Ocean Modelling 72 (2013) 253–263

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Impact of Levantine Intermediate Water on the interannual variability of the Adriatic Sea based on simulations with a fine resolution ocean model

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ARTICLE INFO

Article history:
Received 18 May 2013
Received in revised form 27 September 2013
Accepted 9 October 2013
Available online 21 October 2013

Keywords:
Adriatic Sea
Ocean model
Open boundary
LIW
Dense water

ABSTRACT

A high resolution set-up of a z-level ocean model has been implemented in the Adriatic Sea to investigate the impact of the Levantine Intermediate Water on the Adriatic Sea circulation and dense water formation. The period under investigation starts at the beginning of 2000 and ends at the end 2007. A twin experiment is performed in which the southern boundary conditions are derived from two different operational systems in the Mediterranean Sea. It is shown that the quantity and the characteristics of the Levantine Intermediate Water in the Mediterranean model introduced at the southern boundary may significantly impact the amount of the dense water formed in the Southern Adriatic and the accuracy of the model simulation even in the Northern Adriatic.

1. Introduction

The Adriatic Sea located at the northern part of the Central Mediterranean, between the Italian peninsula and the Balkans, has highly variable depth varying from about 30 m in the Northern Adriatic to 1200 m in the Southern Adriatic (Fig. 1). It is connected to the Mediterranean Sea through the Otranto Strait. The basin is characterized by large seasonal and spatial variability of the atmospheric forcing and rivers discharge. The dense water generated in the Adriatic outflows through the lower layer of the Otranto Strait (Pollak, 1951). It is a significant source of dense water in the Eastern Mediterranean, and may affect the deep layer circulation characteristics of the Mediterranean (Roether and Schlitzer, 1991; Schlitzer et al., 1991).

In the past, the Adriatic Sea has been investigated by using numerical models with different configurations. They differed in their ability to describe the known oceanographic features of the Adriatic Sea. For example, Zavatarelli et al. (2002) have implemented the Princeton Ocean Model (POM, Blumberg and Mellor, 1987) with a sigma coordinate. The POM model had a variable horizontal resolution ranging from 5 km in the Northern Adriatic to 12 km in the southern part of the model domain. The limitations in the models ability to simulate some oceanographic processes were mainly attributed to the coarse resolution of the climatological atmospheric forcing. Oddo et al. (2005) used a higher resolution configuration of the POM model to study Adriatic circulation between 2000 and 2002. By comparing model simulation with the observations Oddo et al. (2005) found that the model had a limited ability to simulate the spreading of salty waters of Levantine origin that enter the Adriatic from the Ionian Sea. Oddo and Guarnieri (2011) applied the POM model at an even higher resolution and conducted an interannual simulation for the period 2000–2008. The results showed that the temperature and the salinity of the Northern Adriatic dense water vary considerably during the investigated period. Furthermore, they found that the presence of the sufficiently salty water of Mediterranean origin entering the Adriatic at the southern boundary is the key factor for determining the dense water processes in the southern Adriatic Sea. In the period from 1991 to 1997, Dobricic (2002) applied a coupled ocean–atmosphere limited-area model in the Adriatic Sea with z-levels in the ocean. Janekovic et al. (2010) implemented the Regional Ocean Modeling System (ROMS) model to hindcast the surface temperature and salinity of the basin for the 2008, showing a high correlation between

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http://dx.doi.org/10.1016/j.ocemod.2013.10.002

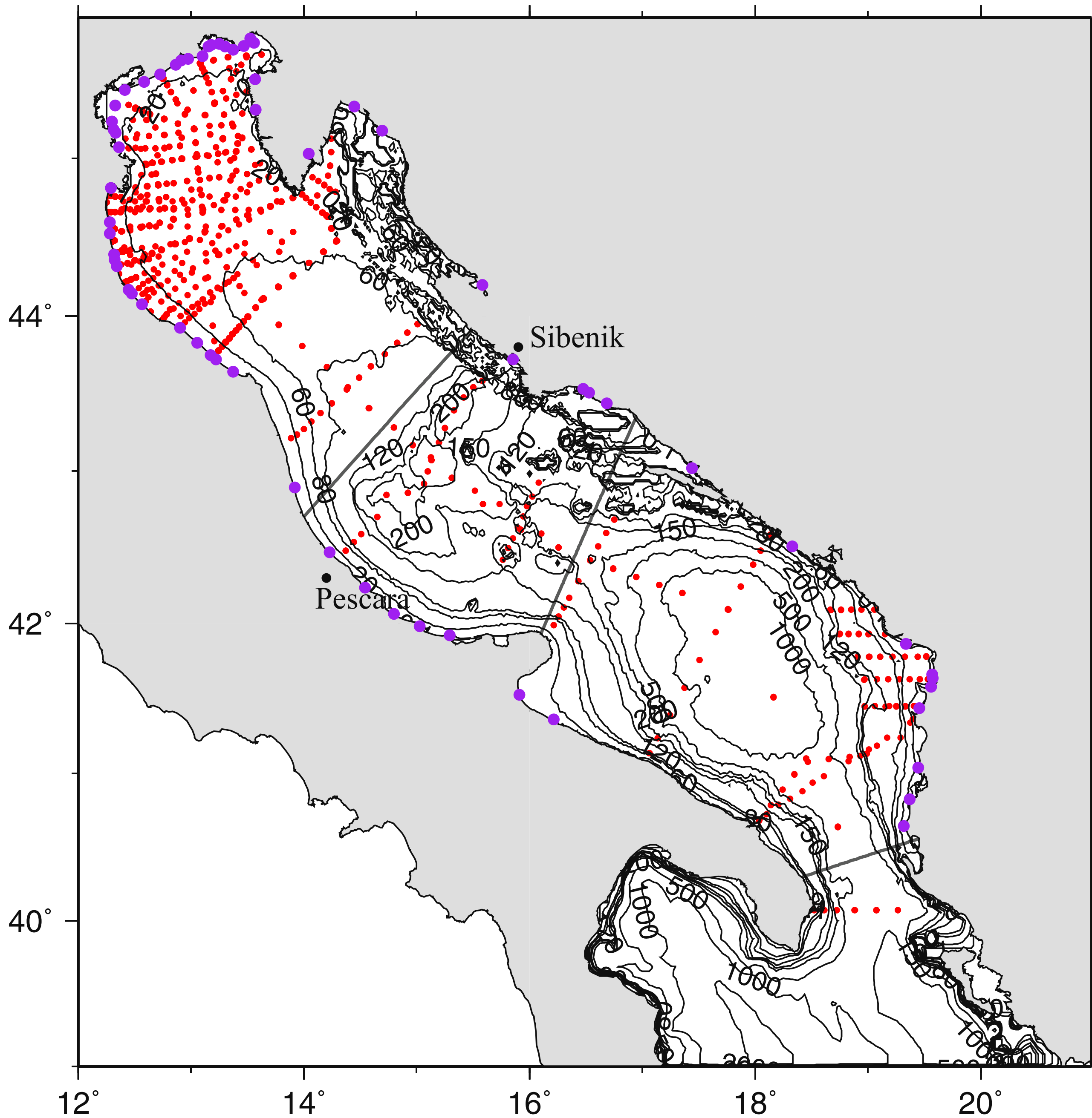

Fig. 1. Bottom topography of the model, the three sub-basins are shown in the figure. The red dots shows the locations of the CTD measurements. The purple shows the model river positions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

modelled and satellite SST data. Cushman-Roisin et al. (2007) setup DieCAST, a z-level coordinate ocean model, in the Adriatic Sea, with a relatively coarse vertical resolution (i.e., 20 unevenly spaced levels). The model reproduced well some meso-scale features observed in the satellite images. Mantziafou and Lascaratos (2008) integrated the POM model for the period of 1979–1999 to investigate the importance of the interannually variable open boundary characteristics on the dense water formation in the Southern Adriatic. Guarnieri et al. (2013) showed the impact of tides specified at the open boundary in the circulation, mixing and stratification structures of the Adriatic Sea by using nested baroclinic numerical ocean model.

In this study, we discretized the model in the vertical direction by levels with constant depth. This approach differs from the most commonly used sigma vertical coordinate. In order to resolve the vertical structure and the bottom flow in the shallow Northern Adriatic Sea, we apply a large number of horizontal layers with a high resolution in the top of the water column. In the study, first we will describe our model set-up. We will further perform an 8 years long model simulation and compare the model simulated fields with observations. We will also show that a variation in the quantity and the characteristics of the Levantine Intermediate Water (LIW) at the southern open boundary may have a significant impact on the accuracy of the simulation and on the amount of simulated dense water formed in the Adriatic Sea. In Section 2 we will give a description of the model set-up, while the comparison with observations and the impact of specification of southern open lateral boundary conditions will be discussed in Section 3. Conclusion will be given in Section 4.

2. Model features and set-up

2.1. Numerical model set-up

NEMO (Nucleus for European Modelling of the Ocean) is a free-surface, finite difference, primitive equation model (Madec, 2008). The model set-up in the Adriatic Sea has a constant grid resolution of 1/48° along the longitudinal and latitudinal directions that approximately corresponds to 1.8–2.3 km respectively. In the vertical direction, it is configured with 120 unevenly spaced horizontal z-levels. The bottom topography is represented using the partial cell method. Vertical grid spacing is 1 m in the top 60 m, then increases to 9 m at 100 m depth and further to 50 m at the deepest point in the Adriatic Sea. The largest spacing of 70 m occurs in the Ionian Sea, at the deepest point (2800 m). The very high vertical resolution and a large number of layers are unique feature of this model. Fig. 2 shows the vertical layers of the NEMO Adriatic Sea model along a transect starting from north (left) to south (right). The high resolution in the top layers may resolve well the bottom flow in the Northern Adriatic. It also facilitates the simulation of the vertical mixing during the high stratification in summer. The use of z-coordinate system with the high resolution may further improve the simulation of the spreading of water masses without excessive mixing. It is often claimed that the shallow water processes are better represented by sigma vertical coordinates (e.g., Mellor et al., 2002). However, the combination of high vertical resolution and the partial cell implementation in z-coordinate models could significantly improve the performance in some applications (e.g., Adcroft et al., 1997).

Initial conditions for temperature and salinity were derived from the SeaDataNet climatology. The horizontal resolution of the climatology is 0.25°. Although the climatology has a coarse horizontal and vertical resolution, it was found that a few months after the start of the model integration fine scale structures developed (not shown).

Model bathymetry is based on 7.5″ regional bathymetry (M. Rixen, NURC, http://mseas.mit.edu/download/phaley/Adriatic/). This bathymetry was available only north from 40 °N. It was extended to the south by combining it with the Mediterranean Forecasting System (MFS) 1/16° operational model bathymetry developed for the MFS basin scale model (Tonani et al., 2008; Oddo et al., 2009).

The horizontal eddy diffusivity for tracers and the horizontal viscosity coefficient for the dynamics use bilaplacian operator. The vertical mixing is parametrized by the Turbulent Kinetic Energy (TKE) scheme embedded in the NEMO model by Blanke and Delecluse (1993). The model applies the implicit scheme for the adjustment of the sea level (Madec, 2008). Although the fast barotropic oscillations are significantly damped, in the model, we assume that it is adequate for the simulation of the interaction between the baroclinic and barotropic processes.

2.2. Rivers, atmospheric forcing and lateral open boundary conditions

The physical characteristics of the Adriatic Sea are strongly influenced by river discharge (Kourafalou, 1999). The most significant contribution is given by the Po River. The low-salinity water originating from the Po River flows along the western coast of the Adriatic Sea forming the permanent Western Adriatic Current (WAC).

The river discharge has a large seasonal and monthly variability. Therefore, a proper representation of the rivers is important for simulating physical processes in the Adriatic Sea. The model uses monthly climatological values of river discharge for all rivers

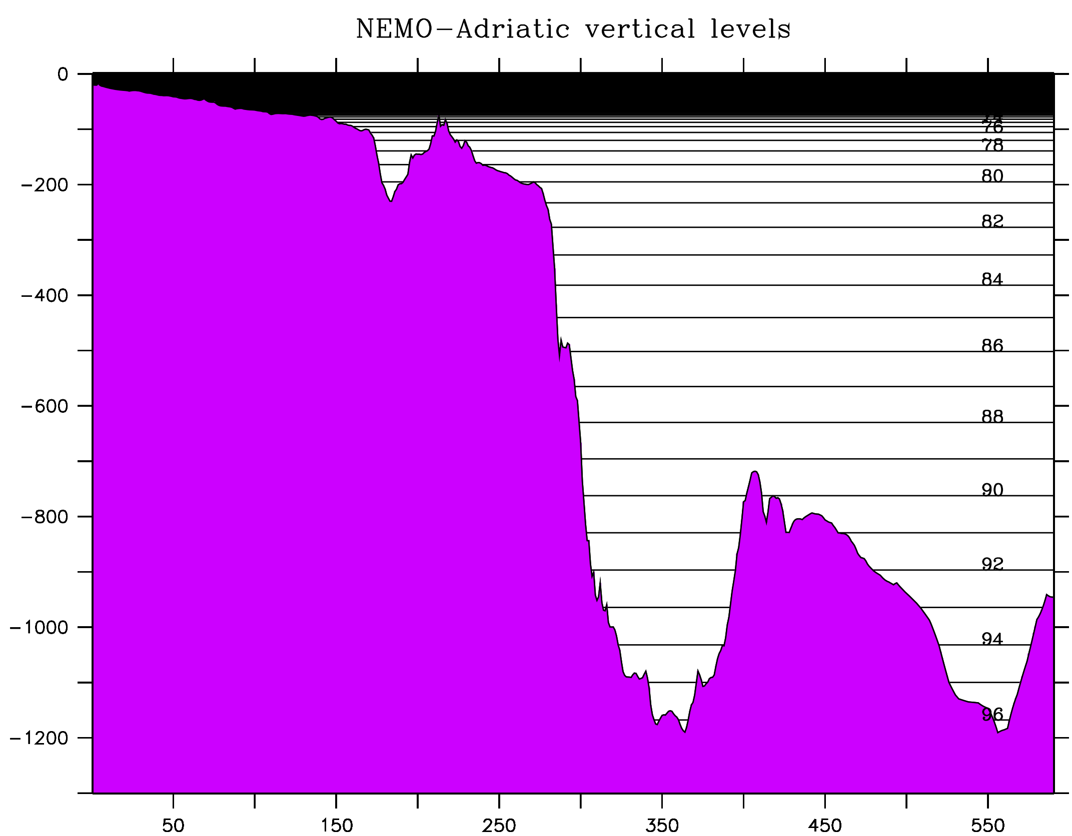

Fig. 2. Vertical layers of the model along a transect starting from north (left) to south (right). The depth is expressed in meters and the horizontal axes is the number of model points along the transect.

except for the Po River, for which daily values have been used. The river discharge values in the rest of the Adriatic Sea were obtained by combining the monthly climatological database by Raicich (1994), and by Pasaric (2004). Special treatment of the river discharge has been implemented by increasing the diffusion at the upper 10 m at the river mouth. In total there are 62 rivers. The positions of the rivers are shown in Fig. 1 as purple dots along the coast.

Atmospheric forcing fields, except for precipitation, were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim data set (Dee et al., 2011). The precipitation was obtained from the Merged Analysis of Precipitation (CMAP) observational data set (Xie and Arkin, 1997). The ERA-Interim atmospheric forcing fields are available at the frequency of 6 h and the horizontal resolution of 0.25°. The monthly mean CMAP data set has the horizontal resolution of 2.5°.

The model set-up has one open boundary communicating with the Mediterranean Sea positioned south of the Otranto Strait (see Fig. 1). The boundary conditions for temperature, salinity, sea surface height, zonal and meridional currents are provided daily from outer basin scale MFS Mediterranean Model. The model uses the generalized Flather lateral boundary condition at the open boundary (Oddo et al., 2008). The conservation of transport at the open boundary is ensured after interpolating the coarse resolution open boundary data by following the procedure in Oddo et al. (2009).

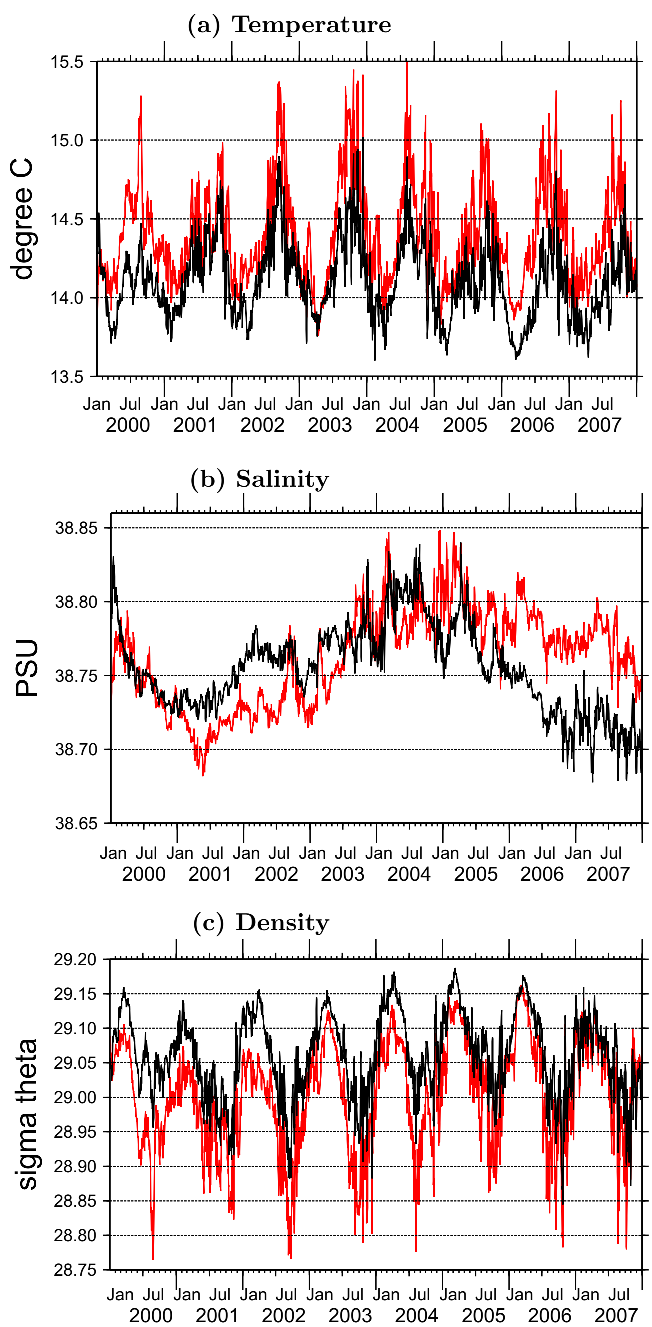

Fig. 3. (a) Temperature, (b) Salinity, (c) Density along the southern Open Boundary. Averaged over depth. Black line is EXP1 and red line is EXP2. The average is calculated only in the part of the boundary east from 19 °E.

3. Model experiments

In this study, there are two experiments which differ with respect to the data sets used for the southern open boundary. The two experiments are named EXP1 and EXP2 respectively. The open boundary data set for the EXP1 is based on Tonani et al. (2008), and for the EXP2 it is based on Oddo et al. (2009) Mediterranean model implementations from the MFS. These two basin scale model configurations in EXP1 and EXP2 share many common characteristics, but the Mediterranean configuration in EXP2 has some modifications with respect to EXP1 (see Oddo et al., 2009).

Fig. 3(a) shows the averaged temperature along the eastern half of the southern open boundary of the two experiments. Only grid points which has positive meridional velocity (i.e., only the inflow water mass) at the eastern half of the boundary are used for the calculation of the average. As it can be seen in the figure, the difference in temperature is generally higher in summer months and two models show more similar behavior in winter periods. The temperature difference is especially pronounced starting from the 2004 with EXP2 having higher temperatures at the boundary throughout the year. Before the 2005 EXP1 has a lower salinity Fig. 3(b), while after the 2005 it has a higher salinity. The salinity does not show the seasonal cycle. Inflowing density at the boundary is lower in EXP1 till the 2006, and more similar afterwards. Till the 2005 higher the temperature and lower the salinity in EXP1 determine the lower density Fig. 3(c), and later differences in temperature and salinity mostly compensate their respective impacts on density.

3.1. Comparison with SST

The simulated spatially averaged Sea Surface Temperature (SST) was compared with the satellite data. The observed SST data were

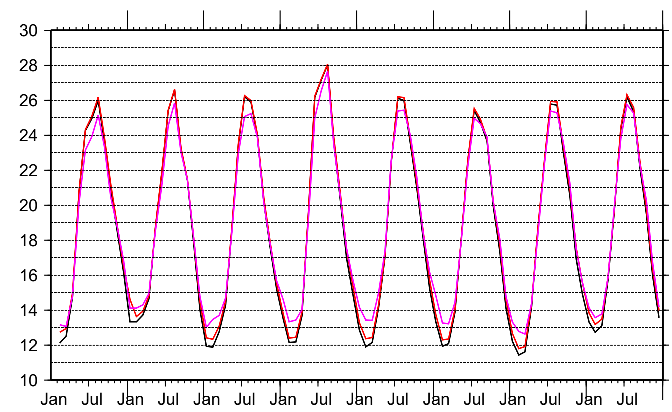

Fig. 4. Model vs Satellite SST comparison. The magenta line is Pathfinder SST, the black line is EXP1 and the red line is EXP2.

obtained from the Pathfinder project (http://www.pathfinder) at 4 km resolution. Fig. 4 shows that both model configurations successfully generated the observed inter-annual variability of the SST. However, both EXP1 and EXP2 show a positive bias in summer months, and a negative bias in winter months, although in summer, EXP2 is closer to the observations throughout the period 2000–2007. The coldest summer over the investigated period is in 2005, and the warmest summer is in 2003. All these events are captured by the model.

3.2. Comparison with in situ observations

The performance of the model was further evaluated by comparing simulated fields with available in situ observations. The locations of the available Conductivity-Temperature-Depth (CTD) profiles are shown in Fig. 1. The Mean Error and the Root Mean Square Error have been calculated for the three sub-basins of the Adriatic Sea. In total there are 2089, 38, 136 profiles in the north, the middle and the southern basins respectively. The data cover the period of 2002–2007.

Fig. 5 shows the averaged differences and Root Mean Square differences between simulation and observation for temperature and salinity in the three sub-regions of the Adriatic Sea. Whole observed and simulated profiles are averaged between September and October 2002. In this particular period, EXP1 is closer to observations in the top 80 m of the water column and the temperature in EXP2 closer to observations below the 80 m. The higher agreement of EXP2 temperature simulated fields and observations in

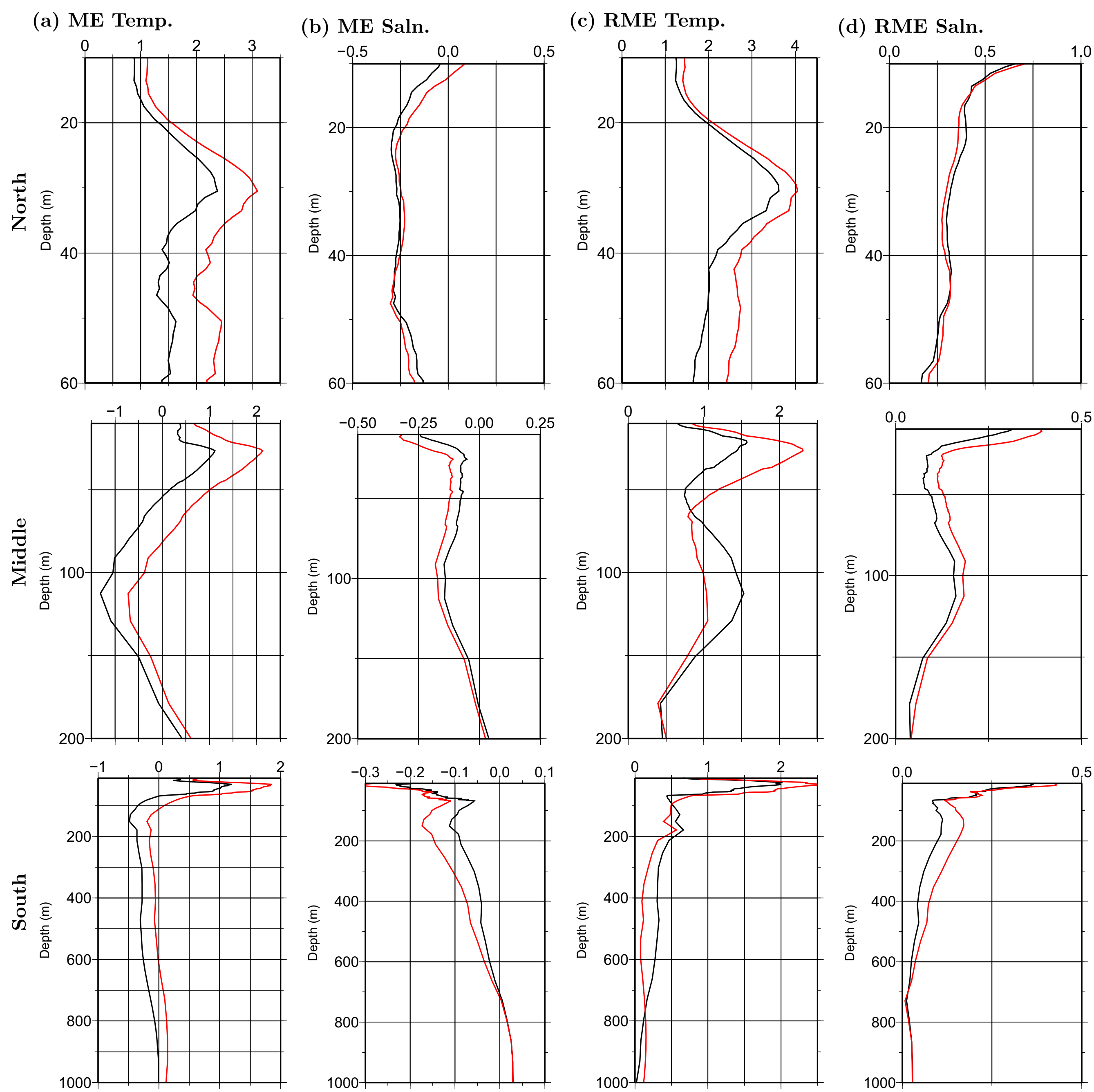

Fig. 5. Temperature and Salinity anomaly and error comparison of the model with observations for different basins of the Adriatic Sea for September–October 2002. The black line is EXP1 and the red line is EXP2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

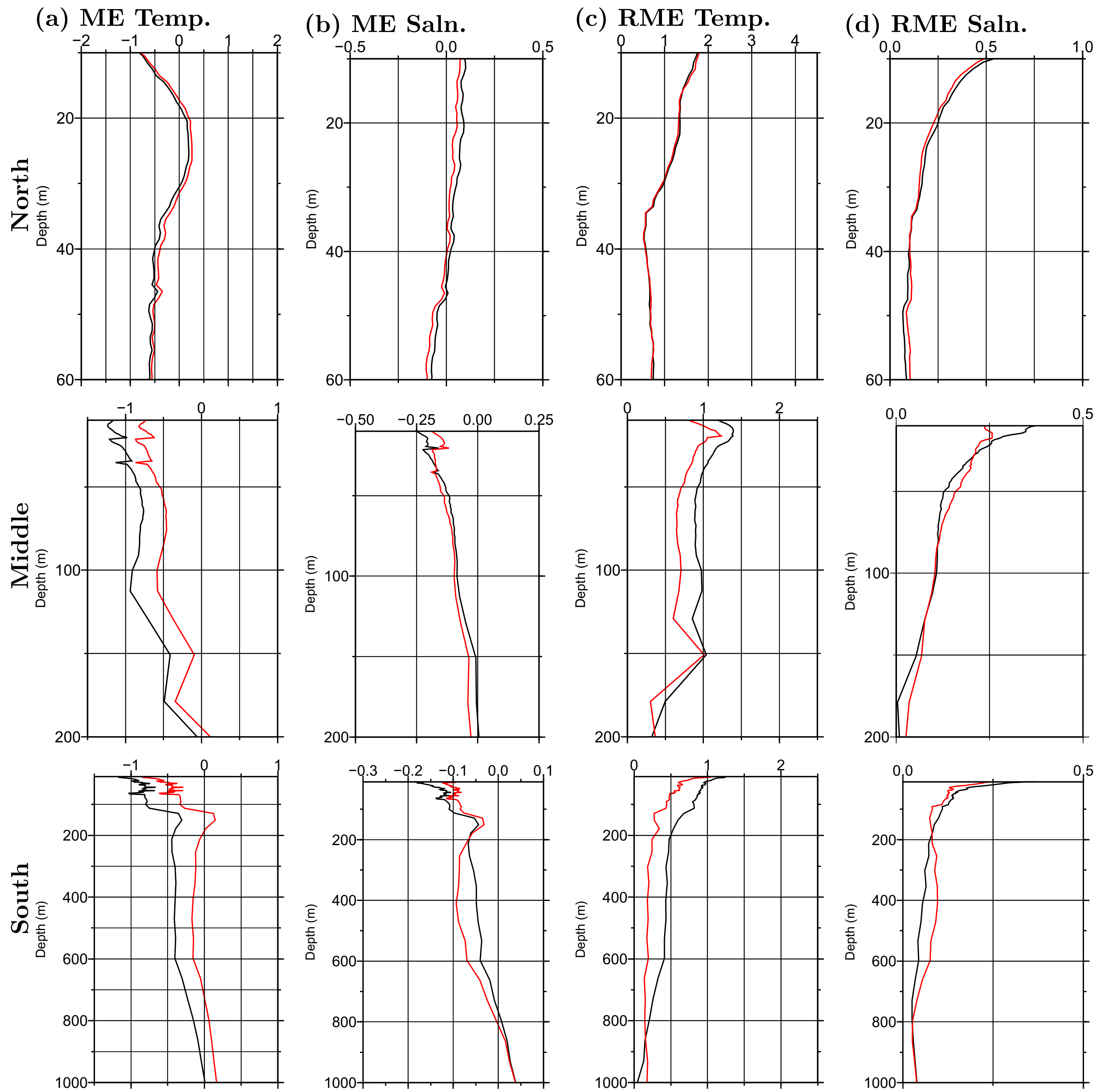

Fig. 6. Temperature and Salinity anomaly and error comparison of the model with observations for different basins of the Adriatic Sea for only for April–May 2003. The black line is EXP1 and the red line is EXP2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

below the 80 m of the water column is consistently present in middle and southern regions of the Adriatic. The improved simulation in EXP2 in the middle and especially Southern Adriatic expands over a large portion of the water column down to the depth of 800 m in the Southern Adriatic Pit. On the other hand, EXP1 and EXP2 show very similar behavior in salinity profiles in each basin. The comparison with the observation shows that the difference in salinity between the two experiments is not significant and it is even smaller in the deeper layers.

The model estimates are also evaluated with the available observations in the spring period. Fig. 6 shows the RMS (also the ME) of differences with in situ observations in April-May 2003. In the Northern Adriatic Sea, the two experiments show similar temperature differences. However, in the Middle and the Southern Adriatic Sea EXP2 is closer to the observations over the whole water column. As in 2002, the difference in salinity are very small in both experiments.

The comparison of the model generated temperature and salinity fields with the CTD observations included all available years and it is shown in Fig. 7. It can be seen that the impact of the boundary conditions on the accuracy of the model simulation extends to the Northern Adriatic. Comparing our results those of Oddo and Guarnieri (2011) who used the same observational data set, it appears that the present simulation has better agreement with the in situ observations.

Fig. 8 shows temperature and currents at 60 m on 1 September 2002, where the largest differences are found between the experiments and the in situ observations in the Northern Adriatic in

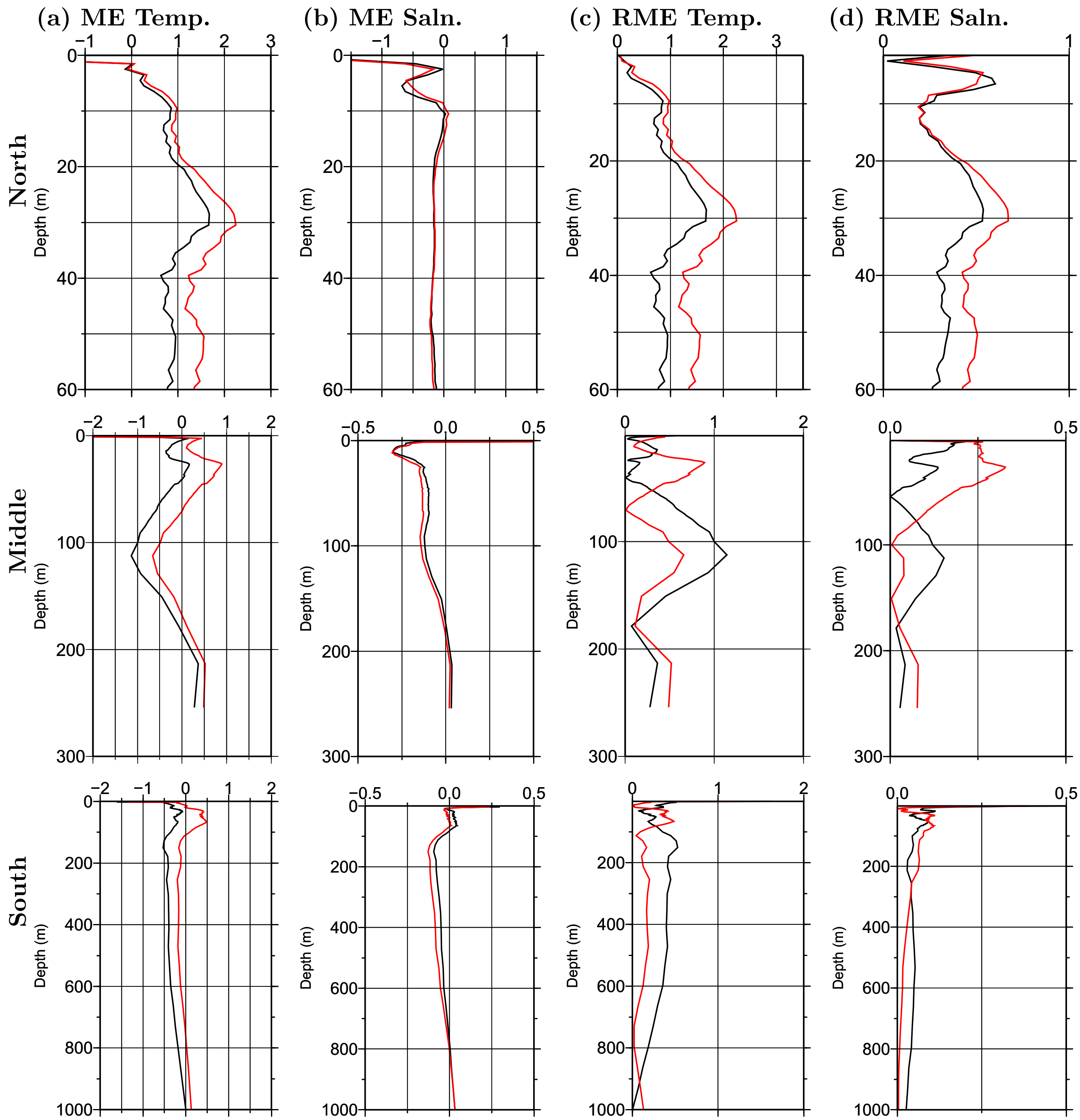

Fig. 7. Temperature and Salinity anomaly and error comparison of the model with observations for different basins of the Adriatic Sea for whole available data set (2002–2007). The black line is EXP1 and the red line is EXP2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

autumn (top plates in Fig. 5). It is evident in Fig. 8 that EXP2 is almost 2 °C higher than EXP1 at the southern boundary. This difference is almost constantly observed along the eastern Adriatic coast up to the Northern Adriatic at 44 °N. It appears that during summer the water mass below the mixed layer is advected from the southern boundary northwards without strong modification of its properties. Therefore, EXP2 has higher temperatures along the whole water mass path along the eastern coast. Assuming that the mean advection velocity is 20 cm/s we may estimate that it takes about one month to advect temperature from the Otranto Strait to 44 °N. The simulation of this process is in agreement with the long term observations of Artegiani et al. (1997) on the advection of LIW from the Otranto Strait into the Adriatic Sea from summer till autumn. The circulation patterns are also very different in each experiment. In EXP2, the eastern coast current is stronger than in EXP1, and therefore extends more northward. Along the Italian coast the boundary currents and gyres in EXP1 are more intense than in EXP2.

Fig. 9 shows the salinity vertical section between Pescara and Sibenik (Fig. 1) in September 2004. In general, EXP1 has higher

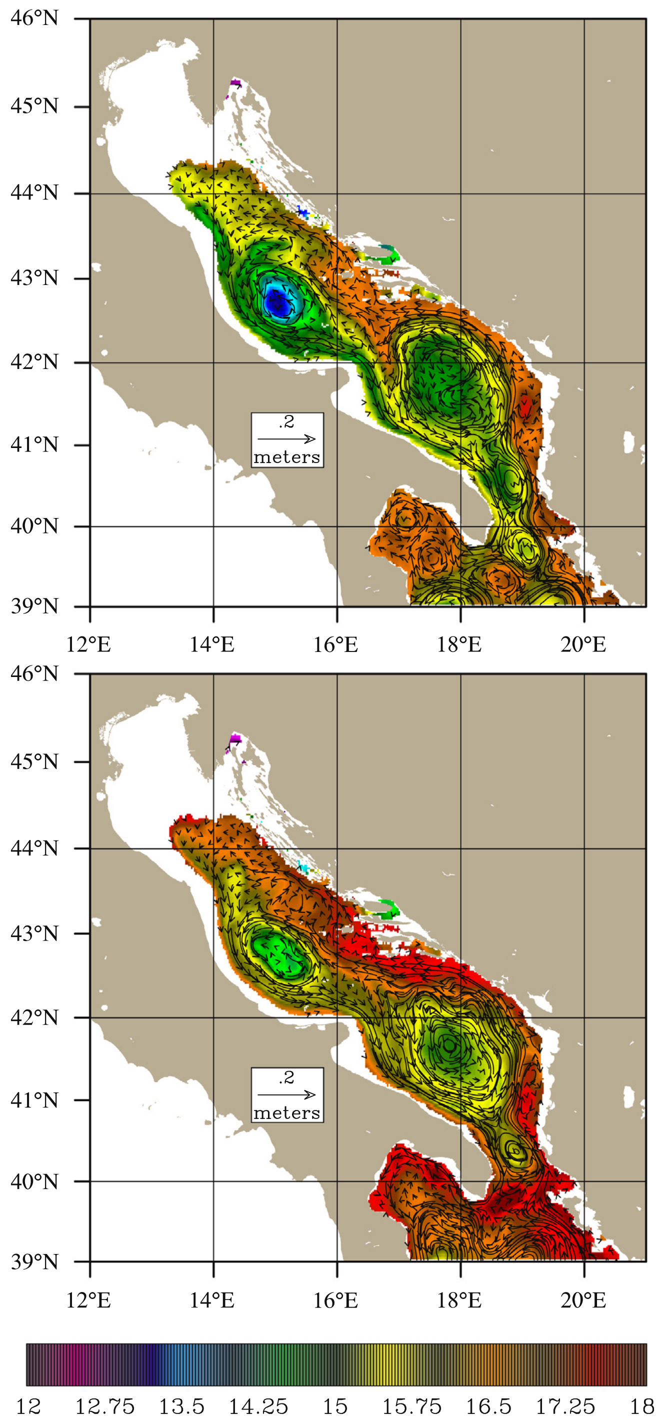

Fig. 8. Temperature over currents at 60 m depth for 1 September 2002. upper: EXP1 lower: EXP2.

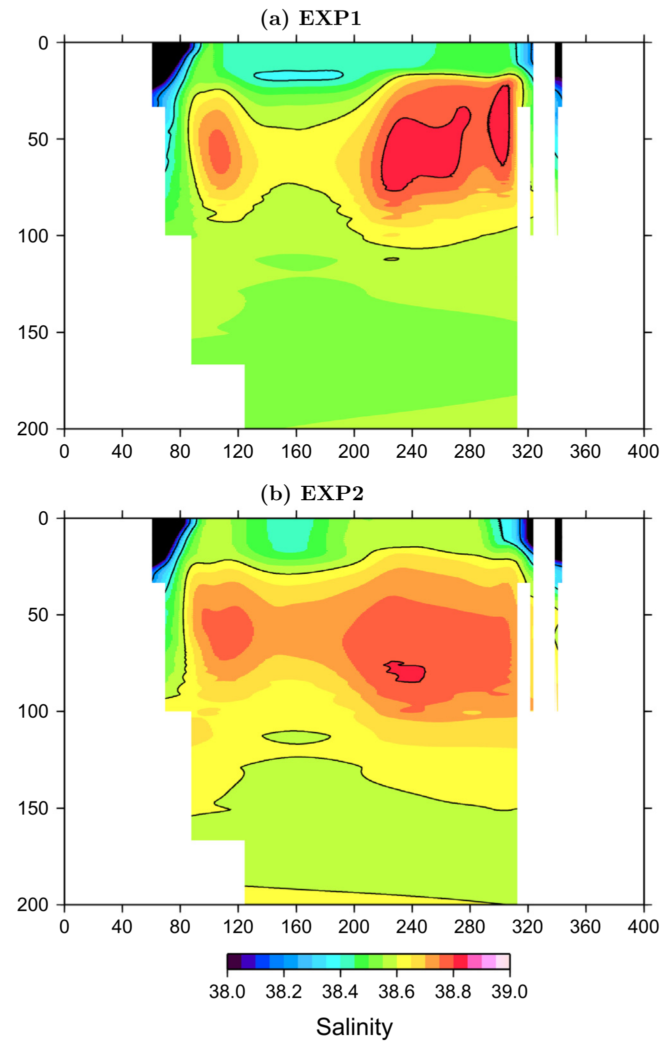

Fig. 9. Salinity section between Pescara and Sibenik for September 2004, (a) EXP1 (b) EXP2.

salinity compared to EXP2. Assuming that high salinity indicates the presence of LIW (Artegiani et al., 1997) we can see that LIW is present in two branches in both EXP1 and EXP2. One is located at the western coast, the other one is positioned at the eastern coast at the depth of around 60–80 m. The two experiments simulate successfully the structure of the LIW, it is very similar to the long term averaged climatology of Artegiani et al. (1997) (Fig. 13 in their paper).

The salinity field in both experiments clearly indicates northward advection of the relatively salty water originating from the south open boundary, while the rate of change along its course are different in the two experiments. In the two experiments it is also differently modified during its course to the north. This may be due to the different mesoscale activity between the two experiments. Fig. 10 shows the eddy kinetic energy (EKE) at the surface and along the vertical transect in January 2004. EXP2 has stronger mesoscale activity compared to EXP1. Due to greater amount of vertical mixing in EXP2, the relatively higher salinity at the core of the LIW water mass is not preserved in EXP2. However, it should be mentioned that in comparison with the observations, these salinity differences did not significantly impact the accuracy of the two experiments in the Northern Adriatic (see Fig. 6). It should be noted that, while EXP2 has slightly larger EKE, more deep water was generated in EXP1. It appears that in our case the advection of denser waters at the upper layers of the ocean from the southern boundary in EXP1 more importantly impacted the deep convection.

Further investigation of the difference in temperature and salinity in the two experiments, based on the annual mean vertical transect (not shown) reveals big differences in salinity at the southern boundary. In general, the salinity distribution in the middle Adriatic is very similar between the two experiments. However, the temperature distribution is quite different. It is obvious that the sea in EXP1 is much cooler during the investigated period. EXP2 has deeper mixed layer as a result of greater mixing in this

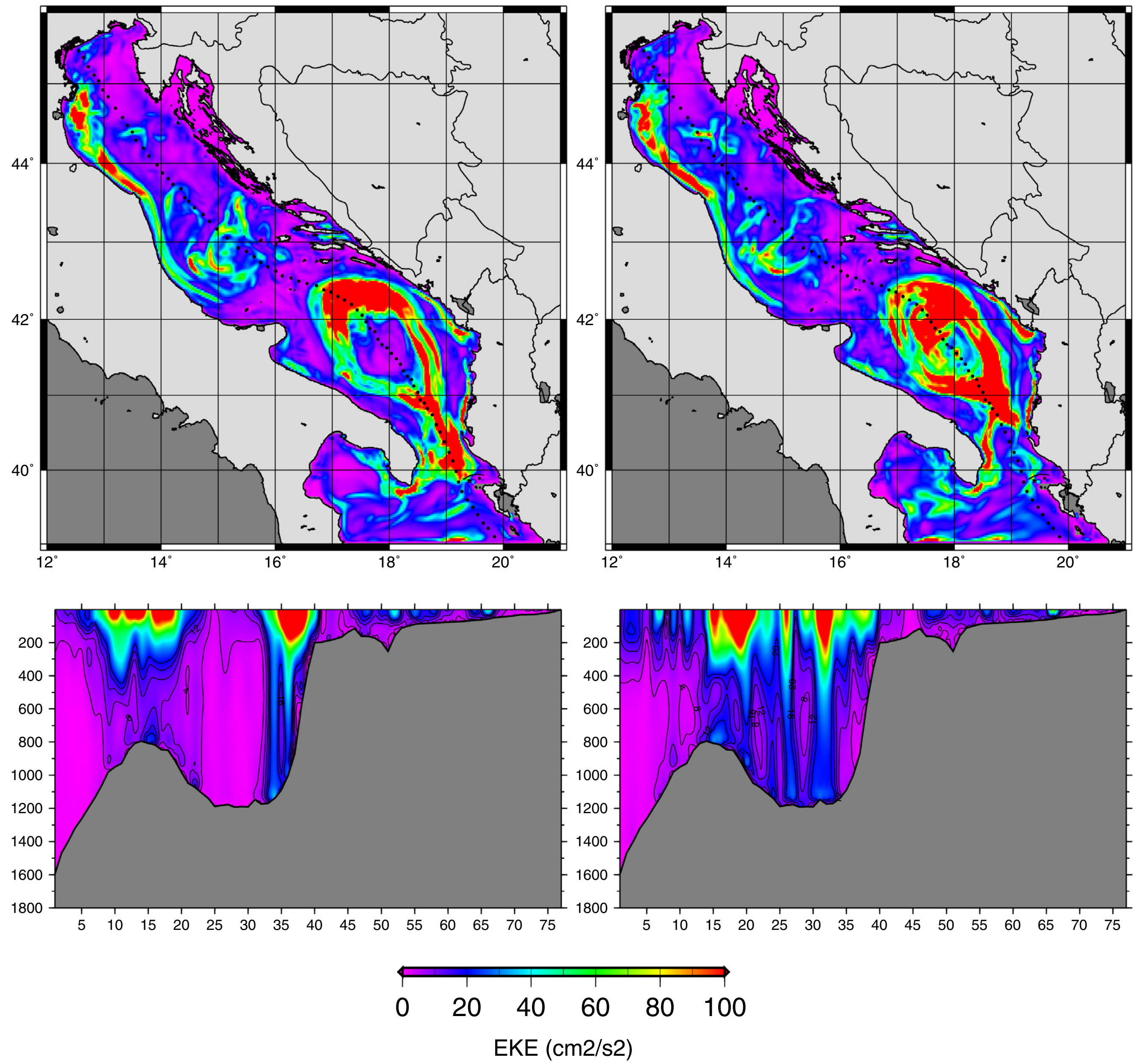

Fig. 10. Monthly mean Eddy Kinetic Energy (EKE) at the surface and along the transect (shown in black dots) for January 2004. left: EXP1 right: EXP2.

experiment, shown by the EKE transect in Fig. 10. EXP2 has deeper mixed layer depth evident over the whole investigated period.

3.3. Impact of the southern open boundary on the dense water formation

The characteristics and the volume of LIW entering the Adriatic Sea through the Otranto Strait at a depth range of 200–600 m with salinity of around 38.75 is an important factor that impacts the generation of the dense water in the Southern Adriatic Sea (e.g., Oddo and Guarnieri, 2011).

The volume of the dense water generated in the three basins of the Adriatic Sea is shown in Fig. 11. The amount of Adriatic Dense Water (ADW) (with density greater than 29.2) in the Northern Adriatic Sea is very similar in EXP1 and EXP2, showing a smaller production of ADW in 2001 and 2007.

Clearly the specification of the southern boundary condition has no observable effect on the winter time production of ADW in the Northern Adriatic. The main factors regulating its production are the variability in heat flux and the Po river runoff (e.g., Oddo and Guarnieri, 2011). In the Middle Adriatic, the two experiments also show similar quantities of ADW, but EXP1 always has denser waters. The differences are quite large in the Southern Adriatic. The volume of the dense water in EXP2 is very small until 2004, and in some years (from 2000 to 2003) there is no dense water formed in the basin. This contradicts the available observations in this period (Cardin et al., 2011). On the other hand EXP1 shows the existence of ADW during the whole integration period. The volume of ADW formed at the beginning of the simulation decreases until 2004. Then there is a consecutive period of dense water generation from 2004 to 2006, which increases the volume of ADW formed in the Southern Adriatic Sea. A larger amount of ADW is generated after 2005, reaching a maximum in 2006 in both

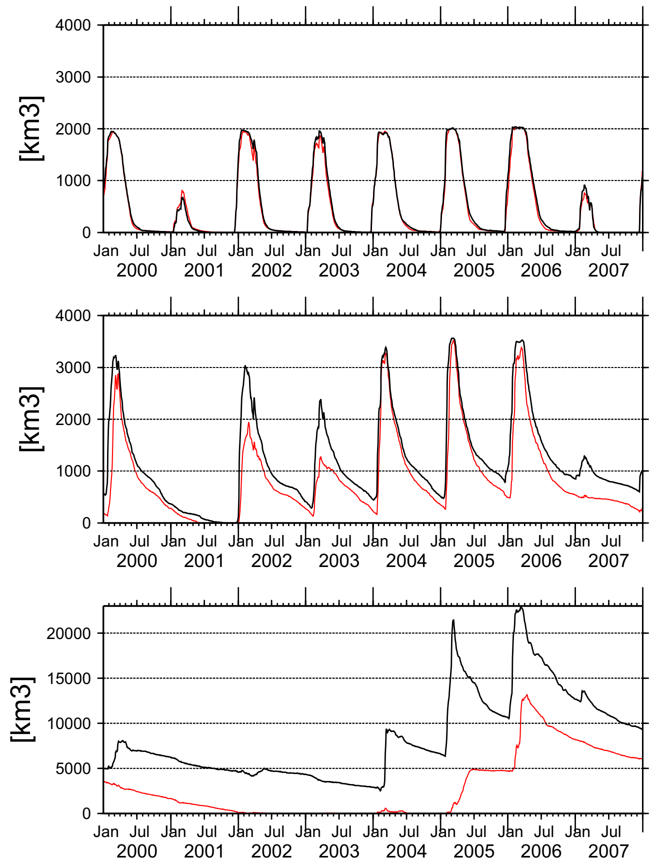

Fig. 11. Volume of the dense water sigma theta greater than 29.2 for north, middle and south Adriatic Sea, the black line is EXP1 and the red line is EXP2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

experiments. In EXP1, almost the whole water column of the South Adriatic Sea consisted of water with density larger than 29.2 in 2005 and 2006. This is in agreement with the observations of ADW formation in the Southern Adriatic Pit (Cardin et al., 2011). It is interesting to notice that although EXP2 is closer to observations in terms of in situ temperature and salinity profiles (Figs. 5–7), EXP1 has better agreement with estimates of the volume of ADW in the Southern Adriatic Sea.

4. Conclusion

An interannual simulation of the Adriatic Sea was conducted with a new set-up of the NEMO model using z-levels vertical coordinate with very high vertical resolution reaching 1 m in the top 70 m. Two experiments (EXP1 and EXP2) have been carried out using different data sets for the open boundary conditions in order to investigate the impact of these data on the properties of the circulation and on the dense water formation in the Adriatic Sea.

The comparison of the model simulated temperature and salinity with the available observations shows that the differences in boundary conditions result in different simulated characteristics over almost the whole model domain. Generally, EXP2 shows better agreement with the observations in the Middle and South Adriatic Sea, while in the Northern Adriatic EXP1 is closer to the observations. The volume of the dense water simulated in the two experiments is also significantly different. While both experiments generate a similar amount of ADW in the Middle and the Northern Adriatic, the volume of the ADW in the Southern Adriatic is much higher in EXP1 and in better agreement with in situ observations.

The results show that in autumn the specification of the properties of the LIW entering at the southern boundary may impact the accuracy of the model predictions in the Middle and even further in the Northern Adriatic. Furthermore, in addition to the atmospheric forcing and river run-off, the quantity and characteristics of the LIW inflowing at the southern boundary may be an important factor in the Adriatic Sea determining the model accuracy and the production of the ADW. It is important to notice that the LIW characteristics at the southern boundary are very realistic, as both EXP1 and EXP2 use operational analysis produced by a similar methodology.

The results of our experiments indicate that the water properties at the southern open boundary should be specified very carefully in order to improve the simulation of the dense water formation in the Adriatic Sea. The possible impact of the Adriatic Sea dense water on the Eastern Mediterranean is expected to be very different in the two experiments due to the different amount of dense water generated in the Southern Adriatic.

A major weakness of our model set-up is that it does not incorporate tidal and atmospheric pressure forcing. It was shown in Guarnieri et al. (2013) that the tides have an important effect on the mixing and the circulation in the shallow parts of the North Adriatic. If we add the tidal forcing at the southern boundary the implicit scheme for the free surface may become inadequate to simulate the propagation of tides, because it may damp barotropic waves with high frequencies. In the future we plan to apply this model with the explicit free surface formulation and to include the tidal and atmospheric pressure forcing.

Acknowledgement

The research by Murat Gunduz and Srdjan Dobricic presented in this study was funded by the project JERICO from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 262584.

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