The tidal and wind induced hydrodynamics of the composite system Adriatic Sea/Lagoon of Venice

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ABSTRACT

A shallow water hydrostatic 2D hydrodynamic numerical model, based on the boundary conforming coordinate system, was used to simulate aspects of both general and small scale oceanic features occurring in the composite system constituted by the Adriatic Sea and the Lagoon of Venice (Italy), under the influence of tide and realistic atmospheric forcing. Due to a specific technique for the treatment of movable lateral boundaries, the model is able to simulate efficiently dry up and flooding processes within the lagoon. Firstly, a model calibration was performed by comparing the results of the model, forced using tides and ECMWF atmospheric pressure and wind fields, with observations collected for a set of 33 mareographic stations uniformly distributed in the Adriatic Sea and in the Lagoon of Venice. A second numerical experiment was then carried out by considering only the tidal forcing. Through a comparison between the results obtained in the two experiments it was possible to assess the reliability of the estimated parameter through the composite forcing. Model results were then verified by comparing simulated amplitude and phase of each tidal constituent as well as tidal velocities simulated at the inlets of the lagoon and in the Northern Adriatic Sea with the corresponding observed values. The model accurately reproduces the observed harmonics: mean amplitude differences rarely exceed 1 cm, while phase errors are commonly confined below 15°. Semidiurnal and diurnal currents were correctly reproduced in the northern basin and a good agreement was obtained with measurements carried out at the lagoon inlets. On this basis, the outcomes of the hydrodynamic model were analyzed in order to investigate: (i) small-scale coastal circulation features observed at the interface between the adjoining basins, which consist often of vortical dipoles connected with the tidal flow of Adriatic water entering and leaving the Lagoon of Venice and with along-shore current fields connected with specific wind patterns; (ii) residual oscillations, which are often connected to meteorological forcing over the basin. In particular, it emerges that small-scale vortical features generated near the lagoon inlet can be efficiently transported toward the open sea, thus contributing to the water exchange between the two marine regions, and a realistic representation of observed residual oscillations in the area would require a very detailed knowledge of atmospheric as well as remote oceanic forcing.

1. Introduction

Coastal lagoons, among other transitional systems, are very sensitive to the hydrodynamic processes of the neighbouring marine regions, which are principally governed by the tidal regimes and the weather conditions. The resulting circulation, which can be profoundly influenced by water injections at the sea shore, can also induce and/or sustain a large spatial and temporal variability of physical, chemical and biological characteristics (Kjerfve, 1994; Ward, 1998). Therefore, a deep understanding of the hydrodynamic processes that govern the fluxes of energy and matter not only within coastal lagoons, but also in the regions of transition toward the open sea, constitutes a strong prerequisite for the integrated management of the coastal ecosystems (see, e.g., Zaldivar et al., 2003; Guyondet and Koutitonsky, 2006).

The hydrodynamics of the Adriatic Sea shelf and its coastal systems were thoroughly investigated using both statistical and deterministic models (Hendershott and Speranza, 1971; Malanotte Rizzoli and Bergamasco, 1983; Orišić et al., 1994; Malavič et al., 2000; Cushman-Roisin and Naimie, 2002; Zavatarelli et al., 2002; Janeković et al., 2003; Petaccia et al., 2006; Lionello et al., 2006; Pullen et al., 2007). As most of these studies
focused on the basin scale circulation and its variability, only a small emphasis was given to processes involving the integrated hydrodynamics of the open sea and its neighbouring coastal areas (see, e.g., Bergamasco et al., 1998; Bellafio et al., 2008). Often in the past, open sea and coastal basins were examined as separated systems. In the case of the Lagoon of Venice, the boundaries between these two systems were usually located near the lagoon inlets (Defina, 2000; Casulli and Zanolli, 2002; Umgiesser et al., 2004) and, in general, the interior lagoon area was completely neglected when modelling the general circulation of the Adriatic Sea (Cushman-Roisin and Naimie, 2002; Janevko and Kuzmić, 2005; Martin et al., 2006). So far, different aspects of the coastal hydrodynamics, which may be influenced by different processes, are still unclear.

Recently, fresh hydrodynamic data were collected from both the Adriatic Sea and the Lagoon of Venice. These data provided new insights on the long-term tidal and non-tidal characteristics of the local coastal currents (Gačić et al., 2004; Book et al., 2005), on the surface circulation and its spatial and temporal variability along the northern Adriatic coast (Kovačević et al., 2004; Chavanne et al., 2007), and on the interpretation of sea surface patterns of both the Adriatic Sea and the Lagoon of Venice (see e.g. Janevko and Kuzmić, 2005; Ferla et al., 2007). Furthermore, recent bathymetric charts for the Lagoon of Venice were compiled by the Venice Water Authority on the basis of in situ measurements collected in the period 2000–2004. These data represent a good basis for the calibration and verification of a new hydrodynamic model of the composite system Lagoon of Venice–North Adriatic basin, which, on such basis, can be used for investigating the local mesoscale and small-scale phenomena which are expected to be markedly influenced by the complex morphology and bathymetry profiles of the lagoon area and the nearby marine region.

In fact, the numerical model provides a means of isolating the influence of tidal forcing on the generation of specific features associated to the water exchange between the lagoon and the open sea, like, e.g., small-scale tidally induced eddies. Previous investigations (Masato, 1983; Geyer and Signell, 1990, 1992) demonstrate that eddies generated in tidal flows and typically localized nearby headlands, inlets, or shoals, are inherently transient and their spatial structure may vary considerably through the tidal cycle. The propagation of local transitional eddies has thus important implications to dispersion processes since their development may strongly enhance the spatial and temporal variability of biogeochemical characteristics of the Lagoon of Venice, as well as, sedimentation rates and/or pollutant spreading.

In order to achieve these goals, a 2D boundary-conforming, finite-difference hydrodynamic numerical model was applied to the composite system constituted by the Adriatic Sea and the Lagoon of Venice. The newest experimental datasets were used to produce a realistic bathymetry, especially in the Lagoon of Venice and its inlets. The model was calibrated for the whole computational domain through a comparison between simulated and observed data sets and the relevant characteristics of the model are discussed and simulated water levels and small-scale flow features are compared to previous experimental evidence. The work is summarized in the final section.

2. Methods

2.1. Formulation of the problem and numerical method

The original numerical hydrodynamic model proposed by Androsov et al. (1995, 2002) was here implemented in a two-dimensional, barotropic version, which includes a specific scheme for the treatment of movable lateral boundaries (see, e.g., Balzano, 1998). In a 2D domain, the initial boundary-value problem in the Cartesian system of coordinates for the vertically averaged equations of motion and continuity is described by

\[
\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + g \nabla z = f \mathbf{k} \times \mathbf{v} - \frac{C_0}{H^2} \mathbf{v} \cdot \mathbf{v} \nabla |\mathbf{v}|^2 + \frac{1}{H} \nabla (K_H \nabla |\mathbf{v}|) + \frac{F}{\rho_w g H} - \frac{1}{\rho_w} \nabla p, \quad \nabla \mathbf{v} + \nabla \cdot (H \mathbf{v}) = 0
\]

(1)

where \( \mathbf{v}=(u,v) \) is the fluid averaged velocity, \( z \) the sea surface displacement, \( H \) the undisturbed water depth, \( H_h=H+h \) the total water depth, \( \nabla = \frac{\partial}{\partial x} \frac{\partial}{\partial y} \) the gradient operator, \( f \) the Coriolis parameter, \( \mathbf{k} \) the unit vector in the vertical direction, \( C_D \) the friction coefficient, \( \rho_a \) the air and water density, respectively, \( p \) the atmospheric pressure, and \( K_H \) the eddy viscosity coefficient. The tangential wind stress, \( F \) is expressed through the resistance quadratic law (Hellerman, 1967) described by

\[
F = C_{DW} \rho_a |\mathbf{U}|^2
\]

(2)

where \( C_{DW} \) is the wind drag coefficient and \( \mathbf{U} \) the wind velocity vector. Note that the wind drag coefficient was considered constant in this investigation.

The parameterization of the bottom stress still represents a major issue when modelling the hydrodynamic circulation in shallow water embayment (see, e.g., Umgiesser et al., 2004; D’Alpaos and Defina, 2007). In the present study, the bottom friction coefficient \( C_D \) was computed according to Blumberg and Mellor (1987) and has the following form:

\[
C_D = \left[ \frac{1}{k} \ln \left( \frac{H}{z_0} \right) \right]^{-2}
\]

(3)

where \( z_0 \) the bed roughness length and \( k \) the von Karman constant. In agreement with the cited work, a minimum value for the bottom friction coefficient was applied in order to avoid the vanishing of the bottom drag effect when the water depth is very large (see Table 1).

The boundary-value problem is transformed into boundary-fitted coordinates mapping the physical domain into a computational rectangle where the sea level and/or current at the open boundary are specified as function of time. At the other boundaries, which are mappings of the shores, we set no-slip conditions. In particular, the open boundary problem is solved through the reduced boundary-value formulation described in Androsov et al. (1995): when it is not possible to prescribe both velocity and elevation values at the open boundaries, only the sea...
level is prescribed, regardless of the boundary regime, and radiation conditions are applied to the water outflow.

The equations, in the form of contravariant fluxes (see Romanenkov et al., 2001), are solved using the so-called pressure-correction method (Van Kan, 1986). At each time step, the velocity field due to the advective transport is determined by splitting in coordinate directions. Advection is approximated by a scheme with a switch allowing for the use of an upstream scheme of the first, second, or third order. Then, for the advection field and the explicit level representation, the momentum equations are integrated by splitting in coordinate directions and preliminary velocities are found. Afterward, the level is determined from the boundary-value problem for a two-dimensional elliptic equation which is obtained from a linear combination of the continuity equation and of the divergence of the momentum equation. Once the water level has been computed, the final velocity components are determined from the momentum equations. The scheme has second-order accuracy in both space and time, with a time step limited only by advection terms in the equation of motion. For a detailed description of the complete formulation of the boundary-value problem and its solution method the reader is referred to the work of Androsov et al. (2002).

### 2.2. Study area and model set up

The physical domain considered in this work extends from the northern Ionian Sea to the Lagoon of Venice (Fig. 1). The Adriatic Sea is a semi-enclosed elongated basin with an extension of approximately 700 km along the major axis in the northwest–southeast direction. This regional sea is characterized by a bathymetric profile which decreases southward, from the northern shallow area (average bottom depth of about 35 m) to the wide depression of the Jabuka Pit (more than 1200 m water deep). The Lagoon of Venice (Fig. 2), which has a surface of about 500 km

The numerical model was applied to the integrated domain by means of a curvilinear boundary-conforming grid, composed by 287 \times 363 nodes (Figs. 1 and 2). The mesh was refined along the three lagoon inlets and the major lagoon navigation channels. In fact, these features are recognized to play a primary role in the propagation of tidal waves inside the lagoon (Umgießner, 1997). The resulting cells have side lengths varying between approximately \sim 50 m, in the most refined areas inside the lagoon, and approximately 12 km in the southern part of the domain, in correspondence of the southern open boundary.

The bottom geometry was obtained through the aggregation of the US Navy unclassified 1/60 bathymetric data base DBDB1 for the Adriatic Sea and the hydrographical chart of the Lagoon of Venice (scale 1:5000) edited by the Venice Water Authority through its concessionary Consorzio Venezia Nuova (MAV, 2005). The bottom discretization was realized by bilinear interpolation of the depth data on the numerical grid. The minimum depth for the tidal flats was set to 0.2 m, namely twice the magnitude of the wet/dry threshold value, in order to avoid numerical instabilities (see e.g., Bates et al., 2005).

The external forcing considered in the simulations were sea water elevation gradient, wind stress, and atmospheric pressure gradient. Other forcings, such as, e.g., temperature and salinity gradients, were not included since it was shown in a number of studies that the tidal and atmospherically induced circulation of the composite system can be adequately described in the barotropic case (see e.g., Janečković et al., 2003; Umgießner et al., 2004; Chavanne et al., 2007; Bellafiore et al., 2008).

According to the existing literature (Tsimpis et al., 1995; Cushman-Roisin and Naimie, 2002; Janečković and Kuzmič, 2005), the sea water level at the open boundary (OB) was first assessed through the superimposition of the seven major tidal harmonics, grouped on the basis of their characteristic frequencies in a semiidiurnal group \(M_2, S_2, N_2, \) and \(K_2\) ) and a diurnal group \(K_1, O_1, \) and \(P_1\). The tidal components thus assessed were then optimized as explained in Section 2.4. The OB of the system was located \sim 250 km south of the Otranto Strait in order to reduce the numerical disturbances introduced by the artificial imposition of the boundary conditions. The tidal data, derived from the OSU-TPXO tidal inverse model (Egbert and Erofeeva, 2002), were linearly interpolated at each node of the boundary line. Data from the OSU dataset for the Mediterranean Sea were used for the \(K_1, O_1, M_2, \) and \(S_2\) constituents and data from the OSU global model were used for \(P_1, K_2, \) and \(N_2\) (see, e.g., Martin et al., 2006).

The meteorological data used to drive the hydrodynamic model were the wind components at 10 m height and the mean sea level pressure obtained from the operational archive of the ECMWF atmospheric model surface analysis (Persson, 2003). The atmospheric fields used in the present work were generated daily at times 00, 06, 12, 18 GMT and were provided on a regular
The meteorological data were interpolated, in order to provide spatial and temporal inputs consistent with the model requirements: at each time step the atmospheric fields were applied to the nodes of the computational grid using a bivariate method (Akima, 1984) and by linearly reconstructing the values within the time interval of the input datasets.

Table 1 summarizes the values of the parameters selected for the numerical simulations. The sea elevation time series, stored with an hourly time step, were analyzed using the least squares method (Foreman, 1977) for a period of approximately 9 months after the spin up of the simulation (2000 h). In fact, the least squares method applied for the extraction of tidal harmonics requires a minimum length of the data sample of approximately half a year in order to reliably determine all tide constituents prescribed at the open boundary. All numerical simulations carried out with the external meteorological forcing refer to the complete year 2004.

2.3. Observational dataset

The observational data used in this study for the calibration and validation of the model are divided in two groups: the tide gauge data and the current meter data. The data belonging to the first group were obtained from 70 stations located along the Adriatic coast and inside the Lagoon of Venice, the data belonging to the second group from 13 current meters located in the northern Adriatic and from 3 long-term ADCP surveys carried out at the three inlets of the lagoon (Figs. 1 and 2).

The harmonic constants for the seven most pronounced tidal constituents \( M_2, S_2, N_2, K_2, K_1, O_1, P_1 \) at the coastal tide gauges were compiled on the basis of the work of Janeković and Kuzmić (2005) and Ferla et al. (2007). For the stations of Rovinj, Bakar, Mali Losinj, Zadar, Split, Vis, and Dubrovnik the data were provided by the Hydrographic Institute of the Republic of Croatia (HIR, 2004). In addition, the harmonic constants for the tide gauge of the CNR Tower (st. 70 in Fig. 1), located in the middle of the Gulf of Venice, were estimated from the hourly time series provided by the Mareographic Centre of the Venice Municipality.

The set of depth averaged tidal velocity data was compiled integrating the current meter data reported by Cushman-Roisin and Naimie (2002), stations 7–16 (Fig. 1), and the measurements conducted along the Italian coast near Senigallia by Book et al. (2005), stations 4–6 (Fig. 1). Both data sets included the semi-major axis amplitude and the ellipse inclination of the two most energetic constituents, \( M_2 \) and \( K_1 \). From the long term current measurements carried out during the period 2001–2002 at the three inlets of the lagoon (Gačić et al., 2004), stations 1–3 (Fig. 2), amplitudes and phases of all the seven principal tidal constituents of the velocity can be retrieved, thus allowing for a quantitative validation of the model results at the adjoining region of the domain.

2.4. Model calibration

The numerical solution of the initial boundary-value problem was realized through the estimation of the optimal values for the bottom roughness length \( \zeta_0 \) and the tidal component values along the open boundary \( \zeta_{OB} \).
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A number of numerical experiments were carried out, in order to tune the model, using both tidal and meteorological forcing for a year long period. Tidal harmonic values for a set of 33 mareographic stations homogeneously distributed within the composite domain (they are marked in Figs. 1 and 2) were used for the comparison with the corresponding values obtained from the least square fit analysis of the simulated sea water levels. The objective of the calibration was to determine the values of the two parameters ($z_0$ and $z_{OB}$) which minimize, for each harmonic component, the function

$$L(z_0, z_{OB}) = \sum_{i=1}^{ns} \frac{|S_{obs}^i - S_{sim}^i|^2}{C_1},$$

where $ns$ is the number of mareographic stations and $S_{obs}$ and $S_{sim}$ the observed and simulated values.

A second numerical experiment was performed without the inclusion of the meteorological forcing in order to evaluate the relevance of non-tidal signals (which are known to occur as consequence of intense meteo-climatic events in the Adriatic basin, see Vilibić, 2006) on the estimation of the tidal harmonics. In fact, the traditional least squares minimization, which is highly sensitive to the presence of such non-tidal components in the input signal, would lead to an over-fit of the non-tidal components in an attempt to minimize the total residual error when the analyzed time series are too short or noisy (Leffler and Jay, 2009). Such a comparison was carried out also to provide a further verification of the approach adopted here for the calibration of the hydrodynamic model.

3. Results

3.1. Tidal harmonics calibration

The results of the calibration experiment are reported in Table 2. The differences between observed and simulated values for the amplitudes and phases of the tidal constituents are summarized using five statistical parameters: mean of absolute differences ($|M|$), standard deviation of differences (STD), root mean squared error (RMSE), correlation ($R$), and the average of simulated values ($M_{sim}$).

The tidally induced water levels were accurately reproduced by the model (Table 2) and the results obtained for the whole domain appear to be in good agreement with the tide gauge dataset, the average correlation of both amplitude and phase being 0.98. The RMSE values generated for the differences of the semidiurnal group components is between 0.4 and 1.1 cm for the amplitude and between 9° and 16° for the phase. Diurnal group constituents presented RMSE values with a reduced range of variability, spanning in this case from 0.6 to 0.9 cm and from 4° to 8° for amplitude and phase, respectively. The standard deviation of the simulated amplitudes exceeded 1 cm only in the case of the lunar semidiurnal constituent M2 (the most energetic component of the tide in the region), while the STD of the phase was circa 9° for the semidiurnal group of constituents and circa 7° for the diurnal group.

The results of the model run carried out with the mere tidal forcing are reported in Table 3. In this case, the correlation between the model output and the observations of both amplitudes and phases was similar for all harmonic constituents, with no significant changes in the RMSE and STD for the more energetic constituents of the tide, namely M2, S2, and K1. Small deviations were produced for the phase of the minor tidal harmonics, in particular for N2 and K2, with differences around 2°.

3.2. Model Verification

The outcomes of the tidal harmonic analysis performed on the water levels simulated for the full set of mareographic stations are presented in Table 4, grouped respectively for the Adriatic Sea.
The mean correlation for the amplitudes and for the phases of all the considered harmonics was 0.96 and 0.89, respectively, in the Adriatic group of stations. Small differences are noticeable in comparison to the results obtained in the calibration experiment for the mean absolute error of the amplitudes, which exceeded 1 cm only for the M$_2$ component of the tide. The mean values of the phase showed differences of nearly 2° for the diurnal group of constituents, while the deviations for each component of the semidiurnal group was between 8° and 14°. A similar behaviour can be noted in the computation of the STD and RMSE statistics.

The means of absolute differences for the group of tide gauges located inside the Lagoon of Venice were remarkably small for each tidal constituent, with average values of 0.5 cm for the amplitude and 4° for the phase. Furthermore, the standard deviation and the RMSE values were in the same range of those obtained in the calibration experiment (see Table 2). Minor constituents of the tide, namely K$_2$ and P$_1$, were characterized by a lower agreement between simulated and observed amplitude, which lead to a decrease in the average correlation in comparison with the calibration results. On the other hand, the correlation achieved in the simulation of the phases for both tidal constituent groups was between 0.97 and 0.99.

The simulated amplitude of the semidiurnal M$_2$ tide varies from 6 cm in the Otranto straight up to 25 cm in northern end of the Adriatic Sea, with a marked minimum near the border of middle and northern parts of the basin. The amplitude of the diurnal K$_1$ tide smoothly increases from the south toward the north and it ranges between 2 and 20 cm. The amplitude

### Table 2
Results of model calibration for the semidiurnal and diurnal constituents at the stations depicted in Figs. 1 and 2, obtained using the tidal and meteorological forcing.

<table>
<thead>
<tr>
<th></th>
<th>M$_2$</th>
<th>S$_2$</th>
<th>N$_2$</th>
<th>K$_2$</th>
<th>K$_1$</th>
<th>O$_1$</th>
<th>P$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp</td>
<td>18.0</td>
<td>253.2</td>
<td>11.1</td>
<td>241.2</td>
<td>3.2</td>
<td>245.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Pha</td>
<td>0.7</td>
<td>6.5</td>
<td>0.7</td>
<td>13.8</td>
<td>0.3</td>
<td>7.5</td>
<td>0.5</td>
</tr>
<tr>
<td>STD</td>
<td>1.2</td>
<td>9.1</td>
<td>0.7</td>
<td>9.7</td>
<td>0.3</td>
<td>11.2</td>
<td>0.6</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.1</td>
<td>9.2</td>
<td>0.8</td>
<td>16.1</td>
<td>0.4</td>
<td>11.1</td>
<td>0.6</td>
</tr>
<tr>
<td>R</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.96</td>
<td>0.98</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Differences between simulated and observed amplitudes and phases are summarized through the mean of absolute differences ($|M|$), standard deviation of differences (STD), root mean square error (RMSE), correlation ($R$). Averages of simulated values of amplitude and phase ($M_{sim}$) are also reported. Amplitudes are in cm and phases are in degrees.

### Table 3
Results of model calibration for the semidiurnal and diurnal constituents at the stations depicted in Figs. 1 and 2, obtained using only the tidal forcing.

<table>
<thead>
<tr>
<th></th>
<th>M$_2$</th>
<th>S$_2$</th>
<th>N$_2$</th>
<th>K$_2$</th>
<th>K$_1$</th>
<th>O$_1$</th>
<th>P$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp</td>
<td>18.2</td>
<td>252.6</td>
<td>11.0</td>
<td>241.4</td>
<td>3.2</td>
<td>243.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Pha</td>
<td>0.9</td>
<td>6.6</td>
<td>0.5</td>
<td>13.8</td>
<td>0.3</td>
<td>7.3</td>
<td>0.5</td>
</tr>
<tr>
<td>STD</td>
<td>1.2</td>
<td>9.1</td>
<td>0.7</td>
<td>9.8</td>
<td>0.3</td>
<td>10.9</td>
<td>0.6</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.2</td>
<td>9.4</td>
<td>0.7</td>
<td>16.0</td>
<td>0.4</td>
<td>10.8</td>
<td>0.6</td>
</tr>
<tr>
<td>R</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.96</td>
<td>0.98</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Results are presented as in Table 2.

### Table 4
Results of model verification for the comprehensive set of 70 mareographic stations available for the Adriatic Sea (a) and the Lagoon of Venice (b), obtained using the tidal and meteorological forcing.

<table>
<thead>
<tr>
<th></th>
<th>M$_2$</th>
<th>S$_2$</th>
<th>N$_2$</th>
<th>K$_2$</th>
<th>K$_1$</th>
<th>O$_1$</th>
<th>P$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>11.5</td>
<td>171.5</td>
<td>7.3</td>
<td>166.8</td>
<td>2.1</td>
<td>175.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Amp</td>
<td>0.9</td>
<td>6.6</td>
<td>0.5</td>
<td>22.4</td>
<td>0.4</td>
<td>16.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Pha</td>
<td>1.0</td>
<td>16.0</td>
<td>0.5</td>
<td>17.5</td>
<td>0.5</td>
<td>23.5</td>
<td>0.5</td>
</tr>
<tr>
<td>STD</td>
<td>1.2</td>
<td>21.0</td>
<td>1.0</td>
<td>27.6</td>
<td>0.5</td>
<td>23.8</td>
<td>0.5</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.96</td>
<td>0.95</td>
<td>0.96</td>
<td>0.93</td>
<td>0.92</td>
<td>0.93</td>
<td>0.92</td>
</tr>
<tr>
<td>R</td>
<td>1.2</td>
<td>8.0</td>
<td>1.0</td>
<td>7.6</td>
<td>0.99</td>
<td>0.90</td>
<td>0.97</td>
</tr>
</tbody>
</table>

| b      | 22.6  | 302.2 | 14.0  | 294.0 | 4.0   | 297.0 | 4.7   |
| Amp    | 0.4   | 3.3   | 0.5   | 9.7   | 0.2   | 4.5   | 0.6   |
| Pha    | 0.5   | 4.5   | 0.4   | 4.5   | 0.1   | 4.8   | 0.4   |
| STD    | 0.6   | 4.3   | 0.4   | 4.5   | 0.5   | 4.8   | 0.4   |
| RMSE   | 0.5   | 4.3   | 0.6   | 10.6  | 0.3   | 5.6   | 0.6   |
| R      | 0.97  | 0.99  | 0.97  | 0.99  | 0.94  | 0.99  | 0.86  |

Results are presented as in Table 2.

(a) and the Lagoon of Venice (b). The model was driven by both tidal and meteorological forcings.

The mean correlation for the amplitudes and for the phases of all the considered harmonics was 0.96 and 0.89, respectively, in the Adriatic group of stations. Small differences are noticeable in comparison to the results obtained in the calibration experiment for the mean absolute error of the amplitudes, which exceeded 1 cm only for the M$_2$ component of the tide. The mean values of the phase showed differences of nearly 2° for the diurnal group of constituents, while the deviations for each component of the semidiurnal group was between 8° and 14°. A similar behaviour can be noted in the computation of the STD and RMSE statistics.

The means of absolute differences for the group of tide gauges located inside the Lagoon of Venice were remarkably small for each tidal constituent, with average values of 0.5 cm for the amplitude and 4° for the phase. Furthermore, the standard deviation and the RMSE values were in the same range of those obtained in the calibration experiment (see Table 2). Minor constituents of the tide, namely K$_2$ and P$_1$, were characterized by a lower agreement between simulated and observed amplitude, which lead to a decrease in the average correlation in comparison with the calibration results. On the other hand, the correlation achieved in the simulation of the phases for both tidal constituent groups was between 0.97 and 0.99.

The simulated amplitude of the semidiurnal M$_2$ tide varies from 6 cm in the Otranto straight up to ~25 cm in northern end of the Adriatic Sea, with a marked minimum near the border of middle and northern parts of the basin. The amplitude of the diurnal K$_1$ tide smoothly increases from the south toward the north and it ranges between 2 and 20 cm. The amplitude
distributions for other harmonics (their average values are shown in Table 4) show qualitatively the same pattern of the principal constituents, depending on the group (semidiurnal or diurnal) they belong to. A straightforward view of the model to data fit for the harmonics of semidiurnal and diurnal groups of the whole domain is showed in Fig. 3. The amplitudes (Fig. 3a and c) of both groups of constituents correctly line up along the equality line, with a lower accuracy for the diurnal component O1, which appears to be slightly biased. The phase of the diurnal components (Fig. 3d) shows a tight correspondence to the ideal fit line, while for the semidiurnal data (Fig. 3b) the dispersion is more pronounced.

The simulated current velocities were analyzed using the same least square method applied to the water level time series, in order to recognize the contribution of each tidal constituent to the current variability. In particular, for each component, we compared simulated and observed major and minor axis components and inclination of the tidal ellipse. In Fig. 4 a comparison between the model and observational sets for the northern Adriatic area (stations 4–16 in Fig. 1) is depicted. A good agreement between observed and simulated semi-major axis can be noted for both M2 and K1 velocities, the absolute mean differences being 0.8 and 0.6 cm/s, respectively. A pronounced scatter in the tidal ellipse inclination appears, instead, for both tidal components, with absolute differences up to 60°.

The degree of realism of the tidal dynamics simulated at the lagoon inlets was assessed through an accurate comparison between simulated velocities and ADCP velocities collected during 3 long term surveys carried out by Gačić et al. (2004). In Table 5 the tidal velocity components, phase, and inclination of the tidal ellipse are reported, computed by mean of a harmonic analysis of the simulated velocity time series in the three inlets (station 1–3 in Fig. 2). The agreement of the simulated values with the corresponding observed values is remarkably good, although the simulated major axis component at the station of Chioggia were commonly overestimated. A good agreement was also achieved between simulated and observed phases for each constituent of the tidal velocity, with minor differences in the values of S2, K2, and O1 harmonics. As one can clearly see, the values obtained for the ellipse inclination indicate a strong polarisation of tidal currents along the principal axis of each inlet.

Fig. 3. Comparison between observed and simulated amplitudes and phases. Upper panels (a–b): group of semidiurnal constituents; lower panels (c–d): group of diurnal constituents.
4. Discussion

The application of both tidal and meteorological forcings allows us to reproduce correctly the tidal characteristics of the integrated domain constituted by the Adriatic Sea and the Lagoon of Venice. A comparison between the results obtained in the calibration and in the pure tidal experiments was carried out to evaluate the influence of wind stress and atmospheric pressure gradient on the computation of the tidal harmonics, derived from the simulated sea water level time series. In semi-enclosed basins like the Adriatic Sea, the wind forcing may generate free oscillations with frequencies close to those of the tidal constituents (see, e.g., Vilibić, 2006), which, consequently, may lead to misleading results in the computation of the tidal harmonics. The differences emerged in this comparison, however, were small. This ensures, a posteriori, the reliability of our model calibration (which was performed including the atmospheric forcing) and the robustness of the adopted method used to compute the tidal harmonic constituents. Moreover, the calibrated bottom roughness length coefficient (see Table 1) was of the same magnitude of values reported in previous studies of the northern Adriatic basin (see, e.g., Zavatarelli and Pinardi, 2003).

The agreement between observed and simulated amplitudes and phases of the tidal harmonics for the whole basin was generally good. Note, however, that the tidal characteristics of the Adriatic Sea were reproduced less satisfactorily (see Table 4a), owing to the lower accuracy obtained for the stations located along the eastern Adriatic coast and, secondly, in the approaches to the open boundary. As reported by Janeković and Kuzmić (2005), errors in the model results can be related both to a coarse resolution used to represent complex morphological structures like, e.g., those existing in the eastern Adriatic coast, and even to the uncertainty in the data. A misfit between observations and model outputs can also be related to the non-tidal circulation of the Mediterranean Sea propagating toward the Adriatic basin (Tsimplis et al., 1995). This aspect, especially manifested in the baroclinic gradient emerging when the Modified Levantine Intermediate Water enters the Adriatic Sea through the Otranto Strait and recirculates within the southern and central Adriatic basins (Socal et al., 2009), has not been considered here and, very probably, it could improve the reproduction of the simulated sea water levels if considered in the model setup. Nevertheless, the accuracy obtained in our simulations was satisfactory and comparable with those reported in previous studies carried out through the application of different hydrodynamic models (Cushman-Roisin and Naimie, 2002; Umgiesser et al., 2004; Janeković and Kuzmić, 2005; Bellafiore et al., 2008). Moreover, the calibrated model reproduced accurately the behaviour of the most energetic constituents of the tide in the Adriatic Sea (Fig. 5), namely M2 and K1. The wave nature of tidal movements in

Table 5

Tidal ellipse parameters for the seven major tidal constituents from observed and simulated data at stations 1–3 (Fig. 2).

<table>
<thead>
<tr>
<th></th>
<th>St. 1 (Chioggia)</th>
<th>St. 2 (Malamocco)</th>
<th>St. 3 (Lido)</th>
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<tr>
<td>M2</td>
<td>U-major (cm/s)</td>
<td>48.1</td>
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<td>U-minor (cm/s)</td>
<td>–0.1</td>
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<td></td>
<td>Phase (deg.)</td>
<td>14.6</td>
<td>13.4</td>
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<tr>
<td></td>
<td>Inclination (deg.)</td>
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<td>–126.0</td>
</tr>
<tr>
<td>S2</td>
<td>U-major (cm/s)</td>
<td>28.3</td>
<td>33.7</td>
</tr>
<tr>
<td></td>
<td>U-minor (cm/s)</td>
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<td>–0.1</td>
</tr>
<tr>
<td></td>
<td>Phase (deg.)</td>
<td>25.2</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>Inclination (deg.)</td>
<td>–120.8</td>
<td>–126.0</td>
</tr>
<tr>
<td>N2</td>
<td>U-major (cm/s)</td>
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<td>U-minor (cm/s)</td>
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</tr>
<tr>
<td></td>
<td>Phase (deg.)</td>
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<td>16.5</td>
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<tr>
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<tr>
<td>K2</td>
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<td>K1</td>
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<td>169.9</td>
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<tr>
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<tr>
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<td>Phase (deg.)</td>
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<tr>
<td></td>
<td>Inclination (deg.)</td>
<td>–120.6</td>
<td>–126.0</td>
</tr>
</tbody>
</table>

Fig. 4. Simulated vs. observed semi-major axis velocity and inclination of M2 and K1 tidal components of the velocity at stations 4–16 located in the North Adriatic Sea (see Fig. 1).
Adriatic Sea has been shown through an analytical model of the M2 tide by Hendershott and Speranza (1971) as a solution of the problem on long wave reflection in the end of elongated basin allowing for Coriolis force (the so-called Taylor’s problem). The occurrence of a semidiurnal tidal amphidrome in the Adriatic Sea has been explained by sufficiently weak energy losses in northern part of the basin. As regards the diurnal tide, the extension of the Adriatic Sea appears to be larger than a quarter of diurnal tidal wave length and, thus, the formation of apparent amphidrome within the basin does not occur. These features of tidal wave dynamics have found a confirmation in the subsequent works and in the present study. The co-tidal charts derived from the model clearly show the evolution of the semidiurnal tide, resembling a progressive Kelvin wave, which cyclonically rotates around an amphidromic point positioned on the Ancona–Sibenik line (Mosetti, 1987), and the nature of the diurnal tide, associated to a topographic wave progressing cross-wise from the eastern to the western coast (Cushman-Roisin et al., 2001).

Beside these well-known characteristics, the simulated spatial distribution of the K1 amplitude and phase is characterized by the presence of an amplitude minimum located in the approaches to Vieste (st. 4 in Fig. 1) and a degenerated amphidromic point near Otranto (st. 1 in Fig. 1), whereas, in the southern Adriatic basin, M2 semidiurnal component shows higher amplitudes than those reported in the work of Cushman-Roisin and Naimie (2002). On the other hand, both M2 and K1 co-tidal charts are in rather good agreement with those presented by Janeković and Kuzmić (2005), who used a refined data assimilation procedure to simulate the tidally induced circulation in the Adriatic Sea. Note that our analysis refers to a much larger number of tide gauge observations than in previous works (see Figs. 1 and 2). In addition a classification of the tide type is usually carried out through the estimation of the tidal factor $F \left( F = \frac{A_{K1} + A_{O1}}{A_{M2} + A_{S2}} \right)$, where $A_C$ is the respective amplitude value) which allows one to estimate the relative importance of individual diurnal and semidiurnal tidal constituents. Calculation of $F$ reveals (not shown) that the mixed semidiurnal type prevails in the Adriatic

Fig. 5. Co-tidal charts of the simulated M2 (left) and K1 (right) tidal constituents for the Adriatic Sea. Amplitudes are in cm and phases are in degrees.
Sea, although the tide maintains a diurnal character in proximity of the semidiurnal amphidromic point.

The comparison between simulated and observed depth averaged tidal velocities showed that the model reliably reproduces the current dynamics in the integrated domain. Differences obtained for the northern Adriatic set of stations were comparable to those reported in earlier works (Cushman-Roisin and Naimie, 2002; Janeković et al., 2003; Bellafiore et al., 2008). Simulated tidal ellipses correspond only partially to observed ones. This is a problem which seems to be common to all numerical models implemented for the simulation of the North Adriatic basin. The causes of such disagreement are possibly in the presence of local bathymetric features that cannot be completely captured even by a very high resolution numerical model (see e.g., Cushman-Roisin and Naimie, 2002; Janeković and Kuzmič, 2005). An additional source of uncertainty in the reproduction of coastal currents regards the absence of baroclinic effects in the simulated circulation. For instance, the fresh water discharges of the Po and other Italian rivers are known to remarkably modulate the spatial pattern and the intensity of the stratification during both summer and winter and, thus, to contribute to shape the current fields along the western Adriatic coast. Such fields appear to be noticeably influenced by the seasonal alternation of regions of enhanced and reduced vertical stability (see Socal et al., 2009). However, the good precision achieved in the simulation of the tidal currents at the inlets of the Lagoon of Venice (see Table 5) confirms the validity of the selected modelling approach: this result would have been difficult to achieve in a disjoint simulation of the two domains.

4.1. Observed water levels and small-scale circulation patterns

Results presented in the previous section showed that the model efficiently reproduces the temporal and spatial evolution of two relevant variables, namely the tidal elevation and the depth averaged currents.

On this basis, the calibrated hydrodynamic model was addressed to the reproduction of observed tidally and atmospherically induced sea water levels characterizing the northern area of the composite system and to the investigation of the small-scale circulation features occurring in the zone between the adjoining basins. Measured and simulated sea water levels were compared, in order to provide an estimation of the performance of the model in reproducing the sea surface evolution at short time scales. Measurements come from the hourly sampling of two

![Fig. 6](image-url)

Fig. 6. Simulated (continuous lines) and observed (crosses) water level referring to 6 stations located in the North Adriatic Sea and inside the Lagoon of Venice (see Figs. 1 and 2 for their locations).
independent monitoring networks: the RMN system of the National Agency for the Environmental Protection and the surveys of the Mareographic Centre of the Venice Municipality. In Fig. 6 the hourly water level time series simulated and measured at 6 tidal stations within the northern Adriatic Sea and the Lagoon of Venice during the late summer 2004 (see their location in Figs. 1 and 2), are depicted. The model correctly reproduces observed phase and amplitude, thus preserving the characteristics of typical mixed tidal regime encountered in the northern Adriatic area (see, e.g., Polli, 1960).

As far as the near shore circulation patterns are concerned, the simulated velocity fields in the approaches to the central inlet of the Lagoon of Venice were compared to surface velocity fields observed in the area by means of a high frequency radar having a spatial resolution of ~750 m (Kovačević et al., 2004). In particular we focused on a descriptive comparison between observed and simulated velocity patterns for a Sirocco and Bora wind episodes, whose average wind speed were ~5 and ~15 m/s, respectively. Besides the discrepancies which may be due to other processes like, e.g., stratification, it must be noted that a precise, quantitative comparison between observations and simulated depth-averaged velocities emerging in the presence of the combined tidal and wind forcing cannot be obtained in principle. However, a qualitative comparison is still possible: it shows that in both wind scenarios considered, the model was able to capture different aspects of the observed velocity patterns, both in intensity and direction (Fig. 7).

The good agreement between observations and simulations suggests that also the dynamics in the very approaches to the inlet, produced by our numerical model, correspond to robust features occurring during Bora and Sirocco episodes. During the simulated Bora episode, for instance, mean current velocities of about 15 cm/s occurred, which contributed to produce a peculiar local circulation, characterized by a noticeable southward displacement of the water plume exiting from the lagoon inlet (Fig. 7d). This, on its turn, led to the formation of a strong, rather persistent eddy located between the inlet dike and the shoreline. The simulated Sirocco episode, instead, was characterized by substantially lower mean water velocities (~5 cm/s) and, consequently, to a less pronounced modifications of the mean local flow

Fig. 7. Vector maps of current (thin line) as observed by Kovačević et al. (2004) (panels a and b) and as reproduced by the model (panels c and d) during an episode of Sirocco wind and during an episode of strong Bora wind. The prevailing wind direction is also indicated (bold line).
pattern (Fig. 7). Moreover, vortical structures on the sea side of the inlets similar to those observed by Kovacevic et al. (2004) using the HF radar are clearly visible in the simulated fields (in this region the model horizontal mean spatial resolution is circa 250 m) during both events.

Numerical experiments carried out under idealized conditions by D’Alpaos and Defina (2007) indicate that the tidally induced flow is responsible for the formation of local transitional eddies in correspondence of the inlet mouths. As follows from the theory and also from experimental data, outflows from a sharp channel end may form a dipole of two large counter-rotating eddies by advection of vorticity created at the boundaries (Wells and van Heijst, 2003). If the dipole structure is sufficiently long-lived, it can self-propagate away from the channel or may be involved by inflow backward into the channel when the flow is periodic. The dipoles propagation away from the source region was found to significantly enhance the efficiency of tidal exchange between a bay and a sea connected by a narrow channel. The prevision of its occurrence was based on the relatively simple criteria $W/U < 0.13$, where $U$ is the tidal velocity of the channel jet, $T$ the tidal period, and $W$ the width of the channel. The present model was thus used to investigate the vortex genesis and evolution at the southern inlet near the town of Chioggia (see Fig. 2) throughout a tidal cycle. Two vortices were simulated, which originated outside the lagoon during ebb (see Fig. 8a, black arrows), while a sharp current plume transported water from the lagoon toward the open sea (see Fig. 8a, white arrow). Then, during the maximum tidal inflow, a smaller vortex was generated inside the lagoon, in the southern area of the inlet (see Fig. 8b, black arrow). For typical values $W$, $U$, and $T$ (550 m, 0.5 m/s, and 12 h, correspondingly) in Chioggia inlet, the criterion proposed by Wells and van Heijst (2003) is satisfied. Accordingly, despite the fact that bed friction can lead to a noticeable decay of vorticity near the outlet, the dipole vortical structure generated during the previous tidal phase is still visible on the outer part of the inlet and it tends to escape the inlet region and to translate toward the

![Flow velocity distributions simulated at the inlet near Chioggia (see Fig. 2) during ebb tide (a) and flood tide (b). During the simulation period, the wind speed was below 1 m/s. The correspondent tidal phase is indicated in the upper-left box.]
4.2. Residual sea level in the northern Adriatic basin

According to the early studies of Finizio et al. (1972) and Godin and Trotti (1975), the concomitant presence over the North Adriatic basin of long-lasting low air-pressure and strong Sirocco winds is able to induce basin-wide oscillations, or seiches, whose characteristic frequencies are found to be close to those of the major tidal constituents, being between 21 and 23 h and around 11 h. Particular features of spatial and temporal evolution of the Adriatic non-tidal oscillations were discussed in a number of subsequent papers (Cerovečki et al., 1997; Vilibić et al., 1998; Tomasin and Pirazzoli, 1999; Pasarić and Orlić, 2001; Sobey, 2003). More recently, through the analysis of long term series of residual observed sea levels for two stations located in the eastern Adriatic coast, Vilibić (2006) found the periods of the first and of the second modes of the Adriatic seiches to be 21.5 and 11 h, respectively.

A statistical procedure based on the wavelet transform (Daubechies, 1990) is here adopted to investigate the spectral composition of both simulated and observed residual sea levels. A well known limit of the Fourier transform is that it only provides time averaged results as the signal is assumed to be stationary. Conversely, the application of the wavelet analysis allows to decompose a one dimensional time series into a two dimensional time-frequency image and thus it provides a synthetic representation of the variable structure of the signal and the changing contribution of its components (for further details see Torrence and Compo, 1998). The main advantage is then represented by the possibility of localising events of interest at their exact temporal location when dealing with non-stationary processes (see, e.g., Drago and Boxall, 2002; Zanchettin et al., 2009). Residual levels simulated for a model point located near the CNR Tower (st. 70 in Fig. 1) were computed by subtracting from the sea water levels -simulated using both tidal and meteorological forcing- the corresponding sea water levels simulated using only tidal forcing (see Section 2.4 for further details). The same procedure was used to compute the residual sea water levels measured at the CNR Tower by the Mareographic Centre of the Venice Municipality.

Fig. 9 displays the wavelet power spectrum of the hourly values of both observed and simulated residual levels, obtained using a Morlet wavelet (data were normalized by their variance). The red contour encloses regions that lie in the 95% confidence interval for a red-noise process with a lag-1 coefficient of 0.7. During autumn and winter seasons, when atmospheric perturbations are more intense (see Artegiani et al, 1997a), the variance close to the period of the first mode is significantly above the confidence interval for both time series. On the other hand, the characteristic period of the second mode cannot be clearly recognized in the power spectrum obtained from observations, while the one derived from the numerical experiment reveals significant regions on this band in correspondence of the winter period. Compared to the analysis of the observed data, the wavelet spectrum of the simulated residual
levels lack of those components with periods lower than 6 h and, thus, a larger weight is assigned to the variance of the spectrum associated to the first and to the second modes of the Adriatic basin. As one can see in Fig. 9b, significant regions exist that largely extend around the diurnal period. This fact may be explained by the effect of sea level variations induced by local meteorological phenomena like land-sea breezes or by the effect of residual tides. We are convinced that our meteorological forcing, characterized by a coarse resolution both in space and time (see Section 2.2), is not adequate to generate diurnal wind-induced variability. In fact, only a very high resolution meteorological model can be able to partly capture land-sea breeze induced dynamics (see, e.g., Pullen et al. (2003)). Probably, these signals can be explained as manifestations of residual spring-neap tidal oscillations possibly interacting with meteorologically induced sea level oscillations at diurnal and semi-diurnal time scales.

5. Conclusion

In this paper, the implementation of a boundary conforming coordinates, finite difference, 2D hydrodynamic model for the composite domain constituted by the Adriatic Sea and the Lagoon of Venice was presented. Numerical simulations were carried out under realistic conditions, including tidal and meteorological forcings. A wide ensemble of recent experimental datasets was used to reproduce the bottom geometry of the physical system and calibrate the model. For validation, the model results were compared to tide gauges derived harmonic constants collected in stations located in the whole domain and current meter data. Simulation results for the diurnal and semi-diurnal tidal constituents were satisfactory, with mean errors in amplitude and phase rarely exceeding 1 cm and 15° for the Adriatic Sea, and 0.5 cm and 9° for the Lagoon of Venice, respectively. Furthermore, the depth averaged velocities agreed quite good with the velocities measured by mean of a current meter, especially in the case of the velocities recorded at the interface between the lagoon and the open sea.

Finally, the model was addressed to the reproduction of the residual water levels collected in the northern part of the system and to the investigation small-scale circulation patterns observed in the marine region near the Lagoon of Venice. The comparison between simulated and observed velocity fields in front of the Venetian littoral evidenced a reliable reproduction of the coastal circulation pattern under the influence of the tide and most important winds (Bora and Sirocco) characterized by the formation of vertical structures near the inlets. The analysis of the simulated and observed sea water levels clearly indicated the capability of the model to capture atmospheric and residual tide contributions to the hydrological fields in the composite domain. The elucidation of these features requires a deeper investigation of the interactions between the tide and the meteorologically induced oscillations, as the residual water levels cannot be considered completelydetided and, thus, the contribution of residual tidal effects may become relevant in the analysis of observed as well as simulated sea water levels.

The results achieved through the numerical simulations performed with the barotropic model allowed to consistently describe the tidal and atmospherically induced hydrodynamic features of the composite system Adriatic Sea–Lagoon of Venice. In particular, the model realistically reproduced the local circulation patterns which characterize the exchanges between the lagoon and the open sea and, thus, it can be used to simulate successfully the transport and dispersion processes which influences the spatial and temporal distribution of nutrients and/or pollutants, which play a crucial role in the simulation of biogeochemical processes in coastal areas.

References


