Modelling ocean currents in the northern Adriatic Sea

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ABSTRACT

Ocean circulation in the northern Adriatic Sea is characterised by the interactions of tidal currents, bathymetric constraints, wind forcing and density gradients induced by river input and heat exchange. The MIKE 3/21 modelling system, together with measurements of wind, waves, currents and water levels at one location, has been used to investigate the currents dynamics of the northern Adriatic basin and to assess model sensitivity to the parameterisation of different processes and implementation strategies. An assessment has been carried out against available in-situ observations (waves, currents, surface elevation, and water temperature), and also in comparison with a high-resolution modelling system (COAWST) implemented in the same area during the corresponding period. The MIKE 3/21 system was implemented for a 1-year simulation period and validation of surface elevation, wind, and waves with data indicated a good model performance, statistically very similar to the COAWST implementation. Depth-averaged, surface and bottom currents were more difficult to reproduce by both models, with the observed high variability not being fully captured by the model systems. Some of the differences between the models results may be due to model configuration, spatial resolution and the way they treat atmosphere–ocean momentum and heat transfers, turbulence, and are therefore discussed in the paper. From the thorough analysis of MIKE 3/21 system, wind is found to be the main forcing factor inducing currents in the northern Adriatic; tides and baroclinic motions were of second order, although some specific events seems to be forced by these processes. Waves were found to be highly correlated with local wind, and a rather weak wave–current interaction was observed. Even if the inclusion of wave effects trough radiation stress did not seem to lead to significant improvements in the modelled currents with MIKE 3/21, the full wave–ocean coupling in COAWST was significant in explaining small scale features, especially in the Gulf of Venice. Spectral and SVD analysis showed energy around diurnal and semi-diurnal frequencies and that about 50% of variance in the current profile was explained by the first mode, which was well captured by both modelling systems.

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1. Introduction

The Adriatic Sea (Fig. 1) is a marginal semi-enclosed basin within the Eastern Mediterranean extending southeastward from (12°E, 46°N) to (19°E, 40°N), approximately 780 km long and 120–200 km wide. The northern Adriatic (NA, north from Ancona, see Fig. 1) is characterised by depths of a few tens of metres, increasing gradually towards the Mid Adriatic Pit, where maximum depth is about 280 m. While the western coastline is mostly featureless except for the Po river delta near 45°N, the eastern coastline is irregular, marked by the mountainous Istrian peninsula and numerous islands and bays. Around and within them, depths are sometimes greater than 80 m.

This portion of the Adriatic Sea has a relatively complex hydrodynamic behaviour, changing its main features during its annual hydrologic cycle, from those of a stratified system to those typical of a homogenous and well-mixed basin (Artegiani et al., 1997a; Russo et al., 2012b). The main thermohaline characteristics of the basin have been described by Artegiani et al. (1997a, 1997b), while Poulin (2001) tackled the surface circulation using Lagrangian devices and a recent thorough climatological assessment has been proposed by Russo et al. (2012a).

During summer time a rather large surface warming is present in the NA area, leading to an almost stratified situation in the shallower portions (Russo et al., 2012a). Evaporation on the northern Adriatic slightly prevails on precipitation giving a net water loss of 30 cm (Picco, 1991). The basin represents a sink of heat, however a fresh
water balance considering also runoff (evaporation - precipitation and runoff) in the Adriatic (Raicich, 1996) indicate that the northern Adriatic is permanently in a negative balance during all seasons. The NA is characterised by a significant river runoff during spring and fall (Artegiani et al., 1997b). Indeed, the Po and the other northern Italian rivers, contributing about 20% of the whole Mediterranean river runoff (Hopkins, 1992), together with atmospheric forcing, are fundamental in determining the NA circulation by injecting fresh water masses (Bergamasco et al., 1999).

The basin is subjected to different wind regimes; during the cold season the prevalent winds are the strong dry and north-easterly (called Bora, see Boldrin et al., 2009; Dorman et al., 2006) and the southeasterly winds (Sirocco), which occasionally blows during warm season (e.g., Signell et al., 2005).

The strong heat and momentum fluxes associated with Bora regime might contribute to the formation of North Adriatic Dense Water (NADW); the episodic production and sinking of these heavier and denser waters characterises the NA during the winter season, leading to strong vertical mixing and overturning (Cushman-Roisin et al., 2001; Mihanovic et al., 2013; Vilibic and Nastjenjka, 2005). Consequently, NADW tends to spread over the basin, moving to the southern region (Carniel et al., 2012) and triggering a return circulation from the Ionian and Aegean region into the basin. Such waters are transported by the Adriatic Sea eastern currents and influence the local climate by transporting a significant amount of heat and nutrients (Boldrin et al., 2009).

Already in 1987, Zore-Armanda and Gaćić (1987) analysed current metre records in the NA under Bora conditions and suggested that the associated wind shear acts on the ocean to form two gyres: one cyclonic gyre forms in the far north. South of it, the circulation is anticyclonic as currents flow northeastward from the Po River mouth to the Istran coast, southeastward along the Istran coast, and southwestward from Kvarner Bay to the Italian coast. More recently, as shown by Bignami et al. (2007) and Boldrin et al. (2009), these results were supported by the adoption of high-resolution meteorological forcings, without which many of the observed features were not previously modelled. Adopting a different numerical model, Malacic et al. (2012) showed the topographic control on wind-driven circulation in the Gulf of Trieste during Bora events.

Studies of tidal currents in the NA (Book et al., 2009; Chavanne et al., 2007) have showed a reversing tidal currents at most of locations, at “Acqua Alta” tower (see Fig. 1) the tidal ellipse is more circular and tidal amplitude is of 0.0146 m/s for $K_1$, 0.0375 m/s for $M_2$ and 0.0219 m/s for $S_2$. It was also observed the support of a Kelvin wave by the $M_2$ energy fluxes, and the possible alteration of the tidal propagation near the coast due to stratification and lateral shear induced by the Western Adriatic Current were outlined.

The combination of a relatively small tidal range, strong seasonal atmospheric effects, baroclinic processes and bathymetric controls on the dynamics of the northern Adriatic make the vertical profile of the currents sheared and it is common to find current inversion from bottom to surface (Cosoli et al., 2008). Cosoli et al. (2008) studied the variability of an observed current profile in the NA from September to October 2002, finding that the main component was barotrophic, explaining 70% of the signal while the second component was baroclinic. The first component was associated with synoptic scale meteorological events, showing a relatively uniform vertical structure with small reductions in amplitude towards the surface and the bottom and a clockwise veering with depth, related to effects of a bottom-friction. The second one has a baroclinic-like structure with one zero-crossing at 8 m depth and relates to a higher
frequency sea-breeze forcing. This, together with the adjustment
time scales found, suggests a frictional dominated flow.

The objectives of the present work are to improve the knowl-
edge upon the above mentioned processes by means of imple-
menting two coupled 3D hydrodynamic and spectral wave models
systems, namely MIKE 3/21 (MIKEbyDHI, 2012a, 2012b) and
COAWST (Warner et al., 2010) in the Adriatic Sea with unstruc-
tured and curvilinear grids respectively. Model performance is
assessed and, together with Acoustic Doppler Current Profiler
(ADCP) and temperature data, used to characterise the vertical
profile of currents, temperature evolution and study the relative
importance of numerical and physical components such as at-
mospheric forcing, river input, heat exchange and wave forcing. A
seasonal assessment of current residuals is also presented.

In this study we add numerical modelling to the considerations of
Cosoli et al. (2008) to provide a physically coherent determini-
istic framework for characterising the flow in both calm and
storm conditions. However, the circulation in the NA is charac-
terised by the interactions of tidals currents, bathymetric con-
trasts, wind forcing and density gradients induced by river
input and heat exchange. Since these interactions represent a
recognised challenge for numerical models and are central to the
present work, the use of two different modelling systems may
help providing a wider picture discussing also limitations and
uncertainties associated to two different state-of-the-art suits.

The paper is structured as follows; Section 2 describes the
modelling tools and their setup for the northern Adriatic. Section 3
presents the measurements and describes the environmental condi-
tions during the studied period and the Bora events. In Section 4 the
results of reference runs are presented together with model compari-
sions for barotropic variables, surface and bottom temperature and
speed, and waves. Discussions on different forcing sources for the
northern Adriatic, the seasonal patterns of residual circulation, spectral
analysis and a discussion of model errors are presented in Section 5.
Finally, in Section 6, the concluding remarks are summarised.

2. Modelling the Northern Adriatic

Two numerical models are used to investigate the sources of
currents in the northern Adriatic: MIKE 3/21 (MIKEbyDHI, 2012a,
2012b; Pietrzak et al., 2002; Sørensen et al., 2004) and COAWST
system (Benetazzo et al., 2013; Sclavo et al., 2013; Warner et al., 2010).
The models and their particular setups in the northern Adriatic have
distinctive differences with respect to resolution, flexibility, computa-
tional resources required, numerical techniques, processes included
and the level of validation for the northern Adriatic. Hence, the
objective is not a thorough comparison of the models, but rather to
use the complementarity of the two model setups for studying the
impact of a range of interactions and model parameters on their
representation of currents in the northern Adriatic. While the flexible,
coarser and faster MIKE 3/21 setup is used for the majority of the
sensitivity studies, the more extensively validated setup of the
COAWST system is used as a benchmark and for investigating the
impact of higher resolution and a more comprehensive inclusion of
interactions and forcing on derived currents.

The skills of the models are assessed by estimating the correla-
tion coefficient ($r$), Bias, Root Mean Square Error (RMSE) and scatter
index (SI) defined as

$$r = \frac{\sum_{i=1}^{n} (M_i - < M >) (O_i - < O >)}{\sqrt{\sum_{i=1}^{n} (M_i - < M >)^2 \sum_{i=1}^{n} (O_i - < O >)^2}}$$

$$\text{Bias} = < M > - < O >$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (M_i - O_i)^2}^{1/2}$$

$$\text{SI} = \frac{\text{RMSE}}{< O >}$$

where $< >$ denotes the mean values, the model prediction is $M_i$ and observations $O_i$.

The two modelling systems were implemented for a 1-year
hindcast period (September 1, 2010–August 31, 2011) in the NA Sea
using the same atmospheric forcing, provided by the Italian
operational atmospheric model COSMO-I7, the Italian version of
the COSMO Model (http://www.cosmo-model.org). The model has
a $7 \times 7$ km$^2$ horizontal resolution providing outputs every hour,
and has been used previously to study the dynamics of the NA basin
(Boldrin et al., 2009), the wave–current interactions (Benetazzo
et al., 2013; Signell et al., 2005) and drift transport (Rixen et al.,
2008) in the Adriatic sea.

Climatological river data were considered for the main 30 rivers
in the Adriatic (Raiich, 1994). The Po is the most important river
having climatological peaks of up to 2220 m$^3$/s in November, while
the second in importance is the Neretva with a climatological peak
of 604 m$^3$/s in December. Measured river discharge values at the
Po river (Benetazzo et al., 2013) were used in the COAWST and
MIKE 3 systems with hourly time resolution. It is noteworthy
that observed runoffs presented differences of up to a factor of 2
compared to the climatological values.

In Sections 2.1 and 2.2 details of each system implementation are
given.

2.1. MIKE 3/21 system description and implementation

MIKE 3 is a component of the MIKE by DHI software
(MIKEbyDHI, 2012a, 2012b; Pietrzak et al., 2002). It is a three-
dimensional hydrodynamic model based on a flexible mesh
approach and it has been developed for applications within
oceanographic, coastal and estuarine environments. The model is
based on the numerical solution of the 3D incompressible
Reynolds Averaged Navier–Stokes equations (RANS) invoking the
assumption of Boussinesq and hydrostatic pressure approxima-
tion. The free surface is taken into account using a sigma-
coordinate system but a combined sigma and z-layer distribution
is possible within the model. For a more detailed discussion of
vertical discretisation in ocean models the reader is referred to Ezer
et al. (2002) and Ezer and Mellor (2004). The spatial discretisation
is performed using a cell-centred finite volume method. In the
horizontal plane an unstructured grid is used. The model equations
are closed by the $k$–$\varepsilon$ turbulence scheme (Canuto et al., 2001; Rodi,
1984; Umlauf and Burchard, 2005). The model is able to take into
account tidal potential (Pugh, 1987), heat exchange, evaporation/precipitation, wind stress, wave radiation stresses, and the open
boundaries can be forced by constant or varying elevation, speed,
salinity and temperature and Flather conditions (Flather, 1976).
Wind stress is based on a drag formulation dependent on wind
speed (Wu, 1984).

MIKE 21 SW (MIKEbyDHI, 2012b; Sørensen et al., 2004) is a third
generation spectral wind–wave energy model (Komen et al.,
1994) based on unstructured meshes and considers wave growth,
dissipation and non-linear wave interactions. Sources formulata-
jons by Janssen (1991) and Komen et al. (1984) are available as
well as an updated version of the white-capping dissipation
(Bidlot et al., 2007). Wave–current interactions in the present
study are considered by a one-way transfer of the 2D radiation
stresses from MIKE 21 SW to MIKE 3 in a similar approach as in
Brown et al. (2013). Stokes drift and wave modification of the
atmospheric boundary layer are not considered in the present
work. Although 2-way interactions are available (e.g. effect of
currents and water level into waves) these were not considered in
the present system implementation.

In order to model the Adriatic Sea with MIKE 3/21 system
considering tidal and baroclinic boundary conditions, two grids
have been used. The first one (tidal run, Fig. 1) was used to run the
2D barotropic version, MIKE 21 HD, in which tidal elevations at the boundary were imposed. Boundary tidal elevations were generated for the first grid using the satellite altimetry based DTU10 Tidal Model (Cheng and Andersen, 2010) (ftp://ftp.space.dtu.dk/pub/DTU10/DTU10_TIDEMODEL). The grid covered a larger area than the second grid (Fig. 1) in order to place the open boundary in an area where the tidal boundary is in relatively deep water. The 2D model was run for the study period and provided tidal elevation and depth-averaged velocities at the open boundary of the second domain (located at the Strait of Otranto, Fig. 1).

Baroclinic (non-tidal) open boundary conditions (sea surface elevation, vertical distribution of 2D (horizontal) momentum, temperature and salinity) and initial conditions for the second domain were taken from the Mediterranean Forecasting System (Pinardi et al., 2003) running at INGV (Istituto Nazionale di Geofisica e Vulcanologia), released through MyOcean service (http://www.myocean.eu.org/, product: MEDSEA_REANALYSIS_PHYS_006_004). The model is supplied by the Nucleous for European Modelling of the Ocean (NEMO), with a variational data assimilation scheme (OceanVAR) for temperature and salinity vertical profiles and satellite Sea Level Anomaly along track data. The model horizontal resolution is uniform at 1/16° and it has 72 unevenly spaced z-levels.

Boundary velocities and surface elevations from MyOcean were linearly combined with the depth-averaged velocity components and surface elevation from the tidal run applying Flather boundary condition (Flather, 1976). Salinity and temperature initial conditions were interpolated from the MyOcean grid to the irregular grid used in MIKE 3. For the horizontal eddy viscosity a Smagorinsky formulation was used while the -ε turbulence model for the vertical. Tidal potential and wind stress were used in all model runs. Bottom friction was described by a constant roughness height of 0.05 m. MIKE 3 was then run with 20 combined sigma and z-layer vertical levels, including 10 sigma levels in the surface 40 m and 10 z-levels below the sigma levels. In the horizontal, the grid consisted in a triangular mesh with a resolution of the order of 4.4 km in the middle of the Adriatic and of the order of 1.1 km near the coast in the northern Adriatic. This grid was also used for the simulation of waves with MIKE 21 SW. MIKE 21 SW was run with 24 directions and 32 frequencies logarithmically distributed and with a lowest frequency of 0.055 s⁻¹. The model was run using low order spatial discretisation with Janssen (1991) wind input formulation. The southern boundary for MIKE 21 SW was open, no waves entered the area and waves were able to leave the area freely. The energy dissipation due to depth-induced wave breaking (Battjes and Janssen, 1978) and to bottom friction (Johnson and Kofod-Hansen, 2000; Weber, 1991) was considered.

Table 1 shows the description of the tidal run and the reference run using MIKE 3/21. Additional model runs, which represent variations of the reference run, were performed to assess the importance of different processes in the northern Adriatic. Table 2 shows the different runs performed with MIKE 3/21 including the processes described in the columns. Most of the runs included tides, the run without tides and wind (MIKE-A) aimed to quantify the strength of baroclinic forcing itself, while rivers were also included in most of the runs. MIKE-B was based in MIKE-A plus the tidal forcing, and MIKE-C also included the wind and atmospheric pressure. Two dimensional wave radiation stress (MIKEbyDHI, 2012b) was used in one run (MIKE-D) to account for wave induced currents in the area. Although MIKE 3 and MIKE 21 SW can be run in 2-way coupled mode, a one-way approach (only wave information was passed to MIKE 3) was considered. For a more detailed discussion of the currents effects on waves over the northern Adriatic the reader is referred to Benetazzo et al. (2013). A run changing the numerical schemes of the model to high order was also performed (MIKE-base), in order to assess the numerical impact. This implies a second order Runge-kutta method for time integration and a Riemann solver with a linear gradient reconstruction technique (Jawahar and Kamath, 2000). Although high order is considered to be a better numerical solution (thus could be considered as the baseline run), its computational cost is 3 times higher and therefore low order was used for most of the numerical experiments, including the reference run to be used to assess forcing terms. In the MIKE-E run, the initial temperature condition extracted from MyOcean was reduced by 2° to account for the bias observed when compared with observations and quantify the long term effect of the temperature initial condition. MIKE-F run was performed by removing river input and heat transfer, in order to assess the density gradients forcing. Lastly, as the river Po is the main source of fresh water in the Adriatic, a run (MIKE-H) with measured discharge instead of climatological data was carried out.

2.2. COAWST system description and implementation

The Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) modelling system, which relies on the ocean model ROMS (Regional Ocean Modelling System version 3.4, see Haidvogel et al. (2008) and http://www.myroms.org), the wave model SWAN (Simulating WAVes Nearshore, Booij et al., 1999), and the CSTMS
(Community Sediment Transport Modelling System) routines, was implemented for the NA by Benetazzo et al. (2013). ROMS solves finite-difference approximations of the 3D Reynolds-averaged equations for conservation of mass and momentum. Wind stress and heat fluxes on the sea surface were calculated using the Coupled Ocean–Atmosphere Response Experiment (COARE, Fairall et al., 1996) 3.0 bulk flux algorithms. A recursive Multidimensional Positive Definite Advection Transport Algorithm (MPDATA) is chosen to model the tracers dynamics (Smolarkiewicz, 1983, 1984). Wind wave simulations were carried out using the Simulating WAves Nearshore (SWAN) model, version 40.81 (Booij et al., 1999; http://www.swan.tudelft.nl). SWAN is a state-of-the-art 3rd generation spectral wave model which computes random, short-crested wind-generated waves in offshore and coastal regions. Details on COAWST system description can be found in Warner et al. (2010).

COAWST system was implemented in the Adriatic Sea based on two different curvilinear orthogonal computational grids (Benetazzo et al., 2013). The coarse parent grid has horizontal spacing of 2.0 km in both directions, and 20 vertical sigma-levels, and covers the whole Adriatic Sea locating the southern open boundary at the Otranto Strait. Open boundary conditions (i.e., sea surface elevation and 3D fields of momentum, temperature, and salinity) were provided as daily fields at 1/16 × 1/16′ by the Mediterranean Forecasting System (MFS; see Pinardi et al., 2003). In addition, five tidal constituents were imposed along the boundary (namely, M2, S2, N2, O1, K1), as obtained through the Oregon State University (OSU) model (http://volkov.oce.orst.edu/tides/). On the southern boundary, ROMS domain was nudged on the outer 3D momentum and tracer fluxes, whereas Chapman (1985) and Flather (1976) conditions were imposed to the free-surface and the 2D momentum forcings, respectively. For the ocean model initial conditions of 3D velocity, depth-integrated 2D velocity, free-surface level, temperature and salinity were obtained from operational version running at the University of Ancona (AdriaROMS; Russo et al., 2012a, 2012b) with 20 sigma levels. Model outputs (e.g., 3D and 2D velocity components, free-surface, temperature and salinity fields) were saved every 0.5 h.

The horizontal grid spacing of the adopted child grid is 0.5 km and with offline nesting to the parent grid (Mason et al., 2010) in the northern Adriatic Sea sub-region (approximately north from Ancona, see Benetazzo et al., 2013). Free surface, 2D momentum, 3D momentum, salinity and temperature fields from the parent model were imposed with a 0.5 h time-step at the southern boundary of the fine grid. On the child grid, the baroclinic and barotropic time-steps used in ROMS were the same adopted for the parent grid. The horizontal viscosity coefficient in the model was set to zero to avoid smoothing/dissipation of eddies.

SWAN model was implemented (both on the parent and child grids) with 24 directions and 32 frequencies (f) geometrically distributed, such that \( f_{2n+1} = 1.1f_n \) with \( f_1 = 0.05 \text{ Hz} \). Exponential wave growth by wind and white-capping were evaluated with the expressions of Komen et al. (1984). The energy dissipation due to depth-induced wave breaking (Battjes and Janssen, 1978) and to bottom friction (Madsen et al., 1988) was also activated: a ratio of maximum individual wave height over depth of 0.73, and an equivalent bottom roughness length scale of 0.05 m were imposed. SWAN was run in non-stationary mode with a 600 s time step. On the parent grid, SWAN was configured assuming that no waves entered the area and that waves were able to leave the area freely at the southern boundary. The computation on the coarse grid provided the spectra at the boundary of the fine grid, imposed with a 30 min time step.

In the COAWST system, the ocean model provides to the wave model currents, free surface elevation, and the bathymetry evolution. An estimation of an effective current (the current which has an influence on the waves) depending on the wave spectra is done following the formulation proposed by Stewart and Joy (1974), and extended to finite depths by Kirby and Chen (1989). In this way the vertical variation of currents is considered when estimating wave refraction and Doppler shift, which has shown to improve the wave results in comparison to when using a depth-averaged velocity. In the adopted configuration of ROMS model, wave parameters were used to predict surface layer dynamics and roughness, bottom boundary layer closure, and momentum fluxes induced by waves (Olabarrieta et al., 2012; Warner et al., 2008). On the sea surface, breaking waves produce an injection of kinetic energy: in these conditions, the near-surface mixing is stronger and the vertical shear is reduced (Carniel et al., 2009). In ROMS, for breaking waves, the surface roughness length is parameterised as proportional to the significant wave height with a coefficient chosen equal to 0.5 (Stacey, 1999). In the COARE algorithm, the default option (Charnock, 1955) for wave roughness formulation in bulk fluxes was used. The stresses on the Bottom Boundary Layer (BBL) are parameterised with a formulation which represents the interactions of currents and wave motions over a moveable bed (Warner et al., 2008). The oceanic wave driven-flows and the effect of surface waves on mass flux transport were simulated with a Vortex-Force (VF) formalism (Kumar et al., 2012; Williams et al., 2004; Olabarrieta et al., 2012; Uchiyama et al., 2010), which enter in ROMS equations as momentum and tracers additional fluxes. Additional wave forces are separated in conservative (Vortex Force terms and Stokes–Coriolis forces) and non-conservative terms.

### 3. Observational data and environmental conditions

An Acoustic Doppler Current Profiler (ADCP) installed at the “Acqua Alta” platform (45°18′ 83° N, 12°30′ 53°E, Fig. 1) location (Cavaleri, 2000) is used to analyse the temporal and vertical structure of the currents as validation for the employed numerical models. The ADCP is bottom mounted at a depth of 17 m and measures current speed and direction with a vertical resolution of 1 m and it further provides measurements of wave parameters \( H_m, T_m \) using an acoustic surface tracking.

The studied period is from September 1, 2010 to August 31, 2011, allowing to capture some of the seasonal features and different atmospheric events. The ADCP contains also a thermometer used to assess bottom temperature; an additional thermometer located 3 m below the surface was also available. At “Acqua Alta” wind measurements were also available and used to validate the wind model. When compared with wind observations at the “Acqua Alta” tower location for the hindcast period (see Fig. 1 for location and Fig. 2 central panel for a time series comparison), the COSMO-17 model 10 m wind speed had a bias of −0.43 m/s, a RMSE of 2.5 m/s, a SI value of 0.52 and a r value of 0.73. Surface elevation data were available from pressure sensor with a time resolution of 5 min.

Fig. 2 (top panel) presents a time series of ADCP depth-averaged current speed and at the surface and bottom (average of 2 m at the top and bottom respectively) showing speeds reaching 0.6 m/s at the surface and 0.4 m/s near the bottom. In most of the water column (from bottom to 11 m above the bottom), 80% of data are under 0.2 m/s while in the top four ADCP bins (not shown) data are around 0.25 m/s with some possible contamination of the top bin due to the surface reflection and waves. The correlation between the top and bottom speed is 0.3, increasing up to 0.7 when correlating the bottom two bins. Fig. 2 also shows the depth-averaged velocity, showing a close agreement with bottom velocity (\( r = 0.6 \)). High frequency (hourly-daily) variability is observed, the grey areas indicating the presence of Bora atmospheric events. Fig. 2 (central panel) shows the observed and modelled time series of wind speed and direction. There are seven main events that reach at least 15 m/s in the observations, all of them Bora events. The bottom panel of Fig. 2 shows the time...
series of significant wave height, because of the small domain of the Adriatic Sea, waves are mainly locally generated and wave height ($H_{m0}$) presents a high correlation with wind ($r = 0.77$).

Table 3 summarises the environmental conditions at “Acqua Alta” during the seven Bora events shown in Fig. 2. These events occurred during autumn and winter, with durations between 3 and 15 days. Winds and depth-averaged current speed reached about 21 m/s and 0.55 m/s respectively. Significant changes of bottom temperature and atmospheric pressure within the events were observed. The persistence of the Bora events is a controlling factor of seasonal dynamics as discussed later.

### 4. Reference runs results. Systems assessment

In this section, an assessment and inter-comparison of models are presented. First, an inspection of the barotropic behaviour (surface elevation and depth-averaged velocity) is carried out, secondly bottom temperature and surface and bottom velocities are analysed, and finally waves are assessed. Section 5 will, by means of numerical experiments and time series analysis, discuss the physical processes inducing currents and forcing mechanisms in the northern Adriatic Sea assessing also the seasonality of currents and model errors.

#### 4.1. Barotropic variables

Surface elevation is a critical variable in the northern Adriatic due to the occurrence of high waters that affect, for example, the Venice lagoon (Day et al., 1998) that is connected to the Adriatic basin via three inlets (Bergamasco et al., 1998). The tidal range is in the order of 1 m and significant contribution to surface elevation comes from atmospheric forcing (e.g. Zampato et al., 2007; Pasaric et al., 2000). Generally speaking, the MIKE 3/21 system predicts very well the patterns of surface elevation for the studied period, showing a RMSE of 0.11 m and a correlation of 0.91. COAWST has errors of the same order of magnitude (RMSE of 0.15 m and $r$ of 0.83). However, differences at specific times can be larger, associated with errors in tidal constituents and atmospheric pressure. Modelled atmospheric pressure presented statistics of bias $=$ $-0.46$ mb, RMSE $=$ $0.98$ mb and a correlation of 0.99. As it will be discussed later, tidal elevations are not a significant source of currents at the “Acqua Alta” during wind events; even though they contribute to the long term residual

![Fig. 2. Observations at the “Acqua Alta” platform and COSMO-I7 winds. Bottom (average of bottom 2 bins) and surface (average of surface 2 bins) current speed (at the top panel). Wind speed and vectors (middle panel) for observed and modelled data, vectors have been displaced – 5 and – 10 for observations and model respectively in the vertical axis for easy reading. Significant wave height ($H_{m0}$) is presented in the bottom panel. Shading areas show the seven Bora events. (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)](image)

<table>
<thead>
<tr>
<th>Event</th>
<th>Season</th>
<th>Duration (days)</th>
<th>Max wind speed (m/s)</th>
<th>Max $H_{m0}$ (m)</th>
<th>Max Po discharge (m$^3$/s)</th>
<th>Bottom temperature variations ($^\circ$C)</th>
<th>Atmospheric pressure variations (mb)</th>
<th>Max depth-av. speed (m/s)</th>
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<td>15</td>
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<tr>
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<tr>
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<td>Autumn</td>
<td>5</td>
<td>20</td>
<td>3.5</td>
<td>2350</td>
<td>5</td>
<td>15</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>Autumn</td>
<td>7</td>
<td>17</td>
<td>2.4</td>
<td>4550</td>
<td>3</td>
<td>15</td>
<td>0.38</td>
</tr>
<tr>
<td>5</td>
<td>Winter</td>
<td>3</td>
<td>16</td>
<td>2.9</td>
<td>4820</td>
<td>0.5</td>
<td>30</td>
<td>0.30</td>
</tr>
<tr>
<td>6</td>
<td>Winter</td>
<td>5</td>
<td>18</td>
<td>3</td>
<td>1640</td>
<td>2.5</td>
<td>5</td>
<td>0.38</td>
</tr>
<tr>
<td>7</td>
<td>Winter</td>
<td>10</td>
<td>21</td>
<td>3.9</td>
<td>1640</td>
<td>1.5</td>
<td>15</td>
<td>0.43</td>
</tr>
</tbody>
</table>
circulation. For a comprehensive review on tidal modelling and its impact on the oceanographic properties (e.g. baroclinic currents) of the Adriatic, the reader is referred to Arabelos et al. (2011), Guarnieri et al. (2013) and Chavanne et al. (2007).

The behaviour of depth-averaged velocities gives a first insight into the hydrodynamic performance of the models. Fig. 3 shows the time series of the observed and modelled depth-averaged speed showing a good level of reproduction during the first and last Bora events when the model follows the general pattern of the measurements, while underestimations are evident during the calms and other intense events not directly associated with Bora winds. The models present different patterns when looking in more detail into the time series of depth-averaged speeds. This can be explained by the combined effect of different model setups (spatial resolution, numerics, physics/parameterisations) and is further discussed in Section 5 together with other sources of momentum in the water column. The second Bora event in Fig. 3 had a long duration and, although winds were not extremely intense (most of time less than 10 m/s while other events reached 15–20 m/s, Fig. 2) they were persistent. The strong currents occurring at the beginning of this event do not seem to have a direct correlation with the modelled Bora winds. It is during this event when the two models present the largest difference, this is likely due to differences in the surface stress and turbulence treatment. In general terms, the model runs presented in Fig. 3 did not produce significant differences in terms of depth-averaged speed statistics. Table 4 presents the overall model statistics for this variable for the reference runs and the MIKE 3/21 baseline run for the yearly time series and for each individual Bora event. No systematic behaviour is observed among the Bora events showing significant differences on statistics. However, the last Bora event is clearly wind dominated and it is when model better reproduce observations and show less differences between them.

### 4.2. Bottom and surface temperature

Temperature data present much less variability than currents, instead a clear seasonal pattern is observed, reaching its minimum in February 2011 and the maximum in the summer 2010. Observed and modelled bottom and surface temperature is presented in Fig. 4. The role of the atmospheric heat transfer in the model is crucial for proper representation of temperature. The initial conditions in both models show a shift on bottom temperature of about 2°C when compared to observations, positive for the MIKE 3/21 and negative for COAWST. This shift is persistent in the bottom temperature for the first half of the study period, MIKE 3/21 being able to converge to the observed temperature in March 2011. A reduction of the initial condition temperature of 2°C (run MIKE-E) improved the performance of the model during the first half of the study period. Statistics of model performance of bottom temperature show for MIKE-ref a bias = 0.89°C, RMSE = 1.8°C, SI = 0.12, and r = 0.93 while for COAWST a bias = −2.1°C, RMSE = 2.1°C, SI = 0.2, and r = 0.79. Measurements show maximum differences (4°C) between bottom and surface temperature during March and April indicating stratified conditions. During winter the temperature does not show a strong depth variation, with only a slight increase of temperature (1°C) towards the bottom. The models are able to reproduce this behaviour with some overestimation of the spring stratification (6.5°C difference between surface and bottom temperature).

### 4.3. Surface and bottom speed

Observed and modelled surface current time series are presented in Fig. 5 (left column). Variability is larger than in the depth-averaged speeds and differences between the models are...
evident: generally, calm conditions produce significant variations. The first Bora event, occurring around September 19, 2010 was simulated similarly by both models. However, other differences in

the model results outline the importance of model settings. Although both systems use the same atmospheric forcing and in a generic sense they model the same processes, the spatial resolution, numerics and physical parameterisations may have a significant effect on model results and thus interpretation of physical processes. For example, because of the different approach to the wind stress within the two models, the different momentum transfer through the surface can produce changes in the size of the boundary layer. The bottom current time series are shown in the right column in Fig. 5. Similarly to the surface speed, the models show the Bora event of September 19, 2010 clearly. The observations also show two events occurring between January 19, 2011 and February 06, 2011. The first is classified as a Bora event (6th event in Fig. 5) while the second is associated with slightly weaker but still predominantly north-easterly winds. The observed surface current for this period shows less distinguishable events, which are somewhat represented by COAWST, while the bottom current events are well depicted by both models indicating a very persisting feature not directly controlled by wind stress. The modelled depth-averaged speed (Fig. 3) also shows two clear different events suggesting most likely that the surface features observed and modelled by COAWST are only representative of a very thin surface layer influenced by the local wind.

Both bottom and surface speed annual statistics (Tables 5 and 6) show large scatter and low correlation associated with the high frequency variability of observations and models. Although the large scale features are represented by model results, the calm conditions and its variability are still not properly reproduced. This would probably partly require an even higher resolution both in space and time and partly have to be attributed to the higher frequency variability in the atmosphere and ocean circulation that is better described as a stochastic component. The internal Rossby radius (10 km summer, 1 km winter; see Bergamasco et al., 1996) implies that the grid resolutions used in the present implementation are not always eddy resolving, and a downscaling to cells less than 0.5 km would be necessary to capture the internal dynamics of ocean circulation. Similarly to the annual depth-averaged statistics, the Bora statistics do not show a systematic pattern between models. However, it is observed that the last event is the one with lowest errors and higher correlation at both surface and bottom. This event is the one

| Table 4 |
| Statistics for prediction of depth-averaged speed at “Acqua Alta” location. |

<table>
<thead>
<tr>
<th>Bias (m/s)</th>
<th>RMSE (m/s)</th>
<th>SI</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>-0.048</td>
<td>0.091</td>
<td>0.63</td>
</tr>
<tr>
<td>COAWST</td>
<td>-0.045</td>
<td>0.085</td>
<td>0.60</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>-0.038</td>
<td>0.087</td>
<td>0.61</td>
</tr>
<tr>
<td><strong>Bora 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>-0.042</td>
<td>0.110</td>
<td>0.64</td>
</tr>
<tr>
<td>COAWST</td>
<td>-0.034</td>
<td>0.076</td>
<td>0.44</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>-0.044</td>
<td>0.104</td>
<td>0.61</td>
</tr>
<tr>
<td><strong>Bora 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>-0.118</td>
<td>0.140</td>
<td>0.58</td>
</tr>
<tr>
<td>COAWST</td>
<td>-0.083</td>
<td>0.121</td>
<td>0.50</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>-0.115</td>
<td>0.137</td>
<td>0.56</td>
</tr>
<tr>
<td><strong>Bora 3</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>0.002</td>
<td>0.088</td>
<td>0.63</td>
</tr>
<tr>
<td>COAWST</td>
<td>-0.006</td>
<td>0.085</td>
<td>0.60</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>0.006</td>
<td>0.095</td>
<td>0.67</td>
</tr>
<tr>
<td><strong>Bora 4</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>-0.073</td>
<td>0.088</td>
<td>0.46</td>
</tr>
<tr>
<td>COAWST</td>
<td>-0.069</td>
<td>0.102</td>
<td>0.53</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>-0.067</td>
<td>0.083</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Bora 5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>0.121</td>
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</tr>
<tr>
<td>COAWST</td>
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<td>0.77</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>0.082</td>
<td>0.171</td>
<td>1.33</td>
</tr>
<tr>
<td><strong>Bora 6</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>0.069</td>
<td>0.111</td>
<td>0.70</td>
</tr>
<tr>
<td>COAWST</td>
<td>-0.038</td>
<td>0.091</td>
<td>0.57</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>0.0778</td>
<td>0.121</td>
<td>0.76</td>
</tr>
<tr>
<td><strong>Bora 7</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIKE-ref</td>
<td>-0.006</td>
<td>0.078</td>
<td>0.35</td>
</tr>
<tr>
<td>COAWST</td>
<td>0.0005</td>
<td>0.074</td>
<td>0.33</td>
</tr>
<tr>
<td>MIKE-base</td>
<td>0.036</td>
<td>0.098</td>
<td>0.44</td>
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</tbody>
</table>

![Fig. 4. Time series of observed (black) and modelled bottom (first panel) and surface (second panel) temperature at “Acqua Alta” location. Shading areas show the seven Bora events. (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)](image-url)
presenting largest wind speed, long duration, the lowest Po river discharge, and small bottom temperature variations, suggesting a wind dominated conditions. The Bora event 5, which has the biggest error and lowest correlations, is the shortest event with the lowest wind speed and the biggest river discharge, suggesting a much less wind-controlled conditions.

Fig. 5. Time series of observed and modelled surface (left column) and bottom (right column) current speed. The studied period (1 year) has been divided into 3 sub-periods which are shown in each row. Shading areas show the seven Bora events. (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)

Table 5
Models statistics for surface current speed.

<table>
<thead>
<tr>
<th></th>
<th>Surface speed</th>
<th>Bias (m/s)</th>
<th>RMSE (m/s)</th>
<th>SI</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
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<td>0.13</td>
<td>0.76</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>COAWST</td>
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<td>0.13</td>
<td>0.78</td>
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</tr>
<tr>
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<td>MIKE-ref</td>
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</tr>
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<td>0.52</td>
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<td>0.13</td>
<td>0.54</td>
<td>0.10</td>
</tr>
<tr>
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<td>0.60</td>
<td>0.34</td>
</tr>
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<td></td>
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<td>0.08</td>
<td>0.50</td>
<td>0.45</td>
</tr>
<tr>
<td>Bora 4</td>
<td>MIKE-ref</td>
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<td>0.62</td>
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<tr>
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<td>COAWST</td>
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<td>0.65</td>
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<tr>
<td>Bora 5</td>
<td>MIKE-ref</td>
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<td>0.31</td>
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</tr>
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<td></td>
<td>COAWST</td>
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<td>0.14</td>
<td>0.84</td>
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</tr>
<tr>
<td>Bora 6</td>
<td>MIKE-ref</td>
<td>0.08</td>
<td>0.15</td>
<td>0.84</td>
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<tr>
<td></td>
<td>COAWST</td>
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<td>0.12</td>
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<td>0.16</td>
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<tr>
<td>Bora 7</td>
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<tr>
<td></td>
<td>COAWST</td>
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<td>0.14</td>
<td>0.56</td>
<td>0.79</td>
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</table>

Table 6
Models statistics for bottom current speed.

<table>
<thead>
<tr>
<th></th>
<th>Bottom speed</th>
<th>Bias (m/s)</th>
<th>RMSE (m/s)</th>
<th>SI</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>MIKE-ref</td>
<td>−0.02</td>
<td>0.08</td>
<td>0.77</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>COAWST</td>
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<td>0.07</td>
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</tr>
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<td>0.79</td>
</tr>
<tr>
<td>Bora 2</td>
<td>MIKE-ref</td>
<td>−0.09</td>
<td>0.11</td>
<td>0.61</td>
<td>0.39</td>
</tr>
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<td></td>
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<td>0.52</td>
<td>0.31</td>
</tr>
<tr>
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<td>0.11</td>
<td>1.34</td>
<td>0.10</td>
</tr>
<tr>
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<td>0.08</td>
<td>1.00</td>
<td>−0.10</td>
</tr>
<tr>
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</tr>
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<td>0.73</td>
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</tr>
<tr>
<td>Bora 5</td>
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</tr>
<tr>
<td></td>
<td>COAWST</td>
<td>−0.02</td>
<td>0.09</td>
<td>0.84</td>
<td>0.35</td>
</tr>
<tr>
<td>Bora 6</td>
<td>MIKE-ref</td>
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<td>0.13</td>
<td>1.15</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>COAWST</td>
<td>0.002</td>
<td>0.07</td>
<td>0.63</td>
<td>0.38</td>
</tr>
<tr>
<td>Bora 7</td>
<td>MIKE-ref</td>
<td>0.01</td>
<td>0.07</td>
<td>0.41</td>
<td>0.78</td>
</tr>
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<td></td>
<td>COAWST</td>
<td>−0.008</td>
<td>0.07</td>
<td>0.45</td>
<td>0.55</td>
</tr>
</tbody>
</table>
4.4. Surface waves

Wind waves have been simulated with both MIKE 21 SW and SWAN in order to take their effect through radiation stresses into account when using MIKE 3/21 (MIKEbyDHI, 2012b; Sørensen et al., 2004) and as a Vortex Force (Uchiyama et al., 2010; Kumar et al., 2012) as a source of momentum when using COAWST. Fig. 6 shows the time series and scatter plot of significant wave height \( (H_{\text{m0}}) \) for both models. It can be observed that, in general terms, both models behave similarly as also shown by the statistics in Table 7. MIKE 21 SW has a slightly larger scatter, but results from COAWST seem to underestimate the largest waves as also seen in the cumulative distribution plot. The high correlation between wind and wave data, certify however the wave models follow the general patterns of winds, predicting accurately the times of the wave events.

Wave modelling in short fetch and sharp wind gradients has been shown to be less accurate than offshore predictions (Cavaleri and Bertotti, 1997, 2004). The use of high resolution wind and wave models in the present work has allowed improved model skills showing statistics similar or better than previous work at the same location (Ardhuin et al., 2007; Cavaleri, 2000). Because one of the objectives of the paper is to assess the effect of waves on the currents and not the improvement of the wave modelling itself, the presented results by both MIKE 21 SW and COAWST are considered to be appropriate for their use in sensitivity analysis.

5. Discussions

5.1. Sources of currents and shear

Fig. 7 shows the MIKE-ref spatial distribution of depth-averaged velocity (panel a), significant wave height (panel b), wave-induced currents (panel c) at December 26, 2010 10:00, during the 5th Bora event. Depth-averaged currents near the northern coast are enhanced by the Bora, reaching 0.5 m/s and being part of a cyclonic circulation in the NA. Significant wave height reaches more than 3 m in the NA with E and NE (coming from) directions. The wave-induced circulation defined as the difference between the run with waves (MIKE-D) and MIKE-ref is small in deep areas, order of 0.01 m/s, but can reach 0.1 m/s at some coastal locations in agreement with the wave direction and coastline orientation. However, in more offshore areas, the wave-induced currents behave in an interesting way: although very small, they show a circulation which is opposite to the depth-averaged velocity as a result of the overall balance.

Fig. 7 (panels d, e and f) shows the current speed at surface, mid-water column and bottom respectively for a small region in the northern Adriatic with MIKE-ref. The figures show the vertical variation in terms of velocity and direction. While the jet at the northern coast is relatively homogeneous due to the strong Bora influence producing currents from NE to SW at all water depths, this is not the case for other southern parts, where currents present stronger directional vertical variations. The effect of the wind producing high currents is very localised at the NE coast, and “Acqua Alta” is slightly out of such area for that period.

Fig. 8 shows the time series for depth-averaged speed and the different MIKE 3 model runs as described in Table 2. It is clear that when excluding atmospheric forcing the model has too little energy (MIKE-B), conditions which rarely are present in the observations. Including wind forcing (MIKE-C) significantly increases the depth-averaged speeds and the model reproduces in some cases the strong current events produced by Bora winds (1st, 3rd, 4th, 5th, 6th and 7th event). The differences in processes accounted for in MIKE-C to MIKE-H only produce minor effects with some localised larger effects. Among the runs with wind forcing, the simulation without heat transfer (MIKE-C) has the largest impact on the current, for example in the Bora events 3 and 6, as well as during some calm conditions such as April 17–27.
Fig. 7. Spatial distribution during the Bora event no. 5. of depth-averaged current (a), significant wave height (b), wave induced currents obtained by the difference of MIKE-D minus MIKE-Ref (c). Vectors at a, b and c have been interpolated to a regular grid for visibility purposes. A close up into the NE part of the Adriatic with vectors at centre of each triangular element are shown at (d) surface current, (e) mid-water column (5th sigma level), and (f) bottom current. (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)

Fig. 8. Time series of depth-averaged speed for MIKE 21/3 runs as described in Table 2. Shading areas show the seven Bora events. The studied period (1 year) has been divided in 3 sub-periods which are shown in each row. (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)
could be explained partially by the considerable underestimation of current speeds. Typically modelled surface currents show a higher speed respectively for the numerical MIKE 3/21 experiment (Fig. 3), which suggests that the higher spatial resolution, the wind–ocean momentum transfer in COAWST may have a significant impact on the ocean modelling in the NA. The adopted initial conditions might be a source of model differences for this period not directly controlled by wind. MIKE-ref shows a more direct relation to the local wind speed at “Acqua Alta”, with correlations of 0.60, 0.56 and 0.53 for depth-averaged, surface and bottom speed respectively while COAWST has a correlation of 0.34, 0.31 and 0.42.

There are some energetic current events occurring during relatively calm wind conditions e.g. January 7, 2011 and around the January 27, 2011 which do not seem to be easily related to atmospheric origin. However the runs to test current sensitivity to river discharge (MIKE-F) showed little variability, which points toward errors in the location of mesoscale features. The area has features with large spatial gradients, and modelled depth-averaged currents in the areas around the observations show a variability of intensity of about 50% within 5 km from observations. Similarly, spatial gradients in surface and bottom current velocities (50%) are observed in model results. Thus, a relatively smaller error in position and propagation of eddies would significantly change the validation results.

The inclusion of wave radiation stress (MIKE-D) did not have a significant impact on depth-averaged speeds at the study location, at least with the spatial resolution used; this however is not the case in more nearshore locations. Fig. 7c shows a map of wave-induced currents (by 2D radiation stress) at the northern Adriatic showing some intensification near the coast. At the same time, recent results seem to indicate how wave effects may lead to better explaining small scale features in temperature blobs or suspended sediment patches (Sclavo et al., 2013). The COAWST without the wave effects (not shown) produced a decrease of up to 0.05 m/s in depth-averaged speed at the “Acqua Alta” location. This difference, together with the difference with the MIKE 3/21 results, and considering that the wind is a main source of currents, seems to indicate that parameters related to wind-ocean transfer are indeed critical for a high-fidelity modelling of this area. In the COAWST system not only the wave induced currents are considered but also a surface roughness that affects wind momentum transfer, while in MIKE 3/21 a wind stress based on a drag formulation was used. Near the coast wave-induced currents are mainly affected by radiation stress processes while at more offshore locations wind–wave interactions and stokes drift may play a more important role. For example, Arduinu et al. (2007) used radar measurements to estimate the Stokes drift current showing that typically it is between 0.6% and 1.3% of the wind speed (the direct wind–induced current is about 1–1.8% the wind speed). This process was not included in the MIKE runs but was in the COAWST system.

Figs. 9 and 10 show the time series for surface and bottom current speed respectively for the numerical MIKE 3/21 experiments. Typically modelled surface currents show a higher correlation with depth-averaged speed (order of 0.94) while bottom currents have a correlation of the order of 0.85. This indicates the strong dominance of wind forcing in the water column within the model. Thus, similar patterns are observed in the surface and bottom velocities and depth-averaged speed. For surface currents, the tidal and baroclinic effects (MIKE-A and MIKE-B) do not contribute greatly to currents. Wind is the main source for surface currents and when wind is present, changes in temperature and heat variables can induce changes in surface velocities as observed for example in the Bora events 2, 3 and 5 and particularly on the 6 when a large deviation of model behaviour is observed. Similarly, for bottom currents the wind represents the largest contributing factor, but the effect of temperature and heat exchange is weaker. Currents near the bed are typically smaller than near the surface and thus differences between models runs are also smaller. From the runs which include wind forcing, the run without heat transfer is the one producing the largest difference among the runs, more clearly seen in the Bora events. As for the depth-averaged speed, the consideration of a high-order numerical scheme (MIKE-base) and observed river discharge (MIKE-H) produced only slight and punctual improvements in the time series of bottom and surface speed.

Considering the effect of waves on current speeds through the inclusion of wave radiation stress does not seem to contribute significantly to the velocity modelling at the location of measurements, producing changes of only a couple of centimetres per second at specific times during the storm events.

Using MIKE 3/21 during calm conditions, a meso-scale clockwise circulation is observed (not shown) in the northern Adriatic which interacts with an anticlockwise circulation in the southern part (double NA gyre). This is in agreement with the seasonal circulation during spring and summer as shown in next section. The lack of heat transfer (e.g. MIKE-F) reduces velocities in the centre of the cyclonic gyre, while the high order scheme (MIKE-base) increases velocities and produce a more heterogeneous field which could be a better representation of currents in the area. The change in the river outflow from climatological to observed values (MIKE-H) only produces small localised changes in the nearby areas of the Po delta.

During the wind events, strong circulation vortices are observed (e.g. Fig. 7a). The calm condition (clockwise) circulation is inverted, and a strong flow along the northern coast is observable. These features are relevant to determine the seasonal and annual patterns of circulation. Compared to the calm scenarios, the meso-scale gyres become smaller and more intense. An intense E–W stream flow in the northern Adriatic is produced (Fig. 7a and d); the different runs change the width of this stream jet. This feature confirms the strong spatial gradients that occur in the area around measurement location under these kinds of conditions and therefore the spatial resolution and bathymetric data could be an important source of error. The importance of the spatial resolution is also highlighted when comparing the results of MIKE 3/21 and COAWST: the latter, with higher resolution, is able to represent smaller current features (e.g. meanders and small eddies) especially when present in calm conditions. During storms, both systems simulate the same features but the coastal flow in the northern Adriatic seems narrower in COAWST, which is also possibly due to a better representation of the coastal bathymetric features.

In an area like the northern Adriatic, with a water depth of less than 40 m, sporadic intense wind events, a significant horizontal gradient imposed by the river outflow and the generation of dense water, it is not surprising that there appear sheared flows. During intense events at the coast, shear is at its minimum, as flow is predominantly wind-dominated with only some shear due to boundary layers. However, at more offshore locations wind, topographic and density controlled flows at different levels in the water column produce a more heterogeneous vertical distribution.
Fig. 9. Surface current speed for MIKE runs as described in Table 2. Shading areas show the seven Bora events. The studied period (1 year) has been divided in 3 sub-periods which are shown in each row. (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)

Fig. 10. Bottom current speed for MIKE runs as described in Table 2. Grey areas show the seven Bora events. The studied period (1 year) has been divided in 3 sub-periods which are shown in each row. (For interpretation of references to color in this figure, the reader is referred to the web version of this article.)
5.2. Seasonal residual currents

Fig. 11 shows the annual and the seasonal residual depth-averaged currents (defined as time-averaged for the different seasons). The annual mean circulation (Fig. 11a) shows a cyclonic and anti-cyclonic structure at the left and right of the northern Adriatic, with velocities of the order of 0.07 m/s. The effect of the Po river is observable in the annual residual, intensifying the SE currents locally (up to 20 km offshore). The seasonal circulation shows that during spring and summer (Fig. 11b and c) an anti-cyclonic feature predominates in the NA, which coincides with the season of no Bora events. The Po plume effect is also observable, although weaker than in the annual residual. During autumn and winter (Fig. 11d and e) the pattern reverses to become cyclonic, with more intense currents than during spring and summer. The effect of the Po river is also stronger, in agreement with the larger discharges during such seasons.

The seasonal wind induced residual currents (obtained by the difference of MIKE-C and MIKE-B, not shown) presented similar features as MIKE-ref, with an anticyclonic circulation in the northern part with smaller velocities (0.02 m/s), but reaching 0.06 m/s near the coast. Spring and summer wind induced circulation north from the Po river is in the opposite direction to the MIKE-ref, while in autumn and winter, with the presence of persistent Bora events, the wind induced circulation is dominant with coastal currents of about 0.09 m/s. Radiation stress induced currents (obtained by the difference of MIKE-D and MIKE-ref, not shown) were generally very weak, especially during spring and summer seasons. The autumn and winter radiation stress residual presented coastal currents of about 0.01 m/s. Because of the short fetches of the Adriatic and the sporadic nature of waves, wave radiation stress is not a first order source of currents, although they could be significant at coastal areas during storms (e.g. Fig. 7c).
5.3. Spectral, statistical and SVD analysis of time series

In order to study the temporal and vertical structure of current, a spectral analysis and a Singular Value Decomposition for coupled fields (SVD, Bjornsson and Venegas, 1997) was performed. Fig. 12 (top) shows the power spectra from observations and models for depth-averaged speed at “Acqua Alta”. Fig. 12 (bottom) shows the power spectra for observed and modelled surface currents and for observed and modelled wind speed. Wind spectra from both observations and the COSMO-I7 model present a peak around the diurnal frequencies which is associated to the land-sea breezes. The observed wind spectra also present a slight peak near semi-diurnal frequencies which may be due to the asymmetry of sea and land breezes combined with an atmospheric tidal signal (e.g. Orlić et al., 1988). This peak is weaker in the modelled wind which indicates model error in such breeze asymmetry. The depth-averaged speed observations also show a strong peak in diurnal frequencies as a direct response to the wind and tidal forcing which is present in the models but slightly weaker than observed. Both observations and models also show a strong signal in the semi-diurnal frequencies. For the observed surface speed, spectra is dominated by diurnal and semi-diurnal frequencies with no clear indication of an energy peak around the inertial frequency although some other work (e.g. Orlić, 1987) has reported it from relatively short periods (few days) and weak signals (10–30% of variance). However, both MIKE-ref and COAWST show energy at such frequency (see MIKE-ref surface speed) together with diurnal and semi-diurnal energy. A co-spectrum of wind and currents (not shown) confirmed the strong coupling at diurnal and semi-diurnal frequencies found in the observations. Fig. 12 (top panel) also shows spectra for some of the MIKE runs described in Table 2. Spectra from MIKE-A show the energy coming from density gradients only, some increase of energy is appreciable just above the inertial band, however energy is much lower compared with the tidal run (MIKE-B) which shows the clear diurnal and semi-diurnal peaks. Fig. 12 (top panel) also shows a spectra from MIKE-ref at 45.1878° N 13.0281° E, this is a location in a deeper, more offshore part on the northern Adriatic and correspond to the location VR4 in Book et al. (2009,2007), the spectra shows that the model is capable of represent the observations at this location as it agrees with Book et al. (2007) work, showing two more clear diurnal and semi-diurnal peaks probably controlled mainly by tides. However, at “Acqua Alta”, the model produces somewhat weaker spectral peaks outlining the model limitation at this location. This could be due to bathymetry resolution, which is a critical parameter under such coastal bathymetry-controlled locations.

ADCP data show a significant current reversal in the water column; indeed for about 30% of observations, differences of more than 90° in the current direction between surface and bottom currents were detected, this is in agreement with the findings of Cosoli et al. (2008). In shallow locations typical ocean Ekman spirals may overlap with the bottom layer. Because of the relatively shallow characteristics of the northern Adriatic and its complicated topographic features, the Ekman layer and bottom layer can interact, the wind induced-flow becomes controlled by wind stress and bottom friction; and the wind induced current tends to align with the wind. The only clear periods with no current reversal were the strong Bora events affecting the whole water column and hence leading to more barotropic behaviour. The Bora events are mainly wind controlled, thus having a unidirectional profile. Current reversal within the water column may be an indication of combined effects of density currents, light winds and topographic control. The cumulative distribution (Fig. 13) of the observed currents show that, for about 70% of the time, velocity components (u and v) are negative, about 80% of the time components are lower than 0.2 m/s and the largest velocities occur more frequently in the SW direction. Models on the other hand simulate a more symmetric distribution between positive and negative components of the current.

Cosoli et al. (2008) found, within a summer period (mild wind conditions), current reversals between surface and bottom currents occurring mostly when the wind showed only daily variability. In the present study a significant current reversal was found (which is attributed to the same processes) and, as the time series cover a longer period, the calm periods represent a significant part of the time series. At first order, the models also present such current reversal, observed in the first mode of the SVD analysis (Fig. 14). However, although SVD analysis of both model time series produced a similar first mode explaining around 80% of variability, the first mode of the observation is around 50%. This highlights the more “simple” water column structure simulated by the models as one SVD mode is able to represent a large percentage of the variance. Cosoli et al. (2008) found that the first EOF mode (barotropic) explained 78% of total variance, while in the present work the first mode of the coupled ADCP data (Fig. 14) represent less (~ 50%). This disagreement between both observational SVD can be explained by the length of the present study period covering a significantly longer time series and thus having more variability and features than the one in Cosoli et al. (2008)
work. Their second mode (∼ 10%) presented a baroclinic structure explained by the water column response to wind sea breeze. Here the second mode from observations correspond to about 20% while models produce, although with the right shape, a second mode that represents only about 10%. The correct simulation of the profile modes indicates that models are able to reproduce main current structure in long term patterns but still missing some of the time varying components.

5.4. Sources of model errors

The numerical methods, spatial discretisation, and physical processes parameterisations included in the ocean models can limit their performance. Firstly, the models used in this work are hydrostatic, this approximation is reasonable at large scales, however as downscaling happens non-hydrostatic effects may appear (processes not in hydrostatic balance, see Marshall et al., 1997). The northern Adriatic, due to small area and complex orography, wind and rivers contribution, and presence of dense water formation site (Vilibić and Nastjenjka, 2005) may be affected by this approximation, and thus it would be ideal to consider non-hydrostatic models. At the same time, their benefit compared to hydrostatic models is difficult to outline as validations with detailed/high resolution observations are very limited. There has also been some model comparison (hydrostatic–non-hydrostatic) for other regions (e.g. Mahadevan, 2006) indicating no significant benefit for some high resolution processes such as vertical motion at ocean fronts. However, full comparison of such models should be done in order to identify limitations and benefits of their approaches.

Spatial discretisation (horizontal and vertical) and related parameterizations are always a limiting factor when modelling small scale features. The bathymetry should be considered continuously in order to resolve topographically-influenced flows. This is particularly important for the Adriatic as shown by several authors (e.g. Malačič et al., 2012 and Vilibić and Nastjenjka (2005)). MIKE 3 was used in the present work with 10 sigma-levels up to 40 m water depth and 10 z-levels underneath, while COAWST used 20 sigma-levels. The use of z-levels in MIKE 3 might potentially affect the results, although no systematic pattern of velocities near the bottom was observed between both models at “Acqua Alta” platform. A cut-cell approach (Ingram et al., 2003; Lock et al., 2012) should be considered in order to improve z-level results near the bottom. Another aspect for both models in the present application is the sigma layers horizontal pressure gradient errors as a function of slope and stratification; in most of the regular bottom of the NA this is not probably a problem, but it can surely affect regions where bathymetry changes abruptly, like in the eastern sector of the NA.

Model forcing may be another significant source of errors. Initial (IC) and boundary conditions (BC) in MIKE 3 come from a coarser Mediterranean model and intrinsically carry along errors and under/overestimations to the higher resolution model. The time resolution of baroclinic forcing IC and BC is daily and RMSE for temperatures of about 0.3–1 °C have been reported, and for salinity of about 0.05–0.3 PSU. This imposes some uncertainties especially during times when dynamics are not dominated by wind. Atmospheric forcing is another source of error particularly for the Adriatic where the difficulty in modelling it has been shown by many studies (Signell et al., 2005) and where several
high resolution attempts have been made. This is also confirmed in the wave modelling efforts of the area where empirical wind factors have been used to improve model results (Cavaleri and Bertotti, 1997). This is also associated with the uncertainties of momentum transfer between atmosphere and ocean which plays a critical role for wind-induced currents and mixing.

6. Concluding remarks

Despite recent improvements in the field, modelling small scale oceanographic features still represents a challenge for ocean modelling. In the present work, high resolution 3D modelling was performed in the northern Adriatic Sea, complemented with observations of wind, currents and waves at “Acqua Alta” platform position. By performing a 1-year long simulation and data analysis it was shown that

- Although prediction of tides is a critical parameter for the Venice lagoon management, tides themselves are not a dominant source of currents in the NA “Acqua Alta” location.
- Wind observations at “Acqua Alta” showed several Bora events. Observed wind spectra was dominated by energy in diurnal, with a smaller contribution in the semidiurnal frequencies.
- Local mesoscale wind model results show good skill when compared with observations. However, in the spectral domain, a weaker diurnal and semidiurnal peaks were found.
- The current at the Acqua Alta location is mainly controlled by diurnal and semi diurnal energy as a combination of tidal and wind forcing. Currents were strongly correlated with winds during Bora events.
- During strong wind events current profiles are unidirectional, while calm conditions can produce significant current reversal when comparing bottom and surface currents.
- Heat transfer is a critical process to simulate seasonal variability in ocean temperature and currents. A run without heat transfer produced unrealistic currents during several times.
- Wave-induced currents through radiation stress was found not to be significant at the region represented by the measurement location. However, the more comprehensive inclusion of wave effects on currents in the Vortex Formalism and wave induced surface roughness can produce some punctual noticeable changes in currents.
- Due to the strong dependence of currents on wind, any error/modification of the wind and wind-ocean transfer of momentum may have a strong impact in ocean modelling.
- Because of the spatial and temporal scales and gradients of processes occurring in the NA, we suggest that the ocean modelling efforts may explore high spatial resolution (< 0.5 km) in order to be able to simulate smaller spatial features.
- Seasonal currents at the northern Adriatic showed to have a tendency to an anticyclonic circulation during spring and summer, periods with light winds. While seasonal circulation reversed during autumn and winter, when persistent Bora wind events are present.

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