MESOSCALE-RESOLVING SIMULATIONS OF SUMMER AND WINTER BORA EVENTS IN THE ADRIATIC SEA

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Abstract

This paper presents simulations of the Adriatic Sea response to two distinct bora wind events, one in summer (11-20 August 2001), when the water is stratified, and the other in winter (11-20 February 2003), when it is vertically homogeneous.

The simulations employ the DieCAST model on a 1.2-min grid (about 2-km resolution) and resolve the mesoscale variability because the grid size falls below the first baroclinic deformation radius (about 5-10 km) and the model has very low horizontal dissipation. The model is initialized with seasonally averaged temperature and salinity data and spun up with climatological winds.

The summer of August 2001 event leads to the generation of a coastal current directed paradoxically to the left of the wind and identified with the summertime Istrian Coastal Countercurrent (ICCC). Analysis of the physics simulated by the model leads to the conclusion that this current is caused by baroclinic geostrophic adjustment of the Istrian coastal waters following a rapid but strong wind impulse. According to both satellite observations and model simulations, the current persists for more than a week after the bora event.

The winter event of February 2003 generates a slightly less complicated situation because the shallow northern Adriatic is then vertically homogeneous, but in-situ observations at the time of this particular event permit a comparison of model results with observations and thus an evaluation of the model performance. In particular, the model simulates correctly a series of currents, bifurcations and confluences of the wind-driven currents across the northern Adriatic basin.

A lesson learned is that a bora event, though generally strong, especially in winter, leaves a legacy that does not obliterate completely what existed prior to the event. In other words, the state of the northern Adriatic basin is fashioned by sequential events, and one bora event may not be viewed in isolation but must be considered as one episode in an unfolding succession of events.

Keywords: Adriatic Sea, numerical modeling, wind-driven currents, geostrophic adjustment, fronts
1. Introduction

The Adriatic Sea basin is a semi-enclosed sea with varied topography (Figure 1), and its circulation is driven by four types of forcings (Cushman-Roisin et al., 2001): Wind stress, freshwater runoff, surface buoyancy fluxes, and water exchange through Otranto Strait. Winds over the Adriatic can be classified in various types (Poulain and Raicich, 2001), each leaving a mark on the sea after its occurrence.

Among the distinct wind types over the Adriatic, bora is of special significance (Jurčec and Brzović, 1995). Its nature as a cold air mass rushing down the Dinaric mountains (along the eastern coast) and spilling over the sea has long been the subject of meteorological studies (Prettner, 1866; Yoshino, 1976; Smith, 1985 and 1987; Pirazzoli and Tomasini, 1999). Finding its way through wind gaps, bora exhibits a multi-jet structure (Kuzmić, 1986, 1993), sometimes called vorticity banners (Grubišić, 2004). The lateral shear on the flank of these jets is indeed marked by strong vorticities, the wind-stress curl of which generates gyres in the water (Orlić et al., 1994). In addition to being a strong wind, bora in winter also brings cold dry air that causes heat loss and evaporation, leading to dense water formation on the shelf (Vested et al., 1998; Beg Paklar et al., 2001; Vilibić et al., 2004).

A number of modeling studies of the Adriatic response to bora have been published over the last few decades. Stravisi (1977) and Orlić et al. (1986) used vertically integrated (2D) and overly viscous models of the northern basin but were able to show that the curl of the bora wind generates a cyclonic gyre in the very northern portion of the basin. Kuzmić (1986 and 1991), Orlić et al. (1994), Bergamasco and Gačić (1996) investigated the Adriatic response to a schematic bora wind field with low-resolution models. These models showed to which extent wind-driven motions could perturb the seasonal circulation but were incapable of reproducing the associated mesoscale activity. Building on Rachev and Purini (2001), Loglisci et al. (2004) developed a coupled atmosphere-ocean model specifically devoted to the air-sea interactions during a bora event. Beg Paklar et al. (2001) and Wang (2005) used the Princeton Ocean Model to simulate a bora event of mid-January 2001. These last several studies emphasized the heat loss resulting from the cold bora rather than the details of the wind-driven circulation, which, in their respective models, was not allowed to develop mesoscale instabilities, either because of inadequate spatial resolution (Rachev and Purini, 2001; Loglisci et al., 2004) or a more dissipative numerical scheme (Beg Paklar et al., 2001; Wang, 2005). In a similar vein, Pullen et al. (2003) and Pullen et al. (2007) coupled an atmospheric model (COAMPS, 4-km resolution) with an oceanic model (NCOM, 2-km resolution) to study the response of the northern Adriatic basin to strong forcing. The emphasis of this work, however, is not so much on the physics of the Adriatic as on ways to improve the performance of the model coupling.

In 2003–04, several cruises and drifter launches provided data on the mesoscale variability in the northern and middle basins of the Adriatic and captured a bora event with unprecedented detail (Lee et al., 2005). The data are providing an important new source of
Figure 1. Geography and bathymetry of the Adriatic Sea, with depth contours in meters. The two straight lines across the northern basin, labeled A and I, indicate lines along which sections will be presented later.
information, and the numerical model presented below was specifically developed to serve as a platform to investigate in particular the mesoscale dynamics observed during these recent observational campaigns.

The approach is to use a numerical model with the least possible amount of horizontal dissipation, in order to allow the instabilities of the flow to develop as freely as possible. The model must also be capable of handling abrupt topography, such as the steep channels and escarpments off the Croatian coast. Under these constraints, DieCAST (Dietrich, 1997; Cushman-Roisin et al., 2007) stands as the model of choice, because of its 4th-order resolution in the horizontal (allowing large Reynolds numbers at the grid level) and its z-level discretization in the vertical (best suited for the representation of topographic steps). The application of this model to the Adriatic basin must also insure that the grid resolution is sufficiently high to resolve scales at the baroclinic radius of deformation, of about 10 kilometers (Cushman-Roisin et al., 2001).

2. Model description

2.1 General model description

The DieCAST ocean model\(^1\) is a z-level, finite-difference, three-dimensional, primitive-equations, hydrostatic, Boussinesq model with very low dissipation thanks to a fully 4th-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 to the Black Sea. Applications to the Adriatic Sea can be found in Rachev and Purini (2001), Loglisci et al. (2004) and Cushman-Roisin et al. (2007).

Here and as in Cushman-Roisin et al. (2007), the horizontal resolution is 1/50° (1.2 nautical miles, about 2 km), and the dimension of the mesh is 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, especially along the Croatian coast.

2.2 Initialization and forcings

Initialization of the model is performed as described in Cushman-Roisin et al. (2007), namely by specification of temperature and salinity distributions corresponding to the season in which the event occurs (ex. summer for an August event and winter for a February event). The velocity field is spun up from rest.

As mentioned in the introduction, there are four types of forcings acting on the Adriatic Sea: river runoff, surface winds, surface buoyancy fluxes and water exchange through Otranto Strait, all of which are included in the present model. Freshwater fluxes from the 38 largest rivers around the perimeter of the basin are specified from climatological data sets (Raicich, 1994 and 1996), with daily values interpolated from perpetual annual cycles.

\(^1\)http://fluid.stanford.edu/yhtseng/research/DieCAST/users manual.pdf
River runoff is implemented 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 mouth is spread over the three closest grid cells. Also, actual daily discharge and temperature values for the periods concerned are used in our simulations.

For surface winds, climatological wind data of Hellerman and Rosenstein (1983) are used during the spin-up phase of the model. Once spun up, the model is forced by hourly winds obtained from COAMPS (Hodur et al., 2002; Pullen et al., 2003) during the event under study and a few days beyond. This wind field given on a 4-km spatial resolution and then interpolated onto our 2-km grid is adequate to resolve the multi-jet nature of bora.

Buoyancy forcings used for model spin-up are taken from Artegaiani et al. (1997), while values used in the actual event simulations are those of COAMPS (opcit). For water exchange through Otranto Strait, values are taken from simulations of a wider model run on a seasonal scale, as described in Cushman-Roisin et al. (2007).

3. Response to summer bora (11–20 August 2001)

For the simulation of a bora event in summer, the period of 11–20 August 2001 was selected because it includes a well defined bora event lasting two days (11–12 August) and is accompanied by a valuable set of satellite images, especially from SeaWiFS, because of clear skies during the bora event proper and some days afterwards.

On 9 August, prior to the bora event, wind blew from WSW and then turned into a slight SE sirocco by 10 August. This sequence drove the Po River plume eastward across the northern basin and then against the Istrian peninsula. The Po River discharge had been normal for this time of year, about 900 to 1000 m$^3$/s. When bora began to blow on 11 August (Figure 2), the wind jet over Rijeka caused upwelling in the Bay of Rijeka, juxtaposing cold and saline waters on the eastern flank of Istria (in the bay) next to warm and fresh water of Po River origin on the western flank (open sea). As the surface chlorophyll distribution of 12 August shows (Figure 3), the water west of Istria is loaded with chlorophyll from the Po, while the chlorophyll-free water inside the bay seems to have originated from further south along the Croatian coast. Because of their respective origins, the chlorophyll-rich water offshore is warmer and fresher than the clear water in the bay.

As the bora wind ceases and some of the dense water has been dragged seaward out of the bay, the situation is away from equilibrium and an adjustment becomes necessary. The numerical model (Figure 4) shows that a southward current develops along the southwestern shore of Istria within a day or so, i.e., on the inertial time scale as we expect for geostrophic adjustment. The current reaches a maximum speed of 25 cm/s about 10 km from the coast. Evidence of its existence is seen in satellite pictures (some of them included in Figure 3, others shown later in Figure 5) in which a tongue of high-chlorophyll water proceeds south-eastward down the coast of Istria and, beyond the southern tip, veers to the right toward of the middle of the basin. This southward current along Istria can perhaps be identified with the occasional Istrian Coastal Countercurrent described by Supić et al. (2000). We shall return to this point in the discussion (Section 5).

The fate of the southward current is eventually to roll up in an anticyclonic vortex, as shown in the comparative plot of Figure 5, with computed sea surface density (left column) compared to SeaWiFS satellite images (right column). The anticyclonic vorticity
Figure 2. Wind stress (white arrows) superimposed on wind-stress curl (color) over the northern Adriatic during two bora events, on 12 August 2001 and 19 February 2003. Note the banded structure of bora, with a jet blowing from Trieste in the northeastern corner, a second jet blowing from Rijeka, South of Istria, and a third one at 44.4°N. The summer bora (left panel) has slightly broader jets than the winter bora (right panel), especially in the northernmost part of the basin, circa 45°N. (Data from COAMPS, courtesy of James D. Doyle)
Figure 3. SeaWiFS and infrared satellite images of 12 and 14 August 2001 showing the surface concentration of Chlorophyll-a and sea surface temperature, respectively. Note how the warm, chlorophyll-rich waters from the Po River have crossed the northern basin and reached the western shore of Istria, while the eastern (interior) side of Istria is flanked by colder and chlorophyll-free waters that have been recently upwelled by the bora wind of the previous day. By 14 August a bulge protrudes on the southern flank of the Po plume in mid-basin. This is the manifestation of a post-wind instability discussed later in the text.
Figure 4. Sea surface currents (daily averaged) during the August 2001 bora event and the following few days. Note the development and persistence of a southward current along the western shore of Istria. This is identified with the Istrian Coastal Countercurrent (ICCC). Note also the anticyclonic (clockwise) eddy at (13°E, 44.2°N) becoming closed on 12 August and persisting for the following two days, and the meandering of the coastal current along the Italian coast, the meanders of which do not travel.
was presumably that imparted to the sea on the right flank of the bora jet (clockwise wind-stress curl) in the region of the current’s origin.

The northern Adriatic response to a summer bora event includes not only the aforementioned upwelling in Rijeka Bay, the upwind flow against Istria, the Istrian Coastal Countercurrent and its decay into a vortex, but a host of other mesoscale instabilities, most of them presumably due to the mixed barotropic–baroclinic nature of the vorticity-laden flow in the presence of summer stratification. There is no room to discuss and analyze all those here, and we shall only mention a swirl occurring on the flank of the upwind flow toward Istria, which like most other mesoscale structures in the sea at the time is reproduced by the model.

In the satellite image of 14 August (right panel of Figure 3) this swirl is seen as the thumb on the southern flank of the Po plume, located slightly south of the mid-point between the Po delta and the southern tip of Istria. It is extruded from the Po plume by an anticyclonic vortex, seen in the simulated currents (last panel of Figure 4). The feature appears to be an instability of the eastward flow. In this region, just north of the bora jet blowing from Rijeka Bay, the wind-stress curl is clockwise, and this has imparted to the water in the area some anticyclonic vorticity. As seen in the vertical sections presented in Figures 6a–6b, this feature is accompanied by simultaneous upwelling with northward flow (just west of the 46.9 km mark in the figures) and downwelling with southward flow (just east of the 46.9 km mark in the figures). Such pattern is symptomatic of a barotropic instability that feeds kinetic energy from the vorticity-laden flow into potential energy of tilted density surfaces.

4. Response to winter bora (11–20 February 2003)

For the simulation of a winter bora, the period of 11–20 February 2003 was selected because it corresponds with the intensive in-situ data collection campaigns reported in Lee et al. (2005), which includes a significant bora event (for a snapshot of the wind field, see right panel of Figure 2). Fortunately, clear skies provide good satellite coverage during the same period (Poulain et al., 2007). This bora event and the attending observations have been described (Lee et al., 2005; Poulain et al., 2007), and there is no need to give here another description of the events and data. We shall instead focus on the simulations by the present model and compare them with field observations.

Figure 7 contrasts the sea surface temperature before (12 February) and after (19 February) the bora event. Two major differences show the effect of bora winds. First, the meridional gradient South of Istria has greatly intensified, to the point of becoming a sharp front. Second, the previously broad temperature gradient in the northern basin, between the Po River delta and Istria, has, too, become more accentuated. It has also rotated to take a southwest-northeast orientation and developed a few meanders, including one south of the Po River delta. It is not a priori clear how the relatively zonal wind jets (right panel of Figure 2) could create such an oblique feature.

These temperature changes and the resulting changes in density are naturally accompanied by currents. Figure 8 shows the surface currents before and after bora, for the same dates as shown in Figure 7. A first current generated by the wind event is a westward coastal jet hugging the northern coast of the Adriatic basin, from Trieste to Venice and down to the Po River Delta. This current is the response to the bora jet at the level of Trieste and is very much expected. Drifter data (Lee et al., 2005; Poulain et al., 2007) confirm its
Figure 5. The ultimate decay of the southward current along Istria, according to both model (computed sea surface density on left) and observations (SeaWiFS images on right). By 17 August, the current closest to the Istrian coast has reversed, now flowing northward (black arrow in upper left panel), while the southward countercurrent is found offshore (yellow arrow in upper left panel) then rolls up in an anticyclonic eddy by 23 August (circled area in bottom left panel). The anticyclonic vorticity was that imparted to the sea by the sheared bora jet in the region of the current’s origin.
Figure 6a. Density and currents along cross-basin Section 1 (indicated in Figure 1) according to the model simulation of 11 to 14 August 2001. The summertime vertical stratification is disrupted by the lighter Po water along the Italian coast (left end of plots), the upwelling-downwelling pattern to its east (straddling the 46.9 km mark) and weak upwelling against Istria (right end of plots). The vertical velocity component is exaggerated to reveal it.
Figure 6b. Currents across Section 1 (indicated in Figure 1) according to the model simulation of 11 to 14 August 2001. Positive values indicate northward currents. Note the Western Adriatic Current (WAC) along the Italian coast (left end of plots), an anticyclonic formation to its east (around the 46.9 km mark), associated with the upwelling noted in Figure 6a, and the ICCC along Istria (far right of plots).
Figure 7. Simulated sea surface temperature on February 12 and 20, 2003, before and after the 10-day bora event. Note the formation of two fronts: a zonal front extending westward from the southern tip of Istria (color variation from orange to yellow) and a wavy front running from the Po River delta to the northern corner of Istria (color variation from yellow to green).

existence. Simulated and observed velocities agree not only in location and direction but also in magnitude (Table 1).

Table 1. Comparison between simulated and observed velocities in the northern Adriatic basin on 19–20 February 2003. Values are in cm/s.

<table>
<thead>
<tr>
<th>Location of current</th>
<th>latitude</th>
<th>longitude</th>
<th>simulated value</th>
<th>drifter value</th>
<th>ADCP value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern tip of Istria</td>
<td>44.6°N</td>
<td>13.8°E</td>
<td>30–35</td>
<td>(no data)</td>
<td>31–34</td>
</tr>
<tr>
<td>Zonal current</td>
<td>44.5°N</td>
<td>13.5°E</td>
<td>25–30</td>
<td>(no data)</td>
<td>20–30</td>
</tr>
<tr>
<td>Oblique current</td>
<td>45.0°N</td>
<td>13.1°E</td>
<td>20–25</td>
<td>22–26</td>
<td>10–25</td>
</tr>
<tr>
<td>Northern shore</td>
<td>44.3°N</td>
<td>12.7°E</td>
<td>18–24</td>
<td>14–16</td>
<td>12–28</td>
</tr>
</tbody>
</table>

Next, we note the strengthening of the westward current South of the Istrian Peninsula, obviously driven by the bora jet at the level of Pula and in geostrophic (thermal-wind) balance with the developing zonal front. A feature noted in the post-bora current chart
Figure 8. Simulated surface currents on February 12 and 20, 2003. Note the double bifurcation of the wind-driven current rounding the southern tip of Istria, with a first, weaker northward branch hugging the coastline and a second, stronger northward branch emerging in mid-basin. The remaining stem of the current cuts across the basin. The zonal part of the current is in geostrophic equilibrium with the front at the same latitude. Note also the reverse current originating from an eddy near the Po River Delta and cutting obliquely across the northern basin to the Gulf of Trieste.

(right panel of Figure 8) is the surprising bifurcation of this current at the southern tip of Istria, with a minor branch turning sharply northward and following the coastline up to 45°N (same latitude as the Po River Delta), where it veers offshore. The other and more important branch of the current begins to diverge upon approaching the Italian coast, with about two thirds of the flow turning left to join the Western Adriatic Current (WAC) down the Italian coastline and the remaining third turning right to augment a current flowing diagonally across the basin from the Po River Delta to the Gulf of Trieste, which we shall hereafter call the oblique current. The smaller branch, that which detaches at the southern tip of Istria and veers westward at 45°N, joins the oblique current and reinforces it.

The physical reason for the bifurcation at the southern tip of Istria, the northward branch flowing along the coast and its abrupt veering eastward toward the open sea at 45°N may seem at first puzzling. Indeed, one would have expected a counterwind (eastward) flow at that latitude of lull in the wind, acting as the flow compensating for the two westward jets at the latitudes of Trieste and Pula. But, one should not forget about Ekman dynamics, which can explain veering to the right of Rijeka Bay waters once they reach the southern tip of Istria. Another and not exclusive reason is friction: The flow hugging the coast inside Rijeka Bay is subjected to a boundary shear stress, which creates anticyclonic vorticity; once in the open sea, water with anticyclonic vorticity has a tendency to turn to the right.

The strength of the oblique current on 20 February 2003, by the end of the bora event, is naturally explained by geostrophy. Computer simulations as well as observations reveal that the current is accompanied by a relatively strong thermal gradient (see Figure 1 of Lee
et al., 2005). So, it is a geostrophic current in thermal-wind balance with a cross-current density gradient. What is more difficult to explain is its oblique orientation, at a definite angle with respect to the main wind direction. To explore this question, we ran our model with the bora wind but no accompanying cooling of the sea surface (simulations not shown), and the result showed a much weaker and more zonal flow, nearly aligned with the wind axis (although obviously in the lull between the Trieste and Rijeka jets), leading us to conclude that the surface heat loss is responsible for the obliquity of the current. The actual heat loss is greater in the Po plume region, and this not only creates a stronger density contrast, and hence a stronger current, but also anchors the current further south at its western origin. The need to return waters to the Gulf of Trieste, where bora creates a sea surface depression, sets the terminal point of the current. The current chooses the straight path between both ends, hence its oblique angle.

The left panel of Figure 9 shows the velocity distribution at 15 m depth on 20 February 2003. By comparing with the surface velocity distribution on the same day (right panel of Figure 8), we note that currents are similarly aligned (barotropic) about everywhere, except at one location. Along the western shore of Istria, there is almost no flow at the surface while there is a noticeable southward current at 15 m. Such flow actually occupy the depth range of 9 to 23 m and is about 3 cm/s strong. Three days later, after the bora wind has died away, this subsurface current has reached the surface, forming a well developed countercurrent about 10 cm/s strong. Such countercurrent at the conclusion of a wintertime bora typically occurs off the southern segment of the Istrian coast and is explained by the negative (anticyclonic) vorticity imparted by the bora wind jet and the sea-level rise in the area (Orlić et al., 1994; Kuzmić et al., 2007).
Figure 10. Salinity and velocity along longitudinal Section A on 20 February 2003. Upper panel: Salinity (colors) and velocity vectors in the plane of the section (arrows); the vertical velocity is exaggerated to reveal the structure of its distribution. Lower panel: Magnitude of the velocity component normal to the section; positive values indicate eastward flow (as indicated by arrows accompanying Section A in Figure 1).

Before concluding this discussion of the simulation of the mid-February 2003 bora event, we present vertical sections to complement the observations which were for the most part on the surface. Figure 10 shows the salinity and velocity along longitudinal section A indicated in Figure 1. The obvious features are the homogeneity of the Adriatic winter waters to a depth of about 20 m and the strong zonal front at the level of Pula (at about position 40 km along the section), together with its associated geostrophic current (up to speed of 22 cm/s at the surface and decreasing with depth). What the section reveals that was not known from the surface plots is the downwelling–upwelling pattern associated with this current. The current is accompanied by downwelling on both flanks and narrow but intense upwelling at its center.

5. Discussion and conclusions

The DieCAST model employed here successfully simulated two distinct bora events over the Adriatic Sea, one in summer when the water is vertically stratified and the other in winter when density differences exist only in the horizontal direction.

The summer case (11–20 August 2001) is complex, with numerous mesoscale features arising, moving and decaying. Paradoxically, the current along the Istrian coast is found to be directed to the left of the wind, in opposition to Ekman dynamics. Far from being an artifact of the model, this current is corroborated by observations and explained by the tip-shaped form of the Istrian Peninsula and the jet-nature of the bora wind.

This southward current along Istria may be identified with the occasional Istrian Coastal
Countercurrent described by Supić et al. (2000). According to these authors, the normally northward current along Istria, which is a leg of the overall cyclonic circulation in the Adriatic basin, occasionally reverses in summer. In-situ data collected during the years 1968 to 1997 have revealed a southward current in the month of August of some but not all years. While Supić et al. (2000) suggest that the appearance of this reversed current, dubbed the Istrian Coastal Countercurrent (ICCC), is somewhat correlated with air-sea fluxes and the Po River discharge over a month-long period or longer prior to the current reversal, this does not exclude that a brief bora event may be the necessary trigger. Indeed, our numerical simulations suggest that two ingredients are necessary for the establishment of the ICCC: first, a preconditioning phase that ends with different water characteristics on the eastern and western shores of Istria, and, second, a bora event that brings the latter water against the former. The ICCC then arises as the geostrophic adjustment to the imbalance caused by the bora-induced water displacement. This mechanism is presented here merely as a conjecture. A further study, across multiple years, should be conducted to assess whether an August occurrence of an extended Po River plume followed by a bora event is a systematic cause of the ICCC. Note also that this conjecture is not exclusive, for there could be different reasons for the occurrence of the ICCC, such as the creation of an anticyclonic circulation pattern in the northern Adriatic under persistent wind and surface flux patterns.

While the ICCC appears to be a spill of less dense water over denser wind-upwelled water leading to a persistent geostrophically adjusted flow, the net effect is quite paradoxical. Normally, when a strong wind blows, Ekman dynamics cause a flow in the water to the right (in the Northern Hemisphere) of the wind. In the case of a NE bora, the current would be northwestward, i.e., up the Istrian coast, not the opposite as observed and modeled. The explanation of a leftward current is two-fold. First, Ekman drift lasts only as long as the wind blows and thus ceases quickly when the event is brief like the bora episode of 10–11 August 2001. Second, the jet-like nature of bora confines the upwelling (and its temporary Ekman drift) to the Gulf of Trieste and Rijeka Bay, while the waters off Istria are not upwelled. On the contrary, the counterwind return flow from Italy toward Istria between the bora jets of Rijeka and Trieste (Figure 2) brings more freshwater against Istria (Figure 3), just the opposite of what upwelling would do! This was already noted by Orlić et al. (1986). The resulting along-basin density gradient between upwelled waters in Rijeka Bay and the less dense water along the western shore of Istria is what triggers the southward current. In sum, the paradoxical direction of the surface current is due to the geography of the coastline and the narrowness of the wind jet.

It is worth noting that Zavatarelli and Pinardi (2003), using a model forced with climatological wind fields, did reproduce what appears to be the ICCC for the summer season and particularly for the month of September, at least with their less dissipative, 1.5-km grid resolution (their Figures 15d and 16b). Their current strength (about 15 cm/s) is higher than the mean value observed by Supić et al. (2000) (less than 8 cm/s) and our event-specific value (about 12 cm/s). Given the low temporal (climatological) and spatial (only 1.125 degrees) resolution of the ECMWF re-analysis winds used by Zavatarelli and Pinardi (2003), it is not possible to associate their countercurrent along Istria with short and strong wind events such as bora, unless there is a cumulative effect in the mean. Zavatarelli and Pinardi (2003) offer no dynamical explanation of their result.

The simulation of the February 2003 bora event reproduces the intricate pattern of current bifurcations and confluences noted in the field observations. The model also reproduces
the so-called oblique current that flowed diagonally from the Po River Delta to the Gulf of Trieste. An earlier version of the simulation, one with climatological heat flux instead of the actual heat flux, was unable to produce this current, and from this, we conclude that this bora event did not only drive waters but also created new water densities, which in turn were driven by the wind, in contrast with summer bora.

Upon closer examination it further appears that it is not so much the cooling caused by bora as its gradient (stronger cooling to the north than to the south, see Kuzmić et al., 2007, Plate 2) that is the root cause of this current. Indeed, the resulting temperature gradient (increasingly lower temperatures to the north) causes a density gradient that is largely responsible for the current. Note that the lower salinity of the Po River plume helps strengthen the current by lowering the density on the other side.

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