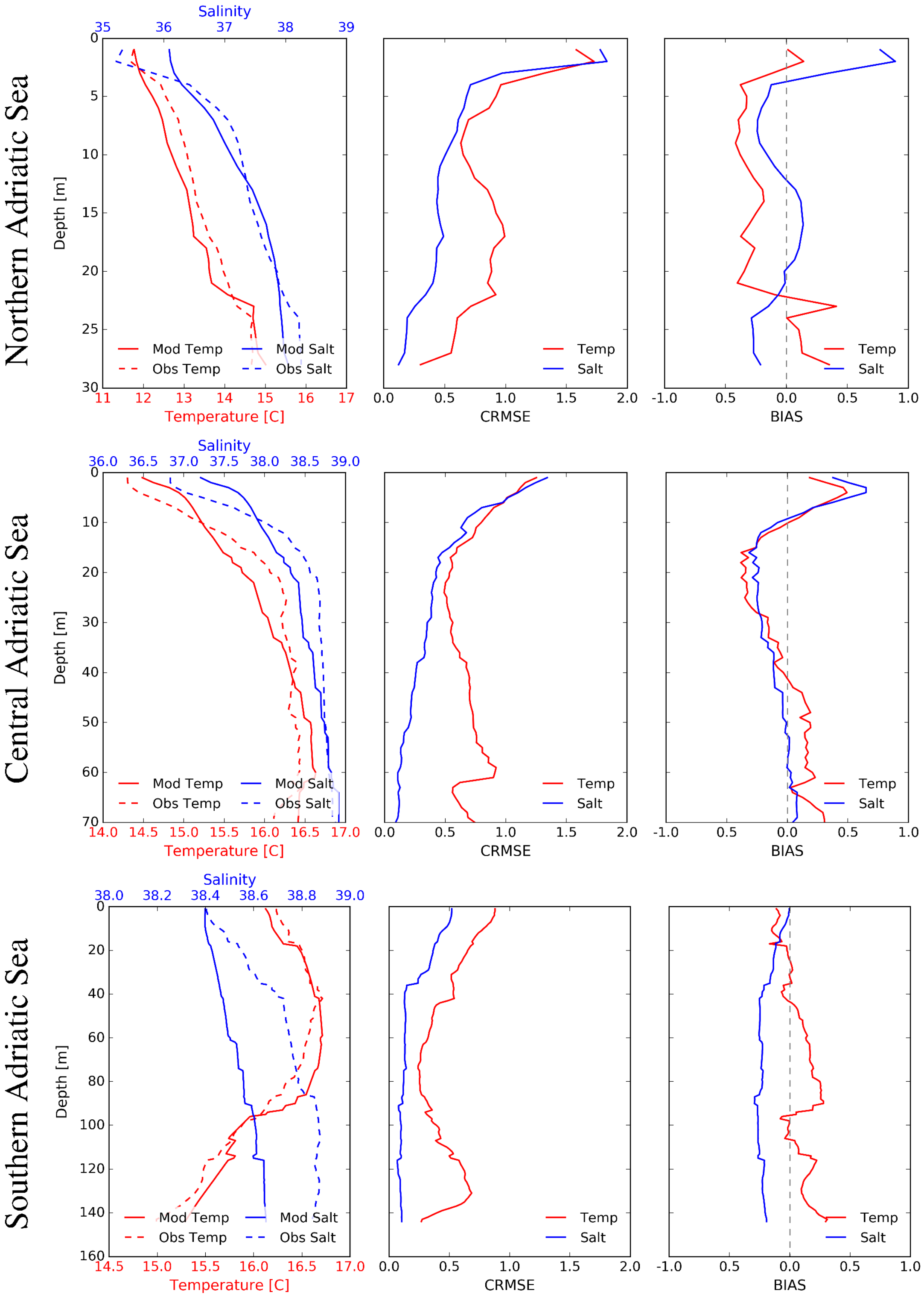

Figure 5. Tiresias average profiles (continuous line) of sea temperature and salinity compared with the observed ones (dashed line) in the northern, central and southern Adriatic Sea. The vertical variations of CRMSE and BIAS are also reported.

The high spatial variability that characterises the water masses in the Adriatic Sea is presented in the top panels of Fig. 6, showing the distribution of the sea surface currents, temperature and salinity fields. The maps were obtained averaging the first day of the Tiresias forecasts for the period of the MS16 campaign. To further validate the model at a regional scale, the analogous fields of the parent model MFS (obtained by averaging the analysis and forecast results retrieved from `http://marine.copernicus.eu/`) are presented in the bottom panels of Fig. 6.

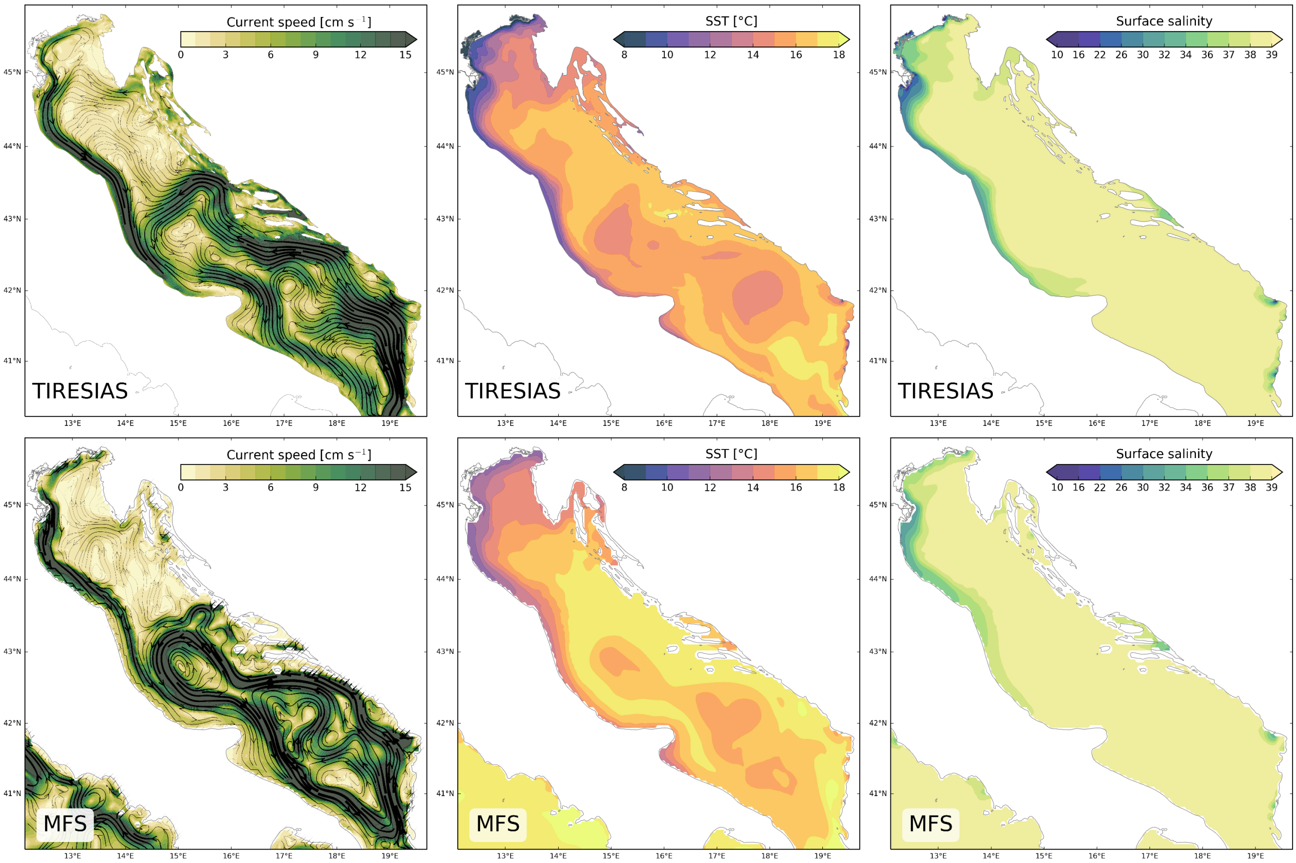

Figure 6. Sea surface currents, temperature and salinity computed averaging the first day of the Tiresias (top panels) and MFS (bottom panels) forecasts over the period 7-17 December 2016.

Tiresias correctly reproduces the main mesoscale and sub-mesoscale features in the Adriatic Sea described by the Mediterranean Forecasting System, and consisting of the characteristic north to south flow of cold and fresh water along the Italian coast, the middle Adriatic and south Adriatic cyclonic gyres, the southward eastern south Adriatic current and the northward western south Adriatic current (Bergamasco et al. 1996; Artegiani et al. 1997). In the deepest basin areas, the average circulation features seem slightly smoother in Tiresias, compared with MFS. This aspect can be due either to a major diffusive effect in Tiresias, to the fact that the Tiresias resolution in the open sea is lower than MFS, or to non-linear tidal interactions, which are considered in Tiresias and not included in MFS. The improvement in resolution in the coastal areas permitted also to reproduce the complex circulation dynamics in the more rugged eastern coast, composed of many islands and headlands (Orlić et al. 1992). This is especially important during Bora events, when the strongest heat flux and wind stress over the sea are concentrated in topographically controlled jets (Dorman et al. 2006; Benetazzo et al. 2014).

On average the sea surface temperature (SST) described by Tiresias ranges between 5 and 18^{o}C, with the lowest values found in the northern Adriatic lagoons and along the Italian coast. Tiresias SST is generally colder than the MFS one (which assimilates satellite SST data). However, the surface values extracted from the Tiresias results agree with the coastal observations acquired within the MS16 campaign (see Fig. 5). The differences with the MFS results demonstrate that over the sea surface the impact of the air-sea heat fluxes is stronger that the restoration contribution of the MFS nudging.

The two forecasting systems produce a similar distribution of the sea surface salinity, with Tiresias simulating a fresher southward surface flow along the eastern Italian coastlines and more detailed river plumes. Therefore, the high-resolution of the unstructured model in the coastal areas allows also to reproduce in details small scale circulation dynamics driven by baroclinic forcing.

3.2. Local scales

3.2.1. Saltwater intrusion in the Delta of the Po River

Coastal zones are dynamic and subject to changing environmental conditions caused by natural variations in climatic and oceanographic processes such as flooding, drought, storm surges and changes in sea level. In deltas and estuaries, freshwater flowing from inland areas meets with saline water from the sea. During drought conditions, saltwater penetrates far upstream increasing the salt content in aquifer and surface water (Werner et al. 2013). Moreover, since sea level is rising as a consequence of climate change, saltwater intrusion is a growing risk (Aslam et al. 2018).

The phenomenon of saltwater intrusion (SWI) is particularly pertinent to the Delta of the Po River, where it strongly affects farming and daily activities of the local people. By considering part of the Po River domain in the computation (up to 40 km upstream the mouth), Tiresias allows the detailed calculation of the river discharge distribution among all branches (Maicu et al. 2018). To assess the capacity of Tiresias in predicting saltwater intrusion in the main Po distributary (Po di Pila), the forecasts were compared with the salinity observed during the drought of the 2017 summer. The SAL17 field campaign was conducted on the 26th July 2017, during spring tides (the tidal range in the open sea facing the delta was about 110 cm) and low river discharge (490 m^{3} s^{-1}). 16 water column salinity profiles were acquired with a Idronaut Ocean Seven 316Plus multiparameter CTD sonde, starting from the river mouth and navigating 15 km upstream along the river talweg following the rising tide. The CTD probe was set for acquiring data along the water column every 10 cm. The observed salinity distribution along the transect is plotted in Fig. 7 together with the forecast results.

A classic estuarine dynamics (Valle-Levinson 2010), can be recognised in the Po River, with the freshwater floating on top of the denser seawater, which moves upstream along the bottom up the river forming a wedge layer. Taking the value of 2 as the threshold for distinguishing fresh and salt waters (the salinity limit for irrigation), the observations show that the salt wedge under the fresh water penetrated into the delta up to 14 km from the river mouth. The maximum SWI extension is well forecasted by the numerical model, which correctly reproduced the horizontal and vertical salinity gradients of the estuarine circulation. This good performance of the model was

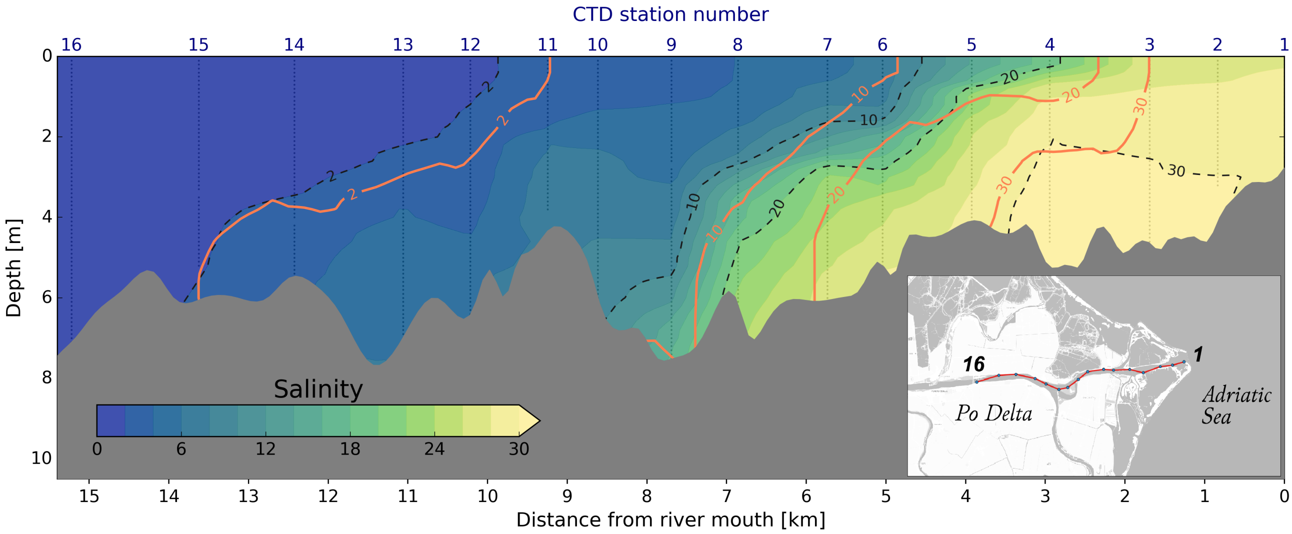

Figure 7. Along-river salinity section in the Po di Pila branch at flood tide (2017/07/26 12:00). Colours and black dashed contours represent the observations, while the orange continuous lines indicate the simulated values. The panel in the bottom right corner displays the survey track along the Po di Pila branch.

somewhat unexpected given the small scale of the SWI processes and the fact that no data assimilation was performed in Tiresias.

The developed forecasting system can therefore be used for improving the management of freshwater reservoirs and/or saltwater barriers to limit SWI in the Po Delta (White and Kaplan 2017). The results of the Tiresias system could be useful also in other coastal zones of the Adriatic Sea affected by saltwater intrusion, like the Adige and Brenta rivers and large areas along the Venice coast and south of the Po Delta (Antonellini et al. 2008; Da Lio et al. 2015).

3.2.2. Storm surge in the Venice Lagoon

Coastal flooding induced by storms can cause many fatalities and damages when associated to tropical cyclones and hurricanes and even in extra-tropical areas, they can sometimes represent a serious threat (Chaumillon et al. 2017). The northern Adriatic Sea is frequently affected by storm surge events, mainly triggered by strong southeasterly moist and warm wind, called *Sirocco*. Although several coastal towns can be impacted and even flooded, the main concern is for Venice, due to its artistic heritage and historical importance. Therefore, water level prediction is of utmost importance in Venice, since storm events often cause the flooding of the city, especially when associated with spring tides (Bajo et al. 2017). It is worth noting that with a sea level of 110 cm (referred to local datum of Punta Salute) about 12% of the city is flooded.

The Tiresias forecasts were compared to the water levels observed in the open sea at approximately 15 km offshore the lagoon inlets (the Acqua Alta oceanographic platform, PTF in Fig. 1), and inside the Venice Lagoon (Punta della Salute, PDS in Fig. 1). The model validation focused on the storm surge events of January 11^{th} 2016 and June 16^{th} 2016, when the water level in Venice reached 114 cm (Fig. 8).

Tiresias provided accurate water level forecasts for the analysed events, reproducing correctly both the tidal signal (the amplitude differences are less than 0.5 cm for all principal constituents) and the meteorological induced surge in the open sea. Addi-

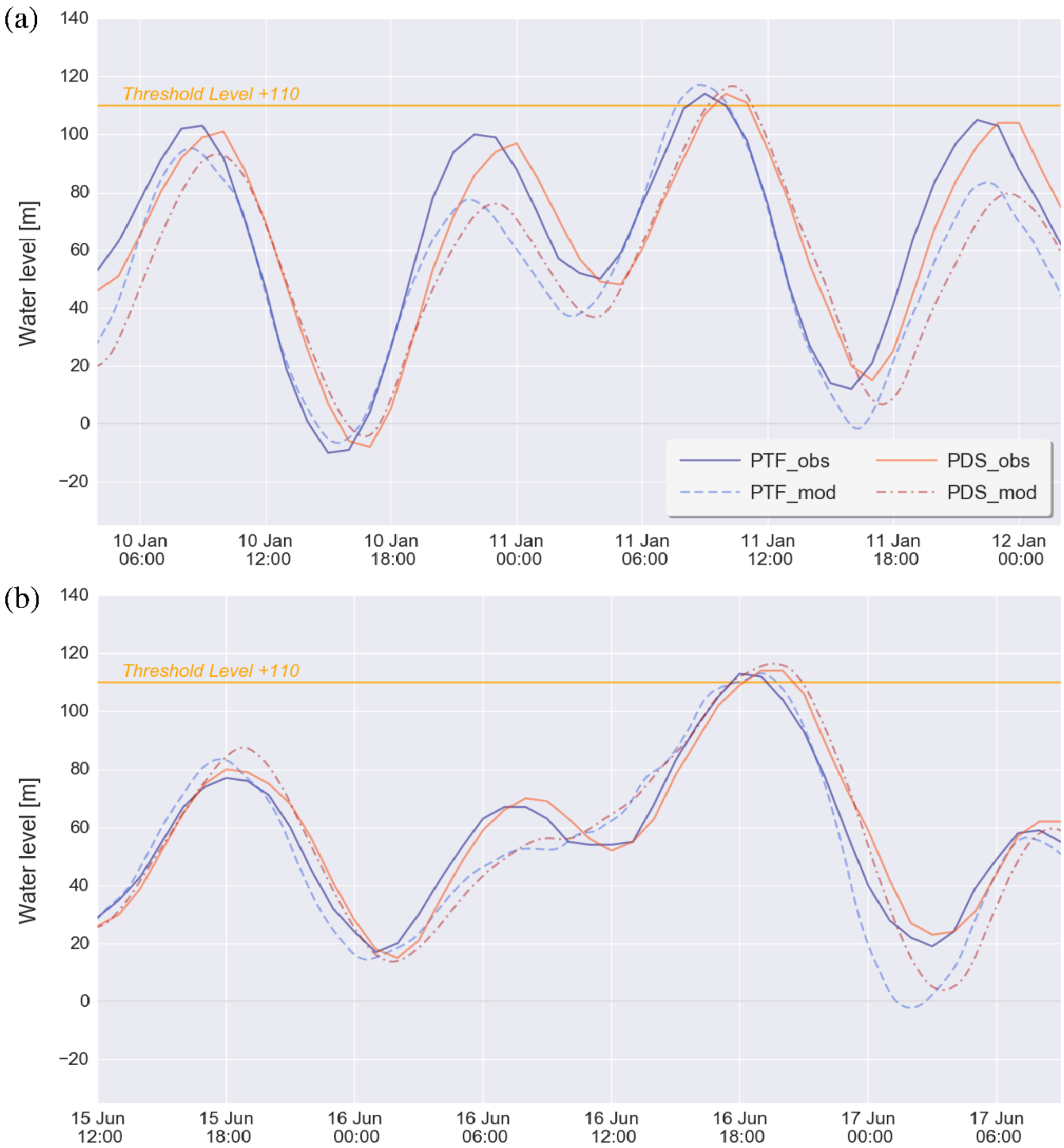

Figure 8. Observed (continuous lines) and forecasted (dashed lines) total water level in the Venice Lagoon (station PDS) and in the shelf facing the lagoon (station PTF), during the storm surge events of 11 January (a) and 16 June 2016 (b).

tionally, the numerical model accurately simulated the propagation of the total water level inside the lagoon, where it experiences, at PDS, a delay of about 1.5 hours with respect to PTF. For both events, the peak water level values were matched at PTF and PDS. Due to the different meteorological conditions, the water level is amplified within the lagoon during the storm of 16^{th} June, while it is slightly damped during the event of 11^{th} January. The mismatch before and after the event can also be due to the model error in reproducing seiches (free oscillations of the basin). In fact, most of the great storm surge events are coupled/followed with seiche oscillations, that start when the forcing vanishes and may last for several days (Vilibić 2000). The correct reproduction of these oscillations is strictly linked to the open-boundary conditions at the Otranto Strait (Vilibić et al. 2017).

Accurate storm surge forecasts are crucial not only for the city of Venice (Medugorac et al. 2015). In particular, extreme sea levels cause flooding of large lowland coastal areas (Perini et al. 2016), and generate saline plumes that infiltrates in shallow coastal aquifer (Giambastiani et al. 2017). Due to the high-resolution of both the meteorological forcing and the oceanographic model, the Tiresias system could also be useful for predicting the probability of atmospherically induced tsunami-like waves, which occasionally hit the eastern Adriatic coast causing considerable damage in some harbours (Orlić 2015; Vilibić et al. 2016).

3.2.3. Particle tracking experiments

Lagrangian analysis provides a powerful tool to evaluate the output of ocean circulation models (van Sebille et al. 2018). The presented forecasting system is equipped with an off-line particle-tracking module, which simulates the trajectory of particles as a function of the hydrodynamics. The 2D particle-tracking model coupled with the hydrodynamic code has been described in Quattrocchi et al. (2016). In Tiresias, we implemented a 3D lagrangian model, where the vertical components of the turbulent diffusion velocity was computed using the Milstein scheme (Gräwe and Wolff 2010). The horizontal diffusion was computed using a random walk technique based on Fisher et al. (1979), with the turbulent diffusion coefficients obtained by means of the Smagorinsky (1993) formulation. The off-line particle-tracking model uses the Eulerian hydrodynamic fields generated by the forecast system. The main advantage of the off-line approach is that the trajectory calculation typically takes much less computational effort than the driving hydrodynamic model.

The particle-tracking module of SHYFEM was successfully applied and validated by Cucco et al. (2012), Cucco et al. (2016) and Quattrocchi et al. (2016) in the Sardinian coastal waters. To validate the model in the Adriatic Sea, the lagrangian results were compared with the trajectory of a GPS-equipped drifter (`http://www.southteksl.com/index.php/products/offshore-nomad`) released the 14^{th} May 2018 in the central Adriatic Sea (north of the city of Ancona). The drifter, floating on the surface, was equipped with a 50 cm long plastic drogue placed at 20 m depth. Therefore, the drifter provided the integral information of the currents in the upper 20 m of the water column. Drifter position was recorded at 10 min intervals and communications occurred each 4 hours.

In the numerical simulation, 400 particles were released (uniformly distributed on the first 20 m of the water column) at the initial drifter location. The particle-tracking module was forced by the hydrodynamic fields obtained by concatenating the first day of the Tiresias forecasts. The observed trajectories along with the paths obtained from the simulation after 13 days from the drifter release are reported in Fig. 9.

The particle-tracking model correctly reproduced the drifter which moved southward along the coast for about 110 km, with a mean speed of 10 cm s^{-1}. The lagrangian particles moving at a depth of 4-7 m best represent the drifter behaviour. The trajectory absolute error of this subgroup of particles (the distances between the average position of the group of numerical particles and the corresponding drifter location; Cucco et al. 2016) remained always lower than 6 km. A remarkable result is that the uncertainty of model-predicted trajectories does not growth with the simulation time, thus confirming the robustness of the followed approach and the consistency of the previous evaluations.

To provide an example of the potential use of the forecast results, the particle-tracking model was applied to investigate the dispersion of the waters flowing into the

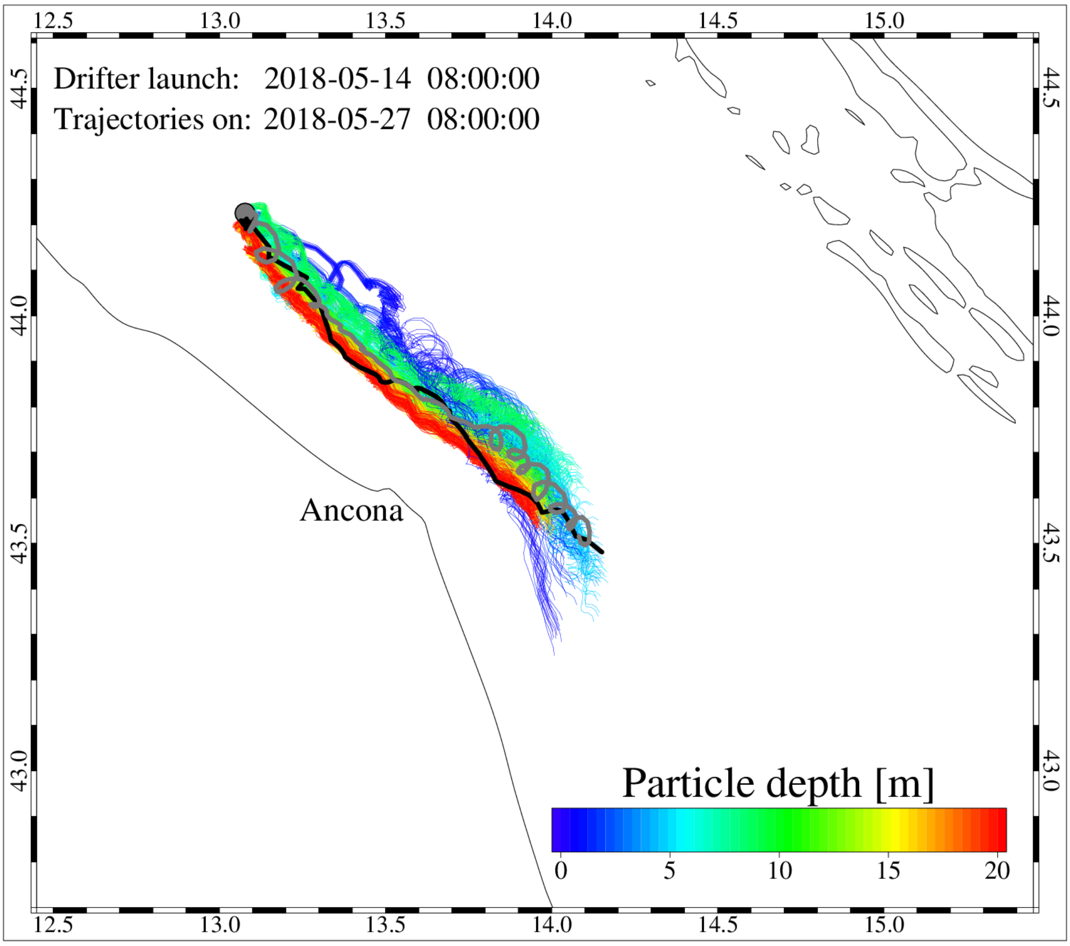

Figure 9. Observed (black thick line) and simulated (multicolour thin lines with the color indicating the depth of the particle) trajectories for the drifters released the 14^{th} May 2018. The gray thick line represents the mean trajectory of the particles in the 4 to 7 m depth range.

Adriatic Sea from the Isonzo River (label 1 in Fig. 1). This specific site was selected because it is well know that the Isonzo River represents the major point source of mercury in the Gulf of Trieste and the Marano-Grado Lagoon (Covelli et al. 2007). Therefore, even if a proper model validation cannot be carried out, since there are no lagrangian observations available in this area, the observed spatial distribution of suspended particulate mercury can be used to trace the Isonzo water dispersion.

In the numerical experiment, the fate of the Isonzo waters was simulated for river flood of 12^{th} January 2016, characterised by a peak discharge of 1220 m^3 s^{-1}. Particles were continuously released at the Isonzo River boundary during the day of the flood, with a concentration of 1 particle per 1000 m^3 of water discharged by the river. In total 80,000 particles were released during the simulation. The lagrangian particles had a settling velocity of 0.5 mm s^{-1} to represent the behaviour of the suspended particulate matter.

The lagrangian model results (integrated over the water column) presented in Fig. 10 agree with the previous findings of Covelli et al. (2007) and Ferrarin et al. (2016), that the river plume is generally diverted to the South-West, under the influence of the coastal circulation, and that the tidal flux acts as a "transport belt" carrying the Isonzo

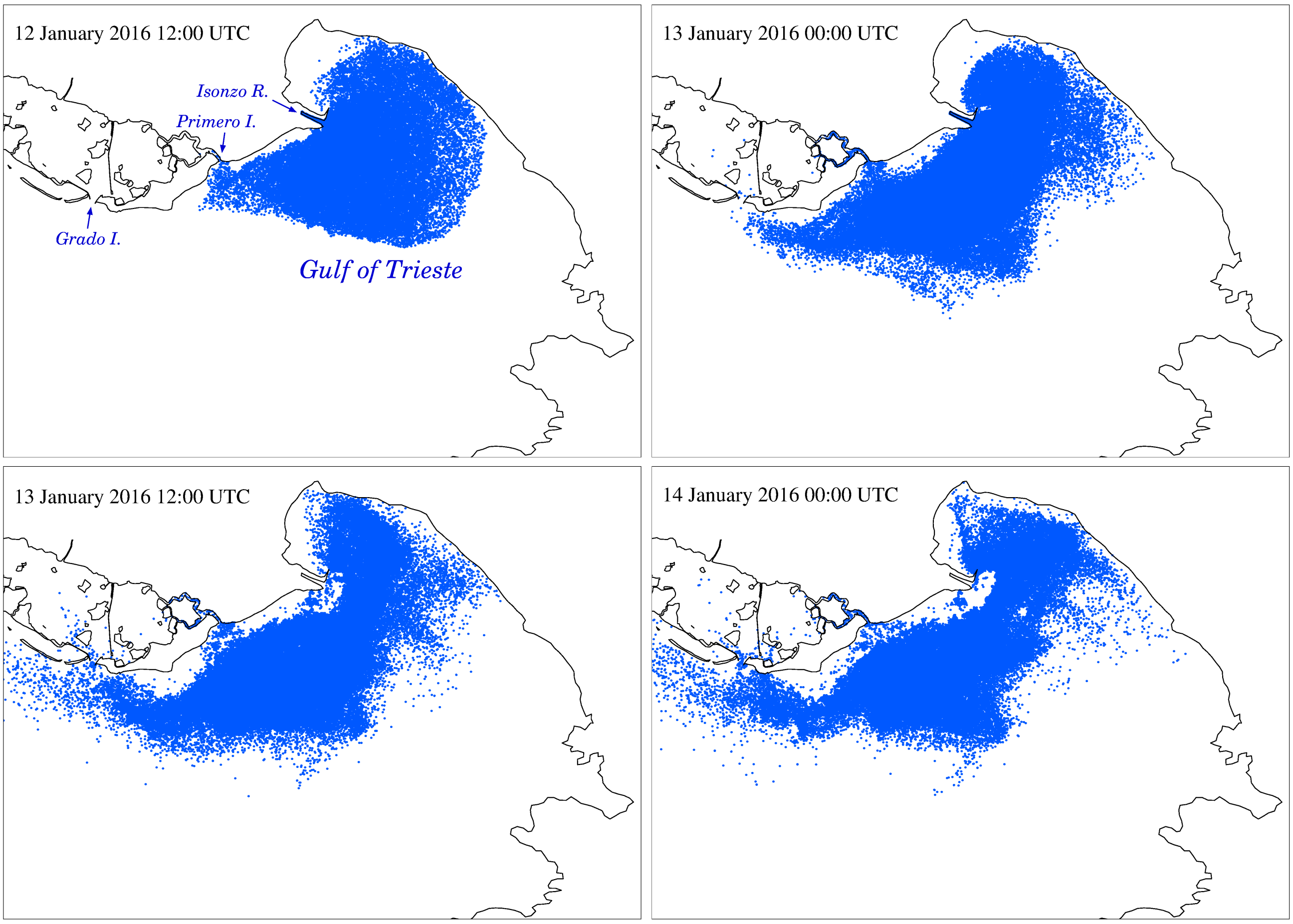

Figure 10. Simulated particles distribution in the Gulf of Trieste and the Marano-Grado Lagoon at intervals of 12 hours. The particles were continuously released at the Isonzo River boundary during the 12^{th} of January 2016.

waters into the Marano-Grado Lagoon. In this dynamics, the Primero and the Grado inlets act as a preferential pathway for dissolved and suspended substances coming from the Isonzo River to enter the eastern sector of the lagoon, where they can be trapped. However, part of those particles can be transported out of the lagoon system through the Grado inlet, confirming the complex exchange dynamics that characterise this area (Turitto et al. 2018).

The same lagrangian methodology could also be used to help the planning and management of the marine space (MSP) by addressing dispersion of particles and pollutants, including those coming from accidental disposal, or for search and rescue operations. To facilitate the use of such tools, we are developing, within theframework of the Portodimare INTERREG Adriatic-Ionian project, a web-based particle tracking interface for the Adriatic Sea, where the user can easily select the deployment location and time of release of the lagrangian particles.

4. Concluding remarks and perspectives

The innovative aspect of the oceanographic operational system for the Adriatic Sea presented in this study is that it accurately addresses land-sea, air-sea, and coastal-offshore interactions. These processes are taken into account in the forecasting system by adopting adjourned discharge for most of the rivers, by forcing the hydrodynamic model with high-resolution meteorological fields, and by resolving the lagoon-sea and the river-sea continuum.

The variable model resolution is of fundamental importance for reproducing the complex morphology of the northern Adriatic Sea. Improving modeling skills for simulating coastal dynamics is a balance between trying to capture the full range of physical processes involved while at the same time introducing suitable numerical approaches for efficient simulation of the processes. The investigation on the different scales showed that Tiresias is able to correctly retain mesoscale and sub-mesoscale features as well as the coastal circulation. The improvement in resolution in the coastal areas does not only improve local dynamics by representing variability in the morphology, but also allows to reproduce in details circulation patterns driven by small-scale thermohaline and atmospheric forcing.

The model applications presented in this study highlight the need to take into account river mouths and coastal water bodies to properly reproduce the coastal dynamics and the exchange processes between the different water basins. The inclusion of these coastal environments in the forecasting system is important to mankind for their ecological relevance and because many industrial, commercial, and recreational activities are concentrated in these regions.

Forecast products could be also useful for addressing critical and relevant coastal issues, such as marine spatial planning, maritime safety, marine pollution protection, integrated coastal zone management. Moreover, the results of the Tiresias operational system could serve to characterise the oceanographic conditions in the northern Adriatic Sea, which has been selected as one of the study areas (Supersites) planned in the pan-European Research Infrastructure DANUBIUS-RI, the International Centre for Advanced Studies on River-Sea Systems (`http://www.danubius-ri.eu/`).

In the Adriatic Sea there is the need to develop an integrated observing system, similar to the ones already implemented in other part of the world, like the US Integrated Ocean Observing System (IOOS, Wilkin et al. 2017). With the perspective of an European Ocean Observing System (EOOS, Sparnocchia et al. 2016), the operational model presented in this study could be integrated with existing observing facilities (remote sensing and in-situ) and other modelling initiatives, for addressing oceanographic forecasts in both the open sea and the coastal zone. Such an observing system would be invaluable for reducing errors in the initial conditions leading to better forecasts. Additionally, an international effort is also required to coordinate the production of consistent boundary conditions (i.e. rivers) for a basin-scale modelling strategy in the Adriatic Sea. To improve the oceanographic forecast, we will next address an integrated monitoring-modelling approach, with the assimilation of sea level, water temperature and salinity observations.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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