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Modeling an unusual upwelling event observed along the western Adriatic coast in the summer of 2003

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The goal of this research was to simulate and analyze the response of the Western Adriatic Current (WAC) to an abnormal event that occurred in the Adriatic Sea in mid-summer of 2003. At this time, a combination of extremely low discharge from the Po River and from other northwestern rivers caused by the prolonged dry season and the dominant Sirocco wind produced an 'unusual' upwelling and caused the WAC to reverse along the northern and central Italian coasts. The simulations employed a high-resolution, low dissipative version of the DieCAST circulation model that was initialized with monthly averaged temperature and salinity data and spun up with a use of climatological wind data. Numerical experiments were performed with the use of COAMPS wind stress and heat flux data. The model runs performed under Sirocco wind forcing in combination with low river discharge (a quarter of the climatic mean) revealed that such these conditions do trigger upwelling and the reversal of the WAC along the Italian coast. The upwelling relaxation caused by changes in the wind direction was also studied. Qualitative simulation results were in agreement with the observations by Poulain et al. (2004).

Keywords: Adriatic Sea, unusual upwelling event, Western Adriatic Current, Sirocco, Mistral, DieCAST

1. Introduction

Bergamasco and Gačić (1996) and Gačić et al. (1997) note that coastal upwelling events in the Adriatic Sea typically occur along the Albanian and Croatian coasts during the late summer and autumn, although these events can also occur in the winter and spring during periods of severe bora winds. The possibility that upwelling events caused by bora winds off the Croatian coast occur during the wintertime has been demonstrated theoretically by Lazar et al. (2007).

Along the Italian coast, and particularly along the northern and central parts of this coast, the large buoyancy input from the Po River and from other north-northwestern Adriatic rivers prevents upwelling from being triggered, even from strong winds like the Sirocco. The climatological mean value of the

Po River discharge rate in July is on the order of 1110–1200 $m^3 s^{-1}$ (Raicich, 1994). During periods of strong Sirocco winds, a decreasing ratio of buoyancy forcing to wind forcing, as demonstrated by (Orlić et al., 1994), may create favorable conditions for the reversal of the Western Adriatic Current (WAC). Upwelling events might even result along the central Italian coast when the ratio decreases to very low values. These unique conditions occurred during an extremely dry summer in 2003 and triggered an 'unusual' upwelling event near the Conero Promontory (see Figures 2a and 2b) accompanied by the reversal of the coastal surface current off the central and northern Italian coast. This unique situation occurred between July 11 and 23, 2003 and was observed and documented by Poulain et al. (2004), hereafter referred to as PMU04. An analysis of a sequence of satellite images of sea surface temperature (SST) and chlorophyll-a concentrations by these authors during this period revealed that the upwelling system first appeared northwest of the Conero Promontory and then propagated to the southeast. The offshore extension of the upwelling zone, including filament structures and eddies, was on the order of 20–30 km long. The SST and chlorophyll-a images were correlated, indicating that upwelled cold waters were also rich in nutrients. In terms of the SST values near the Conero Promontory, the coldest upwelled water appearing at the sea surface was less than 8 °C lower that water of the open sea (i.e., 18.5 °C compared to open sea temperatures of 27 °C).

An analysis of drifter tracks launched between the Conero Promontory and the Gargano Peninsula during the upwelling event showed that the reversal of the WAC lasted for a period of 10 days and ended on July 18 when the wind changed direction towards the southeast (PMU04). According to these observations, the drifters were separated into two groups: the first group moved to a distance of approximately 10 km from the shore and moved rapidly with a speed of approximately 0.4 $m s^{-1}$, while the second group moved further offshore (20–30 km) and towards the northwest at a speed of 0.1 $m s^{-1}$. It is thought that this unusual upwelling event, which occurred in mid-July of 2003, was only possible due to the combined effects of period of dramatically decreasing buoyancy input (almost 4 times lower than normal), which coincided with a period of strong Sirocco winds. These winds were dominating during this period but were interrupted by short passages of northwesterly and bora winds which favor downwelling and which affect the evolution of the upwelling zone. Dominant bora and northwesterly winds started on 18 July and caused the upwelling to dissipate quickly and to re-establish the WAC with its normal southwestward flow.

Complex observations and analyses conducted by PMU04 provide a unique opportunity for modelers to study this exceptional situation in detail. Korotenko (2007) recently conducted preliminary comparative simulations of the Adriatic circulation under the combination of normal/low Po River and Sirocco winds and the analysis of conditions that caused upwelling events along the central Italian coast. This study indicated that the process of triggering upwelling along this part of the Adriatic is very sensitive to the ratio of buoyancy forcing to wind forcing. The 'absence' of upwelling under normal conditions was explained as follows. Under normal conditions, the large inflow of riverine water in the northwestern part of the Adriatic Sea generates the WAC and, as a consequence, forms a buoyant ROFI[1] zone along the Italian coast. In the region of the Conero Promontory, this buoyant zone is powerful and therefore shields the area from the influence of upwelling-favorable winds so that upwelled bottom waters do not reach the sea surface. The shielding effect seems to explain the following: when upwelling is formed under favorable wind conditions, the coastal flow of fresh water moving along the Italian coast from the north seems to be sufficient to compensate for the surface waters 'blown off' by wind, i.e., as the light water flows seaward, it is immediately replaced by new fresh water supplied by the WAC. Note that in this case, the ROFI system is widened during Sirocco wind blowing. From another point of view, as described in Thomson (1974), upwelling-favorable winds can result in a two-cell circulation structure (with both axes being parallel to the coast) over the shelf, an offshore current at the base of the pycnocline, and secondary upwelling near the edge of the shelf. In our case, due to the ROFI formed by the Po River, the surface cell isolated from the bottom layers entraps the buoyant water near the coast. This explains the 'nonexistence' of upwellings during southeasterly winds when the riverine runoff is normal; in this situation, the winds simply speed up the circulation occurring near the surface.

The numerical simulations for the normal riverine runoff show that the effect of the Sirocco wind causes a pronounced widening of the zone of riverine coastal waters, whereas the main gravity current is limited by the offshore zone of the secondary upwelling that lies at a distance of 15–20 km off the coast. Therefore, the horizontal contrasts in the temperature are not so distinguishable so as to reveal the upwelling from satellite observations. Thus, it seems that in both cases, the riverine waters shields deep water from wind forcing and thus does not allow upwelling to develop under normal conditions. In regions where the screen effect is not strong enough (e.g., along the Croatian and Albanian coasts), upwelling occurs frequently.

This work is a continuation of the author's preceding numerical modeling of mesoscale variability in the Adriatic Sea (Cushman-Roisin, 2007; Cushman-Roisin and Korotenko, 2007; Korotenko, 2007), which is now focused on the extraordinary phenomenon observed and documented by PMU04.

The paper is organized as follows: In Section 2, basic features of DieCAST are presented along with the initialization and forcing of this model. The numerical experiments with a low buoyancy input for the two types of wind are

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[1] Region Of Freshwater Influence (Sentchev, Korotenko, 2005)

described in Section 3. Results of numerical simulations and their discussion are presented in Section 4. The summary and conclusion of this study are provided in Section 5.

2. Model description and initialization

The DieCAST ocean model (http://fluid.stanford.edu/yhtseng/research/DieCAST/users_manual.pdf) is a z-level, finite-difference, three-dimensional, primitive-equations, hydrostatic, Boussinesq model with very low dissipation thanks to a fully fourth-order numerical scheme and a weakly filtered leap-frog time integration. For details of the governing equations, the reader is referred to Dietrich (1997) and to Appendix A of the paper by Staneva et al. (2001), which presents an application of this model in the Black Sea. Recently, a high-resolution version of the model was applied to the Adriatic Sea by Cushman-Roisin et al. (2007), Cushman-Roisin and Korotenko (2007) and Korotenko (2007). These studies showed that simulations resolve mesoscale variability because the grid size falls below the first baroclinic deformation radius (approximately 5–10 km) and because DieCAST has a very low horizontal dissipation. Meanders, swirls and eddies are noted along the relatively smooth Italian coast, while offshore jets and filaments better describe the mesoscale activity along the more rugged coast of Croatia.

In the present study, as in the works of Cushman-Roisin et al. (2007), Cushman-Roisin and Korotenko (2007) and Korotenko (2007), the horizontal resolution of the model is 1/50° (1.2 nautical miles, about 2 km). The dimensions of the mesh are 370 × 272, covering the entire Adriatic basin from 12.25° E to 19.6 °E and from 40.4° N to 45.8° N. This resolution allows for a faithful representation of the larger and intermediate-size islands and channels in the Adriatic basin.

The model has 20 unevenly spaced levels in the vertical dimension, with interfacial depths of 0, 4.2, 9.4, 15.9, 23.8, 33.6, 45.7, 60.7, 102, 130, 165, 208, 261, 326, 404, 506, 629, 781, 969 and 1200 m. Smaller intervals near the surface were chosen to better represent surface processes. Dense bathymetric data were provided by the National Biology Institute in Piran, Slovenia and were interpolated onto the present finite-difference grid and fitted to the selected z-levels.

The seafloor is thermally insulated and a standard quadratic-drag coefficient equal to 0.002 was used throughout. In the staircase representation of the topography, the bottom drag applies to the momentum exchange (shear stress) along the horizontal side of each step, while there is no lateral stress against the vertical portion of each step (as this would generate undesirable horizontal dissipation).

Horizontal viscosity and diffusivity are set to a constant value of 10 $m^2 s^{-1}$, while vertical viscosity and diffusivity obey formulas given in Appendix B of

Staneva et al. (2001). In brief, these formulas are the sum of a minimum laminar viscosity, a standard Pacanowski and Philander (1981) mixing parameterization dependent on the local Richardson number and a small third term that is dependent on the vertical spacing and grid Reynolds number. This last term was designed to avoid overshoots by vertical advection (Cushman-Roisin et al., 2007) while producing the extremely weak vertical mixing necessary to maintain the properties of intermediate water masses (with vertical eddy viscosity and diffusivity at near-laminar values of O (0.01 cm^2 s^{-1}) for most of the water below a thin mixed layer). These small values are implied by the observed formation and maintenance of the thin Cold Intermediate Layer in the Black Sea throughout the year (Staneva et al., 2001). The Black Sea and the Adriatic Sea are near the same latitude and thus are similar with respect to vertical mixing. Further, the higher resolution used in the present model reduces the appropriate sub-grid scale vertical mixing.

Four types of forcing acting on the Adriatic Sea are included in the present model: river runoff, surface winds, surface buoyancy fluxes and water exchange through Otranto Strait. Freshwater fluxes from the 38 largest rivers around the perimeter of the basin are specified from climatological data sets (Raicich, 1994, 1996), with daily values interpolated from perpetual annual cycles. River runoff is included in the model as a freshwater source in the topmost level of the grid cell closest to the river mouth. An exception is made for the Po River because of its size; its discharge is divided among its four branches, and the discharge at each river mouth is spread over the three closest grid cells. The actual daily discharge and temperature values for the periods concerned are also used in the simulations. For water exchange through Otranto Strait, values are taken from simulations of a wider model run on a seasonal scale, as described by Cushman-Roisin et al. (2007).

For surface winds, climatological wind data of Hellerman and Rosenstein (1983) were used during the spin-up phase of the model. Once the spin-up phase was complete, the model was forced by hourly winds obtained from COAMPS (Hodur et al., 2002, Pullen et al., 2003) throughout the upwelling event and for a few days afterward. This wind field was given at a spatial resolution of 4 km and was then interpolated onto our 1/50° grid, which was adequate to resolve the multi-jet nature of Adriatic winds (Cushman-Roisin and Korotenko, 2007).

Buoyancy forcing used for the model spin-up phase were taken from Artegiani et al. (1997), while values used in the actual event simulations were those from COAMPS which were provided by J. Doyle. Water exchange values through Otranto Strait were taken from simulations of a wider model run on a seasonal scale, as described by Cushman-Roisin et al. (2007).

Note that in 1999, 2001, a series of process-oriented numerical studies were performed by Kourafalou to elucidate the role of the Po River on the dynamics of the northern Adriatic Sea with the use of the Princeton Ocean Model. Particular attention was focused on the influence of wind fields, including the effects of Sirocco-type winds on the evolution of the Po River Plume. Upwelling-favorable winds were shown to eliminate the region of the westward current along the western coast, while waters from the Po River were advected northward and offshore.

3. Organization of numerical experiments

Numerical experiments were set up as follows to study the upwelling event: the model was initially spun up from rest with temperature and salinity values taken from the climatological summer data of Galos (2000) and under Hellerman-Rosenstein winds. By the fifth day of the simulation, the disjointed aspects of the initial fields had diffused, and subsequent days revealed new developments, including some mesoscale structures and instabilities. The spin--up continued for a total of 40 days, by which time the kinetic energy in the currents approached the stationary value. The 40th day of the simulation was arbitrarily identified as Julian Day 180 (30 June), the middle of the calendar year and a typical day in the summer season. At the following step, the model was re- spun-up for 30 days under hourly COAMPS fluxes and wind stresses taken for June 2003. This step was conducted to obtain the thermodynamic prehistory preceding the event of interest. During this run, the discharge rate of Po River and all other northwestern rivers was reduced to 700 $m^3\ s^{-1}$, which is half of the climatological mean value for this period.

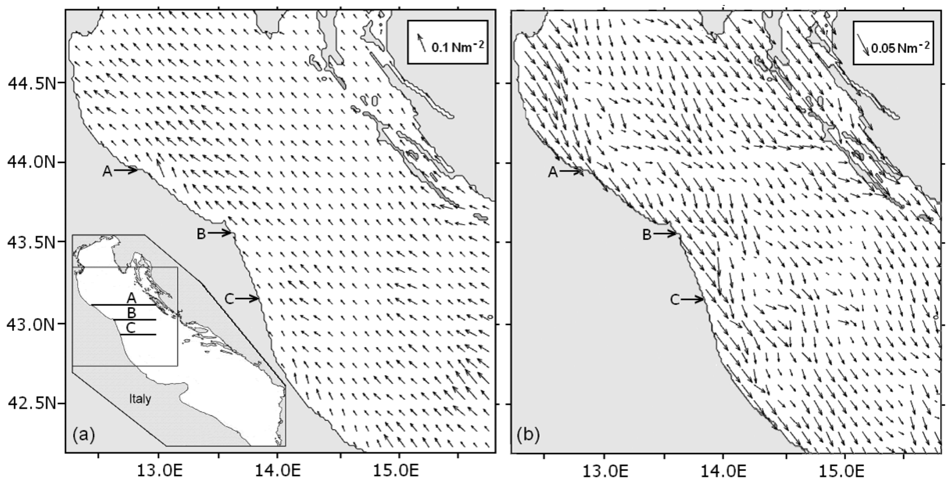

Figure 1. Patterns of Sirocco (a) and Mistral COAMPS (b) winds over the northern and central Adriatic. The three straight lines across the Adriatic basin shown in the frame and labeled by A, B and C indicate transects for the simulations of current velocity and density. In the panel, arrows A, B, and C denote initial points of each transect.

The next two steps were designed to examine: (1) the development of the upwelling zone along the central Italian coast under the competing influence of the Sirocco forcing and the rivers when their discharge rates were reduced considerably; and (2) the weakening of upwelling under northwesterly winds (Mistral) following the Sirocco. Unfortunately, available COAMPS data for July 2003 were sparse and did not allow the model to be run with realistic forcing for this month. Instead, the model used 'frozen' wind patterns, i.e., snapshots of typical patterns for the Sirocco and Mistral wind stresses. These patterns were extracted from the COAMPS data set for June, 2003 and are shown in Fig. 1a (Sirocco) and Fig. 1b (Mistral). To compare the numerical simulations with the observations by PMU04, the model run was with no forcing for 10 days (the relaxation period) after the abovementioned 30-day period of spin-up using forcing values from June, 2003. Thereafter, the model was run using 'frozen' wind forcing for the following 9 days, i.e., conditionally from

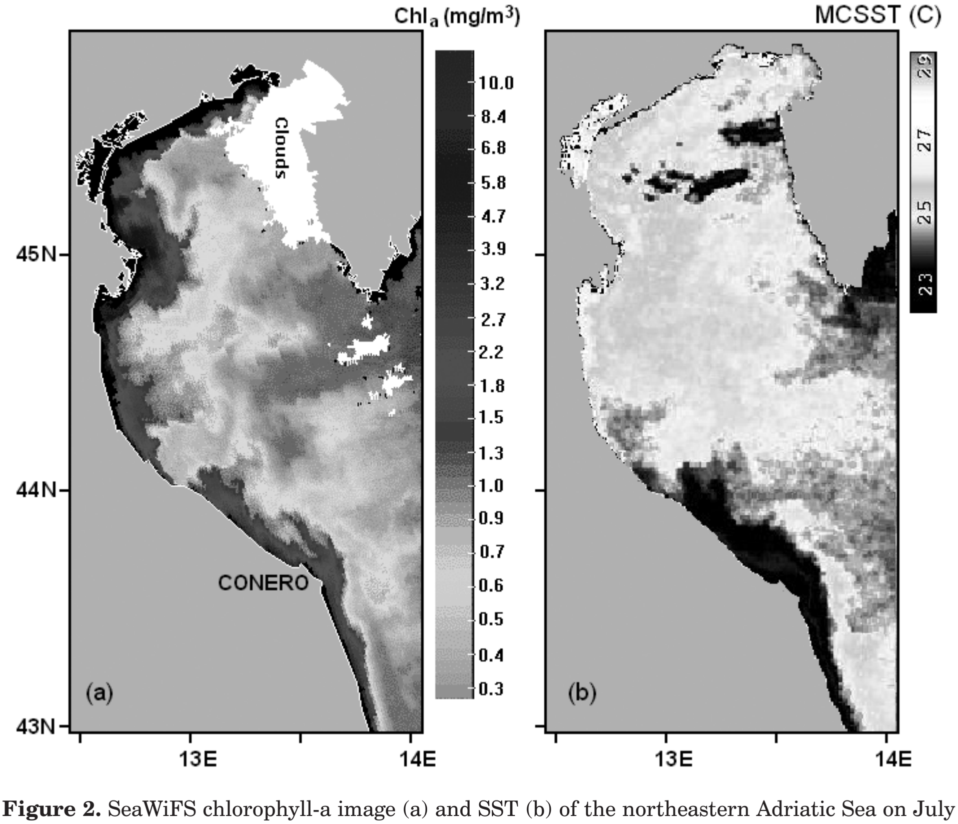

Figure 2. SeaWiFS chlorophyll-a image (a) and SST (b) of the northeastern Adriatic Sea on July 17, 2003. Along the Italian coast, darker colors indicate chlorophyll-rich waters (a) and low SST values (b).

11 to 19 July. In doing so, the model was forced with a Sirocco pattern for the first week (11–17 July) and was then forced with a Mistral pattern for the following 2 days. Note that between the two Sirocco-Mistral forcing regimes, i.e. on July 18, the wind gradually (over a 2 hour period) turned from a Sirocco pattern to a Mistral pattern. The Mistral winds blew for the next two days. The daily Po River discharge rate was reduced to 250 $m^3 s^{-1}$ during the period from July 11 to 19 according to PMU04.

4. Results and discussion

Simulations performed with the DieCAST circulation model exhibited significant changes in the surface circulation and SST along the Italian coast caused by Sirocco winds when the discharge rates of the Po River and other northwestern rivers were considerably reduced. The coincidence of conditions causing upwelling systems along the northern and central Italian coast to be triggered appears to be very rare in the Adriatic and deserve a detailed scrutiny.

Note that at normal discharge rates, northern rivers, and particularly the Po River, create a strong ROFI system along the northern and central Italian coasts which usually inhibits the initiation of upwelling events, even during the periods of strong upwelling-favorable winds. An abnormal drought, such

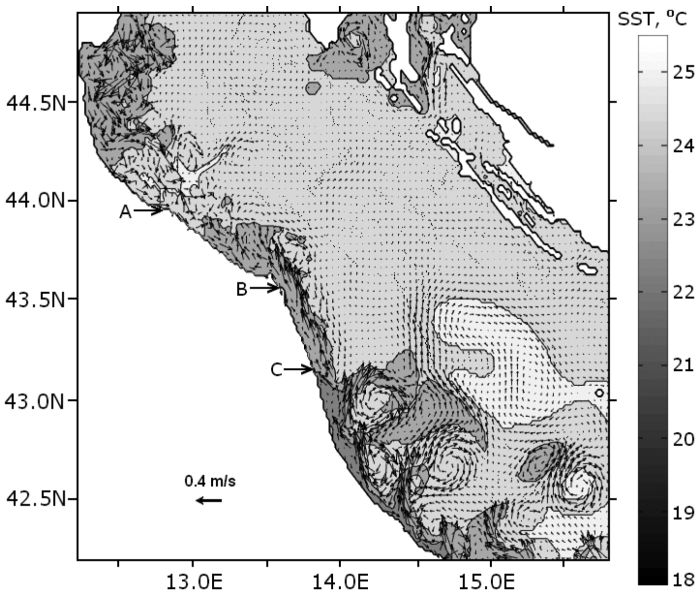

Figure 3. Daily averaged SST and SSV (for July 12, 2003) at the beginning of the development of upwelling zones and the WAC reversal along the Italian coast under the combination of steadily blowing Sirocco winds (see Figures 1a) and a low Po River discharge rate.

as that which occurred during the prolonged dry season of 2003, appears to weaken the ROFI system. In this situation, the dominant Sirocco winds of mid-July triggered (the unusual) upwelling event along with the WAC reversal.

In this section, the response of the model to southeastward and northwestward wind forcing is examined with a particular focus on its effects when combined with a low discharge rate from the Po River. Model results are compared with those obtained by PMU04 in field observations carried out in mid-July of 2003. It should be noted, however, that because satellite AVHRR data and drifters deployed during the observations only provide information regarding the processes developing at the sea surface, 3D-modeling is certain to reveal additional features of this upwelling event and its internal structure that enrich our understanding this phenomenon. For this purpose, in addition to planar plots of SST and sea surface velocity (SSV), the model output provides vertical transects of density and current velocity. There were the three zonal cross-basin transects (Fig. 1): transect A was located along 43.94° N, transect B was located along 43.56° N and transect C was located along 43.14° N.

4.1. Response to Sirocco wind

Planar plots presented in Figure 3 show daily averaged SST and SSV distribution (on July 12, 2003) at the beginning of the development of upwelling zones and the WAC reversal along the Italian coast under the combined effects of the steady blowing Sirocco wind (see Fig. 1a) and the low Po River discharge rate. It is interesting to note that at the Conero Promontory, the wide area covered by upwelling appears northwest of the promontory and is distinctly separated at 44° N from the upwelling zone south of the Po River. South of 43°, the Sirocco wind generates a series of anticyclonic eddies and the tongue of a dense water squirt that moved offshore between two anticyclonic eddies. The latter caused juxtaposing cold (saline) waters next to warm and fresh water on the southern flank of the upwelling zone. Within the northwestward coastal jet, south of the promontory, the velocity reached a maximum value of approximately 0.4 m s^{-1}

Figure 4 presents the daily averaged density (a) and cross-transect current[2] (b) along cross-basin transects A, B and C obtained in simulation for July 12, 2003. As seen in the upper transect (A), the summertime vertical density stratification was still disrupted by the lighter Po water along the Italian coast (left end of the plots), while transects B and C indicated rising of dense water at and south of the Conero Promontory. Transect C also showed the rising dense water at 14.36° E associated with the tongue of upwelled water moving further to the east and crossing the transect (see Figure 3). The zonal cur-

[2] In Figures 4b, 6b and 8b, the range of velocity (–0.01, +0.01) m s^{-1} is marked by white color at the color bar.

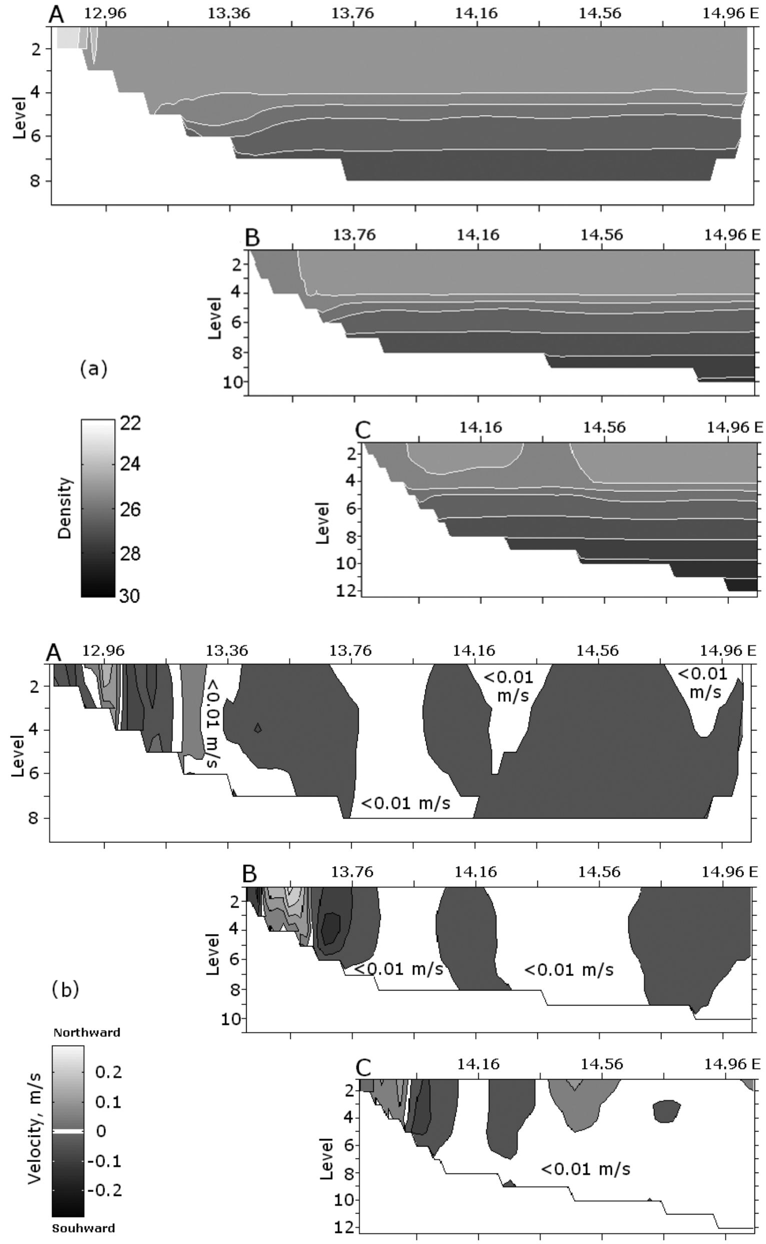

Figure 4. Daily average density (a) and cross-sectional (meridional) current velocity (b) along cross-basin zonal transects A, B and C according to the model simulation for July 12, 2003. Note that model z-levels depicted on the vertical axis look equidistantly however real depths corresponded to these levels are the follows: level '1' is the surface, '2' is 4.2m, '3' is 9.4m, '4' is 15.9m, '5' is 23.8m, '6' is 33.6m, '7' is 45.7m, '8' is 60.7m, '9' is 102m, '11' is 130m and '12' is 165m.

rents at all of the transects showed the formation of the northward (positive) component of velocity in wide cells that were shifted offshore, while compensative southward (negative) currents were pressed to the coast (left end of the plots).

Figure 5 presents daily averaged SST and SSV (on 17 July 2003) indicating the progression of the upwelling zones to the north along the Italian coast. Off of the Conero Promontory, SST shows the development of sharp temperature contrasts between cold water in the upwelling zone and warm waters offshore. The difference in the temperatures was greater than 7 °C. According to the simulation, during the development of the upwelling, the reversal in the current along the upwelling zone became unstable. This instability was manifested through the meandering of the alongshore current, the generation of lateral jet-like flows and the expansion of the zone further to the east. As seen, by July 17, the cold upwelled water south of the promontory protrudes into the mid-basin up to 60 miles, while north of the promontory, the cold water expanded to only approximately 30 miles offshore.

Note that the gap between the northern flank of the central upwelling zone (44° N) and the southern flank of the zone of upwelled water around the Po River did not disappear with the development of both upwelling zones during the Sirocco wind forcing. It seems that particular conditions must have inhibited the development of upwelling along this part of the Italian coast. The

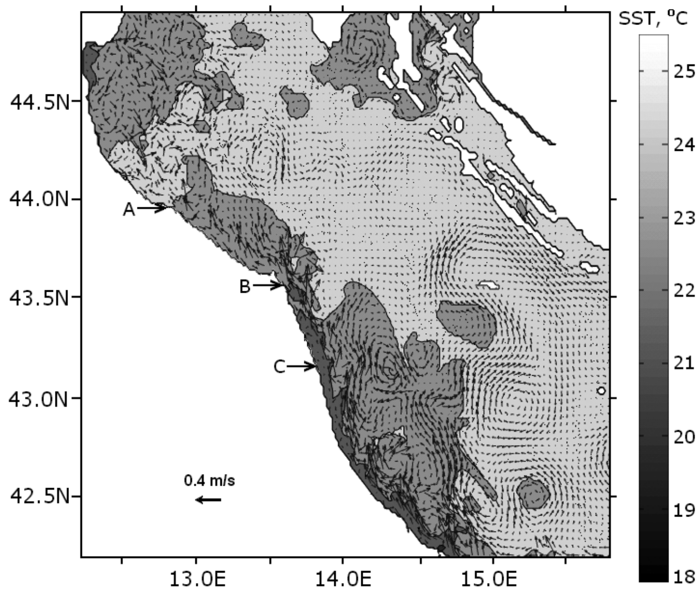

Figure 5. Daily averaged SST and SSV (for July 17, 2003) indicate further progression of the upwelling zones to the north along the Italian coast (same conditions as described in Figure 3).

satellite images of chlorophyll-a and SST shown in Figure 2 reveal the similar gap between the two upwelling zones. The specific processes controlling this upwelling structure deserve close scrutiny in the future. More details of the upwelling event progressing along the Italian coast can be observed in Figure 6, which presents simulations of density (a) and meridional current velocity (b) along transects A, B and C on July 17, 2003.

Figure 6b reveals the propagation of dense water at the zonal transect B up to 14.56° E, while transect A shows downwelling and light water at the west end of the transect. Note that zonal transect A starts at the coast where the abovementioned gap between two separate upwelling zones is located. The plot of density along transect C shows classical evidence of dense water rising caused by Ekman transport (at the west end of the transect). Comparing meridional current velocity along the transects B and C shows the essential difference in the currents. At transect B, the southward current is squeezed in the narrow cell near the west end of transect and separated from coast by the slack water. At transect B, meandering and bifurcation of the southward current causes it to split into two branches (see Figure 6b). The right branch of this current is wide (it is adjacent to an anticyclonic eddy), its center is located at 14.16° E and it becomes wider with depth (the current is detectable to the bottom depth of 60.7 m). The left branch of this current also reaches the bottom, but it is narrow and is close to the coast. The right branch of the southward current connects with northward current that is produced by the same anticyclonic eddy as that shown in Figure 6a.

4.2. Response to Mistral wind

The goal of this experiment was to examine how fast the wind changes from a northwestward to a southeastward direction and how this change might affect the dynamics of coastal waters along the Italian coast. In particular, we were interested in how the change in wind direction would impact upwelling and the WAC reversal analyzed above. Simulations have shown that when Sirocco winds become Mistral winds, the WAC is re-established, thus the recovery of its southeastward flow occurs very rapidly while the upwelling zones along the Italian coast are dissipated relatively slowly. Modeling has also revealed that the strong upwelling zone along the Croatian coast is developed very quickly.

Figure 7 shows the daily averaged SST and SSV (for July 18, 2003) which demonstrate features of the relaxation processes a day after the wind changed direction. While the southeastward coastal flow at approximately 0.3 m s^{-1} has been already formed at this stage, remnants of the upwelling zone along the coast still exist a day after the wind changes direction, though differences in SST between upwelled and offshore waters decreased significantly. Note also that the upwelling zone became seamless along the coast, i.e., the gap at 44° N disappeared. Next, along the Italian coast between 43.5° N and 44° N, one can

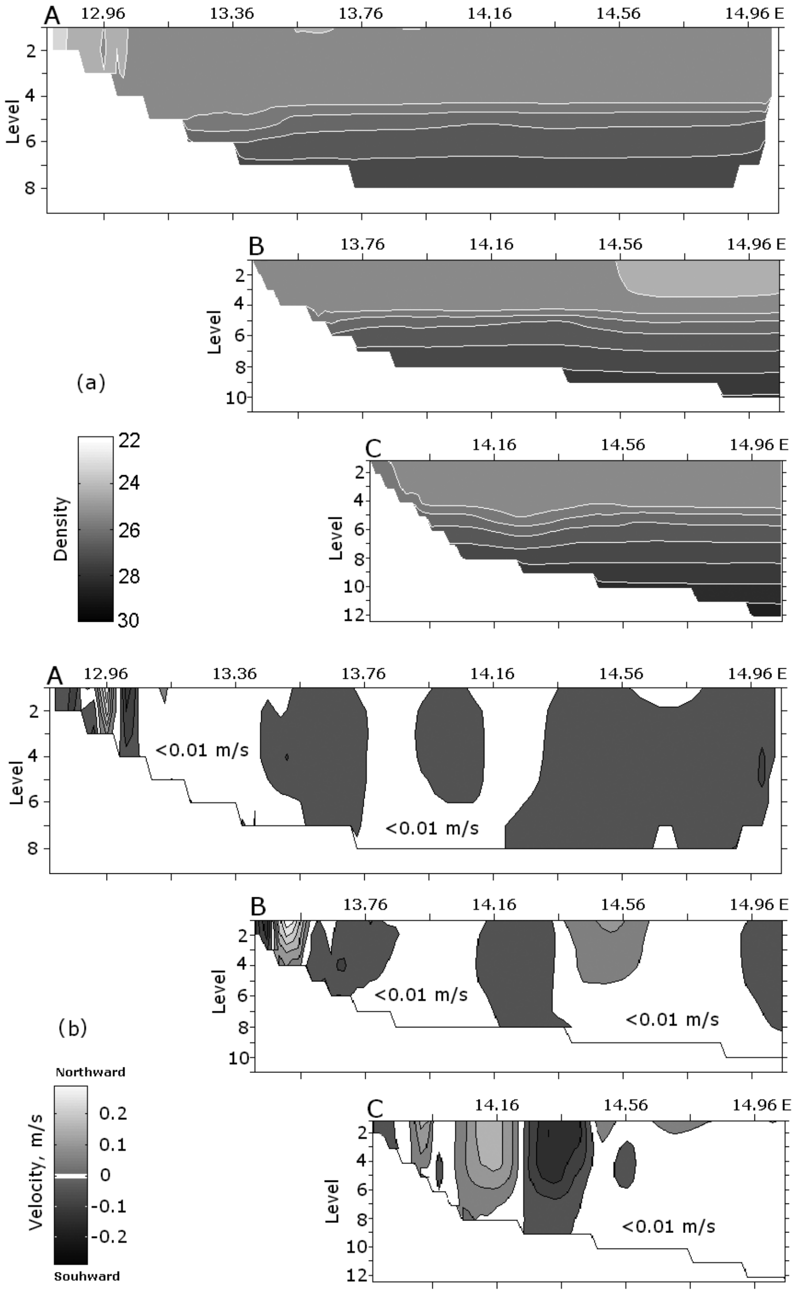

Figure 6. Daily averaged density (a) and meridional current velocity (b) along cross-basin zonal transects A, B and C (indicated in Figure 1a) according to the model simulation for July 17, 2003. The depths corresponding to the model vertical levels are indicated in Figure 4.

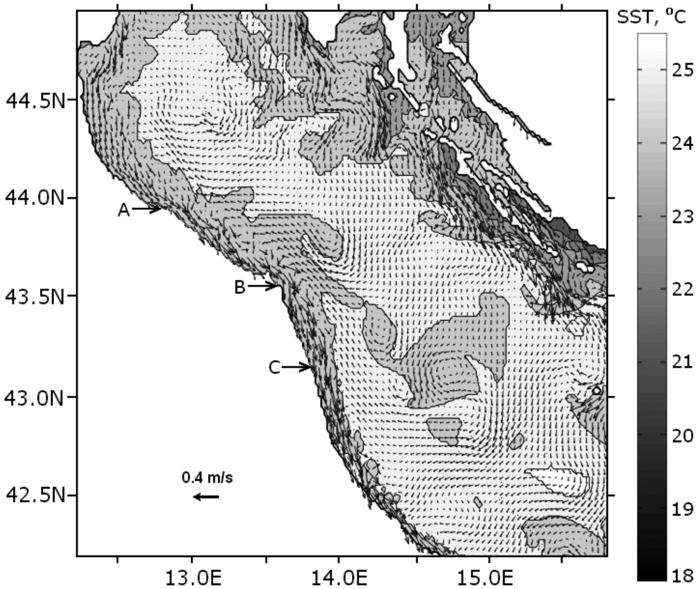

Figure 7. Daily averaged SST and SSV (for July 18, 2003) demonstrate the relaxation process when the wind turned from Sirocco to Mistral. As the simulations show, this process starts from the recovery of the WAC accompanied by the weakening of upwelling along the Italian coast and the development of a strong upwelling zone along the Croatian coast.

see a system of high-density bulges that extend a quarter to a third of the distance across the basin. The bulges formed along the front and separated the WAC. The offshore countercurrent was approximately 0.1 m s^{-1}.

As seen from vertical transect A presented in Figures 8a and 8b, the change in the wind direction to the northwest causes the upward movement of dense waters along the Croatian coast, which is also accompanied by the production of surface protuberances of high-density water spreading to the east. In Figure 8a, all three transects indicate that the vertical density stratification is disrupted by lighter riverine waters along the Italian coast (at the west end of the plots). The light waters reach a depth of 16 m, which is the depth of the WAC core shown in Figure 8b. This is evidence of a gradual re-establishing of the 'thermal wind' system along the Italian coast.

5. Summary and conclusions

The DieCAST circulation model was set up to reproduce the evolution of the WAC and the generation of the upwelling system along the northern and central Italian coasts caused by extraordinary conditions that occurred in the

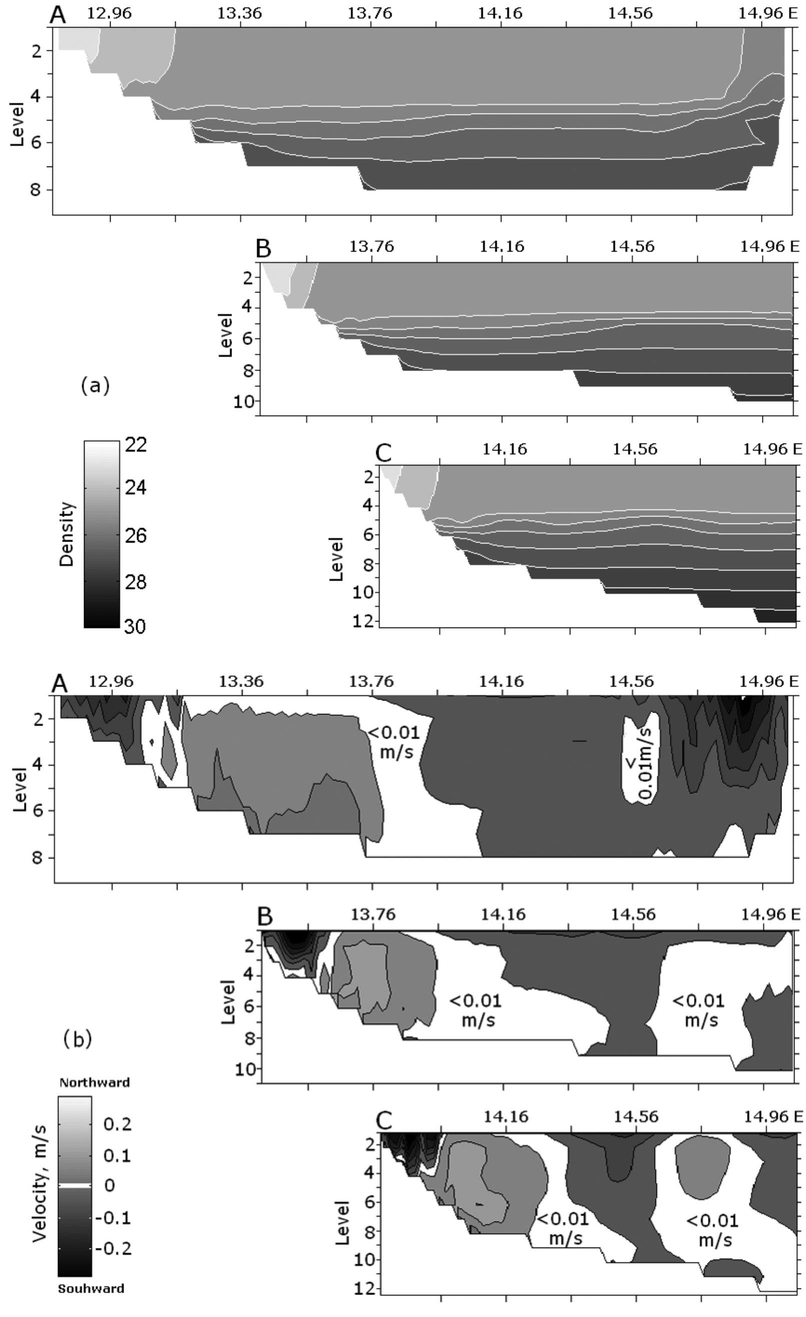

Figure 8. Model simulations of daily averaged density (a) and meridional current velocity (b) along cross-basin zonal transects A, B and C (indicated in Figure 1) when Sirocco wind became Mistral on July 18, 2003. The depths corresponding to the model vertical levels are shown in Figure 4.

dry summer of 2003. Observations and documentation of this phenomenon performed by PMU04 provides the framework for the present study.

Two steps were selected for the numerical experiments: (1) the model run with a low discharge rate of northwestern rivers in combination with Sirocco wind forcing; and (2) the same low discharge rate but with southwestward (Mistral) wind forcing. The former step spanned seven days and the latter spanned two days. At the beginning of the last step, the Sirocco wind gradually (over a two hour period) turned to the southeast. COAMPS data were used to obtain typical wind stress patterns for both Sirocco and Mistral winds. These patterns were used to force the model with 'frozen' winds.

According to the simulations, the temporal and spatial scale of the development and dissipation of the upwelling off the Conero Promontory showed a good qualitative agreement with the abovementioned observations by PMU04. In the case of the reduced river discharge rate and the sustainable Sirocco wind, the reversal of the WAC and the cold water front caused by an upwelling system along the central and north Italian coast occurs over a short time interval, i.e., during the first day of simulations (July 11). During the next 6 days of the simulations, the upwelling zone expanded offshore, mostly in the forms of bulges, and extended up to 60 miles offshore south of the Conero Promontory and 30 miles north of it. The simulations also revealed that near the coast when upwelling was established, the sea surface temperature fell to 19 °C, indicating that the water was upwelled from 15–20 m. During the period of WAC reversal, a maximum northwestward velocity (0.35 m s^{-1}) was observed near the coast south of the promontory, which is in a good agreement with the results inferred from the drifter experiment by PMU04.

An interesting result obtained in the simulations was the persistent coastal area of absence (or weakening) of upwelling (at least its nonproliferation offshore) at approximately 44° N. This area separates the upwelling zone off the Conero Promontory from that located south of the Po River. Satellite images (Figure 2) revealed a similar gap in the upwelling zone near the shore close to 44° N. This gap appeared to be associated with the morphology of the coastline or/and topography of this area (Magaldi et al, 2009). However, the gap could also be associated with the dynamics of the Sirocco forcing as well. As demonstrated by Orlic et al. (1994), the response of the Adriatic Sea to the Sirocco forcing is highly dependent on the structure of the wind field; when the Sirocco is stronger along the east than along the west Adriatic coast, it imparts a pronounced cyclonic shear to the current field and reinforces the WAC. When the Sirocco is more uniform, the bottom-slope effect becomes important and the Adriatic currents are organized into two gyres (cyclonic on the east side of the basin and anticyclonic on the west side) and the WAC tends to invert (see Figures 10 and 11 of Orlic et al. (1994)). Note that the relatively pronounced positive wind shear close to the latitude of 44° N, as seen in Figure 1a, may explain the relatively weak upwelling that was observed in this area.

It is also worthwhile to note that 44° N is the exact latitude of the offshore jet, the so-called Rimini Squirt, described by Cushman-Roisin et al. (2007). This squirt was caused by baroclinic instability which occurred periodically under more common forcing conditions. It appears that the particular conditions studied here would not allow for the development such the instability and, moreover, that these conditions appear to restrict any offshore movement along the latitude of 44° N, although additional studies are required to unravel this peculiarity.

The second numerical experiment simulated the process of upwelling dissipation and revealed some interesting patterns. As the Sirocco wind ceased and the Mistral wind started to blow, the WAC was re-established to its normal southwestward direction very quickly (over ~4 hours), which in turn allowed the 'thermal wind' system to be restored along the Italian coast. The simulations also indicate that the temperature of upwelled water increased rapidly and significantly up to 22 °C although this water was still less than 3 °C cooler than offshore waters. Along the Croatian coast, the Mistral wind rapidly created a strong upwelling zone.

In conclusion, some discrepancies between the obtained numerical results and the observations by PMU04 should be noted. The discrepancies mostly relate to features of upwelling zone evolution and seem to be the result of model initializations and forcing that were unlike the actual conditions observed during the field observations. In this aspect, this work should be considered to be a preliminary communication and its further progress will be directed to studying details of dynamics underlying the development and relaxation of upwelling under the abovementioned particular conditions.

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SAŽETAK

Modeliranje neobičnog izranjanja morske vode opaženog duž zapadne obale Jadrana u ljeto 2003. godine

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Motivacija ove studije je bila da se simulira i analizira odgovor zapadno-jadranske struje (WAC) na izrazito neobičnu dinamičku situaciju koja se dogodila u Jadranu sredinom ljeta 2003. godine. Tada je kombinacija ekstremno niskih protoka rijeke Po i drugih sjeverozapadnih rijeka (kao posljedica dugotrajnog sušnog razdoblja i dominantnog juga) izazvala tzv. 'neobično' izranjanje morske vode i promjenu WAC duž sjeverne i centralne talijanske obale. Za simulacije smo koristili DieCAST model male disipativnosti i visoke rezolucije koji je inicijaliziran podacima srednjih mjesečnih temperatura i saliniteta te klimatološkim vjetrom. Numerički eksperimenti su rađeni pomoću napetosti vjetra i tokova topline dobivenih COAMPS modelom. Model je, simulirajući jugo epizodu u kombinaciji s niskim (četvrtinom klimatološkog prosjeka) riječnim protocima, pokazao da takvi uvjeti uzrokuju izranjanje morske vode i obrtanje WAC duž talijanske obale. Također se proučavaju i karakteristike slabljenja izranjanja vode uzrokovanih promjenama u smjeru vjetra. Rezultati simulacije se uspoređuju kvalitativno s opažanjima koje su napravili Poulain i sur. (2004) te daju dobro podudaranje s postojećim mjerenjima.

Ključne riječi: Jadran, neobično izranjanje morske vode, zapadno-jadranska struja, jugo, mistral, DieCAST

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