Modeling the trajectories of satellite-tracked drifters in the Adriatic Sea during a summertime bora event

Gordana Beg Paklar,1 Nedjelka Žagar,2,3 Mark Žagar,2,4 Ramesh Vellore,5 Darko Koračin,5 Pierre-Marie Poulain,6 Mirko Orlić,7 Ivica Vilibić,1 and Vlado Dadić1

Received 31 August 2007; revised 23 June 2008; accepted 12 August 2008; published 15 November 2008.

During the summertime bora episode of 22–25 June 1995, characterized by hazardous weather conditions with strong winds of over 20 m s⁻¹, two satellite-tracked drifters were present in the Adriatic shelf area. One was on the open sea south of the Istrian Peninsula, while the other, which measured the surface current of 70 cm s⁻¹, was tracked along the western coastal strip. An oceanographic model, forced by the outputs of mesoscale meteorological models and by river discharges, was applied to simulate drifter trajectories during the event. Process-oriented studies performed to determine governing forcings for the drifter movements in different areas of the Adriatic revealed that strong current along the western Adriatic coast resulted from a combined influence of the wind stress and the river discharges. The wind was responsible for the strong drifter movements, while the baroclinic current due to the coastal buoyancy fluxes prevented the drifter from moving close to the shore and from colliding with the coast. At the same time, drifter movements in the open sea resulted from the wind action solely. Differences in the alongshore and offshore vertical density profiles, primarily due to the river inflows, caused 3 times stronger currents in the coastal area as compared to the currents in the open sea. The proper formulation of the drag coefficient was crucial for the successful simulations of the drifter trajectories, as simulations with increased values of the drag coefficient reproduced well the effects of the sea surface roughness and atmospheric instability above the sea.


1. Introduction

[2] In the period between 1990 and 1999 more than 200 satellite-tracked drifters were deployed in the Adriatic [Poulain, 1999, 2001], a shallow semienclosed basin positioned in the northernmost part of the Mediterranean (Figure 1). Analysis of the entire data set indicates complex and variable structure of the surface current field with two cyclonic gyres around the main pits [Poulain, 1999], whose contours agree with early results [Buljan and Zore-Armanda, 1976]. However, the comparison between geostrophic cur-

1Institute of Oceanography and Fisheries, Split, Croatia.
2Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia.
3National Center for Atmospheric Research, Boulder, Colorado, USA.
4Meteorological Office, Environmental Agency of Slovenia, Ljubljana, Slovenia.
5Desert Research Institute, Reno, Nevada, USA.
6Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy.
7Andrija Mohorovičić Geophysical Institute, Faculty of Science, University of Zagreb, Zagreb, Croatia.

Copyright 2008 by the American Geophysical Union.
0148-0227/08/2007JC004536$09.00
is not well documented. Besides, this situation is also interesting as it is controlled by a mesoscale atmospheric disturbance that imparts strong cyclonic vorticity to the wind field, with orographic effect being of secondary importance.

Generally, the bora wind is a dominant feature of the mesoscale atmospheric circulation in the Adriatic region.
was also recognized by other authors [e.g., Ivančan-Picek and Tutiš, 1996; Belušić and Bencetić-Klaić, 2006]. Its main local characteristics are a sudden occurrence and strong variations [e.g., Grubišić, 2004; Belušić and Bencetić-Klaić, 2004]. Onset, duration and strength of the bora are related to the interaction of the synoptic-scale flow with the Alps and, in particular, with the Dinaric Alps, a mountain range extending along the eastern Adriatic coast with maximal height of up to 2 km. The bora flow crosses the Dinaric Alps and reaches the Adriatic Sea as a cold, gusty, northeasterly wind blowing in the offshore direction. Large alongshore variability in the bora speed is mainly related to local topographic effects [e.g., Grubišić, 2004]. Both observational evidence and modeling studies show that the strongest bora events occur during the winter, being related to the passages of fronts from the northwest [e.g., Brzović, 1999b]. In a typical sequence of events over the Adriatic bora begins first in the northern Adriatic following a frontal passage and then gradually spreads along the coast to the southeast. Depending on the synoptic situation and the intensity of the cold air outbreak across the Dinaric Alps strong bora can extend far offshore. Besides a cold air supply over the Dinaric Alps, the bora flow over the Adriatic depends also on the temperature difference between the Adriatic Sea and atmosphere above it [Enger and Grisogono, 1998].

Bora-induced circulation in the Adriatic Sea has been studied from both in situ and satellite data, as well as from the results of numerical models. The analyses of the simultaneous wind and Eulerian current measurements [Orlić et al., 1986; Zore-Armanda and Gačić, 1987] have shown that the bora wind induces currents which may surpass in order of magnitude all the other components of the current field [Orlić et al., 1994]. The horizontal distribution of the bora-induced currents in the northern Adriatic is mostly controlled by the wind-curl effect, since the bottom is almost flat [Kuzmić and Orlić, 1987]. Moreover, oppositely directed wind-driven currents along transect Rovinj-Po River are documented for different types of bora [Beg Paklar et al., 2005]: (1) they are downwind for weaker bora with faster offshore decay, and (2) they are upwind for severe bora with slow offshore decay.

Numerical models forced by climatological bora wind fields with horizontal resolution close to 10 km successfully reproduced either semicircular [Stravisi, 1977] or full cyclonic [Kuzmić and Orlić, 1987; Bone, 1993; Bergamasco and Gačić, 1996] flow in the northernmost part of the Adriatic. However, these time constant wind fields excluded inertial effects which are important for the strongly transient bora forcing. Numerical simulations with more realistic space- and time-varying atmospheric forcing fields have been performed in recent years. For example, fine resolution atmospheric forcing with realistic time variability used in simulations of the offshore Po River spreading resulted in successful reproduction of the northern Adriatic cyclonic gyre [Beg Paklar et al., 2001]. The importance of the high-resolution atmospheric forcing during bora was also recognized by other authors [Pullen et al., 2003; Kuzmić et al., 2007].

In the present study drifter trajectories during summer bora episode are simulated by an oceanographic model forced by the outputs from two mesoscale atmospheric models and by river discharges. The atmospheric models provide realistic spatiotemporal variability of atmospheric fields (wind, air temperature and air humidity) on the mesoscale horizontal resolution (10 km and higher). Two different atmospheric models are used to show the sensitivity of the oceanographic model response to the imposed wind forcing.

Our investigation aims at isolating and understanding processes governing the drifter movements during the strong and relatively rare summertime bora event by comparing the observed and modeled trajectories. Therefore, a number of numerical experiments with different combinations of the three forcing agents (wind stress, river discharge and surface heat fluxes) are carried out and their results are compared to the drifter data. Predictions of the drifter trajectories in the Adriatic were made also by Castellari et al. [2001], but their simulations were made using climatological mean flow field obtained from the drifter data set collected from 1994 to 1996, and the question about their applicability in the periods with strong bora and significant advection arose.

The paper is organized as follows. A brief description of the drifter data set collected in the Adriatic in the 1990s is given in the second section, together with the basic characteristic of the applied meteorological and oceanographic models. The description of the meteorological situation, results of two meteorological models and their comparison with measurements is provided in the third section. This section also presents results of the process-oriented studies performed with an oceanographic model forced by one of the atmospheric models (the ALADIN model) and by the river discharges. The impact of the atmospheric forcing on the results of the oceanographic model is discussed in subsection 3.3, on the basis of a comparison of oceanographic simulations forced by two atmospheric models. Discussion and conclusions are presented in two last, fourth and fifth, sections.

2. Drifter Data Set and Numerical Models

2.1. Drifters

The drifters launched in the Adriatic in the period from 1990 to 1999 were similar to the ones used in the Coastal Ocean Dynamics Experiment (CODE) in the early 1980s [Davis, 1985]. Drifters consist of a slender, vertical, 1 m long negatively buoyant tube with four drag-producing vanes extending radially from the tube over its entire length [Poulain, 1999]. The drifters were tracked by the Argos system onboard the NOAA (National Oceanic and Atmospheric Administration) polar-orbiting satellites. The typical number of good drifter positions per day for the latitude range of the Adriatic Sea using two satellites was eight. The raw position data were despiked using statistical and manual techniques, followed by optimal interpolation or “kriging” which produced regularly sampled data at 2-hour intervals [Hansen and Poulain, 1996]. Velocity components were estimated from centered finite differences of the interpolated positions. The interpolated position and velocity time series were subsequently low-pass filtered (designed filter with cutoff period of 36 hours) and were subsampled at 6-hour intervals. On the basis of the typical Argos location accuracy and the characteristics of the above averaging/filtering, the
low-pass filtered velocity accuracy is estimated to be 2–3 cm s$^{-1}$, being significantly lower than the observed and modeled currents during bora event (see subsection 3.2).

[11] Comparison with current meter measurements [Davis, 1985] and studies using dye to measure relative water movements showed that the CODE drifter-inferred velocities are accurate to about 3 cm s$^{-1}$, even during strong wind conditions. This accuracy was confirmed by recent direct slip measurements with acoustic current meters fitted on the CODE drifters. Theoretically, Stokes drift $u_s$ for monochromatic waves may be estimated by the formula [Skyllingstad and Dembo, 1995]:

$$u_s = \left( \frac{H}{\lambda} \right)^2 \frac{g \lambda}{2 \pi} \exp \left( -\frac{4 \pi z}{\lambda} \right)$$

(1)

where $H$ is the wave height (double amplitude), $\lambda$ is the wavelength, $z$ is the depth and $g$ is acceleration due to gravity (9.81 m s$^{-2}$). During strong bora conditions average $H$ may reach 1.7 m and average $\lambda$ is about 50 m in the middle of the northern Adriatic, as indicated by instrumental measurements during a bora episode in January 1980 [Smircić et al., 2001]. These values result in theoretical Stokes drift of about 8 cm s$^{-1}$ in the first meter of the water. However, bora-related surface waves are usually a mixture of the waves with various spectral characteristics and directions, because of a rather large temporal and spatial variability of the wind. This is also the case for the examined bora episode of 22–25 June 1995 (see subsection 3.1), probably resulting in an even lower Stokes drift and therefore being much lower than the measured and modeled currents in the area (see subsection 3.2).

### 2.2. Meteorological Models

[12] Selected bora event of 22–25 June 1995 was simulated by two mesoscale numerical weather prediction (NWP) models: the Aire Limitée Adaptation dynamique et Développment InterNational (ALADIN) and the Mesoscale Model 5 (MM5) models. Simulated wind time series from the models were verified against the surface wind observations from stations along the Adriatic coast, to insure the models’ validity for the forcing of the oceanographic model. Since the atmospheric observations were limited only to the coastal stations, we were not able to directly verify details of the atmospheric models’ outputs above the Adriatic Sea. However, as shown in subsection 3.3, some ocean data can be used as an indirect verification of the employed meteorological models above the sea.

[13] The central part of the study is based on the results of ALADIN, whereas the nonhydrostatic MM5 model is used for a sensitivity study presented in subsection 3.3, to illustrate the impact of using the different meteorological models in the system for the prediction of the surface transport in the sea. Our choice of the primary model for atmospheric forcings is determined by the following: (1) the ALADIN model is an operational NWP model at the national weather service in Croatia, and (2) a better agreement with coastal meteorological and ocean data is obtained in case of using ALADIN fields, as will be discussed in subsections 3.1 and 3.3, even though the MM5 model is a nonhydrostatic model so that it can be run at a higher horizontal resolution than the hydrostatic ALADIN.

#### 2.2.1. ALADIN Model

[14] The ALADIN model is a hydrostatic, primitive equation model developed in the framework of an international cooperation currently involving around twenty national meteorological services across Europe and northern Africa. The model-evolved from the global ARPEGE (Action de Recherche Petite Echelle Grande Echelle) model of METEO-FRANCE [Courtier et al., 1991], with which it shares most of the physical parameterizations [Cordoneau and Geleyn, 1998] and which provides it with the initial and boundary conditions. The main difference for the limited area is that Fourier transformation is used in both horizontal directions, with an extension zone to ensure periodicity [Bubnova et al., 1993]. The model is running operationally on a daily basis on different domains over participating countries. In all cases initial states and time-dependent lateral boundary fields are obtained from the operational outputs of the ARPEGE model.

[15] The model has been extensively used and verified over the broader area of the Adriatic [e.g., Brzović, 1999a, 1999b] before it became the operational model at the Meteorological and Hydrological Service of Croatia in 2001. In particular, the model has been applied for studying the mesoscale environment in which severe winds in the Adriatic region occur [Brzović, 1999b; Brzović and Strellec-Mahović, 1999; Ivatek-Sahdan and Tudor, 2004].

[16] The bora case of 22–25 June 1995 was simulated on a domain which covered the Adriatic region together with the surrounding orography of the Alps, the Dinaric Alps and the Apennines. A Lambert grid of 135 × 111 points and 27 unequally spaced hybrid $\eta$ levels in the vertical direction was used. The horizontal resolution was 10.8 km. Physical parameterizations used in the model setup were presented by Cordoneanu and Geleyn [1998]. Initial and lateral boundary conditions were operational analyses of the ARPEGE model which, thanks to its stretched grid, has a mesoscale resolution (30–35 km) over this area.

#### 2.2.2. MM5 Model

[17] The fifth-generation Penn State/National Center for Atmospheric Research (NCAR) Mesoscale Model (MMS) was configured in a nonhydrostatic mode with 36 vertical layers in a terrain following (sigma) vertical coordinate system [Grell et al., 1995]. The physical parameterizations including the processes involving planetary boundary layer (PBL), cloud microphysics and radiation are described by Grell et al. [1995]. The MM5 model has been used worldwide in a variety of research and application studies. Specifically, it has been employed in studies of the atmospheric dynamics along the California coast [Koračin et al., 2004] and as a driver of the POM model applied to study a wintertime bora case from 1987 [Beg Paklar et al., 2001].

[18] The model domain consists of 208 × 208 (286 × 235) grid points in the horizontal plane for 9-km (3-km) resolution grid. The topography and land use data in two inner domains were obtained by interpolating the 30' (~0.9 km) U. S. Geological Survey data sets to the model grid. The domains are two way nested and interact through their lateral boundaries. First guess surface and upper air model variables were obtained by interpolating the operational model outputs from the U.S. National Centers for Environmental Predictions (NCEP) archived at a horizontal resolution of 2.5° × 2.5° to the model grids. Cressman's
objective analysis [Cressman, 1959] was used to assimilate the surface and upper air observations into the first guess fields to create the initial and boundary conditions for the model run.

2.3. Oceanographic Model

[19] The Princeton Ocean Model (POM), a three-dimensional primitive equation nonlinear model, was used to simulate the thermodynamic properties of the Adriatic Sea. Physical and numerical properties of the model are described in detail by Blumberg and Mellor [1987]. The equations which capture the model physics are traditional equations for the conservation of mass, momentum, heat and salt coupled with the equation of state [Mellor, 1991]. In the application on the Adriatic shelf three simplifying approximations were used: the hydrostatic, Boussinesq and “f-plane” approximations. Parameterization of vertical mixing of momentum, heat and salinity is provided by a “Level 2.5” turbulence closure scheme on the basis of the evolution of turbulence kinetic energy and turbulence macroscale [Mellor and Yamada, 1982]. The horizontal subgrid-scale mixing is provided by a Smagorinsky [1963] type formulation, adapted to the model vertical coordinate system [Mellor and Blumberg, 1985]. Simulations of the bora influence on the Adriatic were carried out on a rectangular grid with 5 km resolution in the horizontal plane and 16 vertical sigma layers. The horizontal grid spacing was constant and $48 \times 94$ points covered the Adriatic shelf area, while the vertical spacing varied to accommodate better resolution near the surface and bottom. A minimum coastal depth was set to 10 m. The model grid has $x$ axis rotated by 45° from the east in the anticlockwise direction. The topography of the studied area was digitized from bathymetric chart by the Hydrographic Institute [1990] in the Mercator projection and smoothed with the Shapiro [1970] filter. In the numerical experiments an external time step of 20 s and an internal time step of 600 s satisfied the Courant-Friedrichs-Lewy criterion.

[20] The wind stress and heat fluxes representing the POM surface boundary conditions were calculated from the ALADIN and MM5 hourly wind vectors, air temperatures and humidities and instantaneous sea surface temperatures (SST) from the ocean model. Values of the atmospheric fields at intermediate time steps were obtained by the linear interpolation. Atmospheric fields from ALADIN and 9 km MM5 were inserted into the 5 km grid of the oceanographic model using bilinear interpolation, whereas in forcing POM with 3 km MM5 we used the bin averaging. Surface water fluxes were neglected in all experiments since their influence cannot be recognized for short-lived wind episodes such as the one considered in this study. It was not the case with surface heat fluxes because of their importance for the atmospheric stability and momentum transfer as will be discussed in subsection 3.2.

[21] The wind stress at the sea surface was modeled using a bulk coefficient approach with the drag coefficient $C_D$ according to Large and Pond [1981] for the stable atmosphere. The drag coefficient dependence on the atmospheric stability and the aerodynamic surface roughness (which is in turn a function of the sea state) was also allowed for. The wind wavefield during the bora changes the roughness of the sea surface and therefore modifies the wind stress. Since we had no information on the wind wavefield during the simulated bora event, the effect of the surface roughness was introduced by simple linear increase of the wind stress, which is in agreement with wind stress estimations during the bora in the Adriatic [Cavaleri and Zecchetto, 1987; Lionello et al., 1998]. Furthermore, during a bora event, the continental air that bursts over the Adriatic can be up to 15°C colder than the sea surface and the atmospheric layer above the sea is extremely unstable. Increase of the drag coefficient with atmospheric instability has been demonstrated by many authors [e.g., Leetmaa and Bunker, 1978; Behringer et al., 1979; Cavaleri and Zecchetto, 1987]. The effect of atmospheric stability on the wind stress $\tau$ was introduced according to Behringer et al. [1979]:

$$\tau = \tau_0 (1 + \varepsilon \theta), \quad \theta = T_a - T_s, \quad (2)$$

where $\tau_0$ is the wind stress according to Large and Pond [1981] (or the linearly increased value) and the parameter $\varepsilon$ describes the strength of the thermal influence on the wind stress. The air temperature $T_a$ was obtained from the selected atmospheric model and the sea surface temperature $T_s$ from the oceanographic model.

[22] The longwave radiation and the turbulent exchange of heat between the sea and the atmosphere due to the sensible and latent heat flux were calculated according to Large [1996]. The incoming shortwave radiation was calculated according to Haurwitz [1941], assuming that the sun altitude is a function of local time, geographic latitude and declination. The attenuation of the shortwave radiation with depth for chosen 1B optic type water followed Paulson and Simpson [1977] and the attenuated values were added to the heat equation as a source term.

[23] The rivers were introduced in the model as the source terms in the continuity equation [Kourafalou et al., 1996] and, moreover, were assumed to have a zero salinity and 1°C higher temperature than the seawater [Sturm et al., 1992]. The Po River was introduced in the top model layer of six coastal nodes that correspond to the position of the Po River delta as a line source. Other rivers on the Adriatic shelf were introduced in the model as point sources at the model coastal nodes that correspond to the river locations (Table 1). Climatological discharges for June according to Raichic [1994] for all rivers outflowing on the Adriatic shelf were used in the initialization experiments for salinity (Table 1). In order to improve the realism of simulations during this bora event we used daily Po River discharges, while discharges for the other rivers were scaled according to the Po River values. Namely, we multiplied climatological June discharge of each river by ratio of the realistic Po River discharge to the Po River values. During this bora event we used daily Po River discharges, while discharges for the other rivers were scaled according to the Po River values. Namely, we multiplied climatological June discharge of each river by ratio of the realistic Po River discharge to the Po River values. In each case June climatological values followed estimations by Raichic [1994].

[24] At the seafloor water and heat fluxes vanished, while the bottom stress was determined by matching velocities to the logarithmic law at the wall, at least in the sufficiently shallow water. The upstream advection was used for temperature and salinity at the southern open boundary employing climatological values from the MEDAS database [Ivanković et al., 2000] while the normal velocity component was prescribed by the Sommerfeld radiation condition.
On the synoptic scale, this was a typical blocking situation, known to be very persistent. In such cases, the upper level flow is characterized by a NE–SW oriented trough over Italy and an anticyclone over England and the North Sea. A cold air supply over the Dinaric Alps ensured a longer lasting bora episode, characterized by unstable weather conditions. The bora began on 22 June following the passage of a cold front from the northwest. After the front air temperature decreased sharply in the area around the northern Adriatic. The decrease of noon air temperature between 22 and 23 June was 10–16°C at all stations in this region. On the basis of the numerical results of Enger and Grisogono [1998], the air temperature decrease, which was stronger over land, could have further contributed to the bora strength over the open Adriatic. Different aspects of the case were described in more details by Brzović et al. [1997] together with the results of various numerical simulations.

[27] Figure 2 shows 10 m wind and 2 m air temperature fields over the Adriatic Sea for 23 June (0000 UTC), 24 June (0000 and 1200 UTC) and 25 June (0000 UTC) obtained from the ALADIN model. Figure 2a illustrates a typical distribution in the surface wind field in the Adriatic related to the passage of strong atmospheric fronts. Strong bora covers the northern Adriatic while a weaker southeasterly wind locally called jugo blows in the southern Adriatic. Such structure of the surface wind field is accompanied by a cyclonic circulation in the lower troposphere over the Adriatic, which, depending on the larger-scale flow, may last for a few days triggering local instabilities [Brzović and Strelec-Mahović, 1999]. A dominant feature in Figure 2 is a cyclonic wind structure over the northern Adriatic Sea, which was strongest at 0000 UTC on 25 June. During the following 12 hours this cyclonic vortex weakened and northwesterly uniform winds covered the whole Adriatic (not shown). It is important to notice that the strong bora does not reach the western coast of the northern Adriatic, but turns to northwesterly directions within the strong cyclonic vortex (Figures 2c and 2d). Similar cyclonic structure in the surface wind field is seen in the mid-Adriatic somewhat earlier (Figure 2b), but the vortex was much weaker at that time.

[28] The outputs of the simulations were verified against surface observations along the eastern Adriatic coast. Comparison between measured hourly wind vectors at two meteorological stations in Trieste and Melina and the model output at the corresponding grid points shows a very good agreement (Figure 3). A remarkable feature in Figure 3 is a good timing and variability of modeled winds. This is probably due to parameterization of subgrid-scale orography in the ALADIN model [Cordoneanu and Geleyn, 1998], especially tuned for the orographically complex Alpine region where the model is used most extensively.

[29] Similar to Figure 2, Figure 4 shows 10 m wind and 2 m air temperature fields over the Adriatic Sea obtained from the MM5 model. Bora features simulated by MM5 generally correspond to ALADIN fields in the northern Adriatic during 23 and 24 June 1995 (Figures 4a, 4b, and 4c). However, the horizontal extent of the cyclonic wind gyres were weak in the simulations by MM5, and the positioning of the gyres were to the east of the ALADIN simulated positions. A gradual weakening of the cyclonic
wind vortex simulated by ALADIN can hardly be noticed in the result from MM5. The verification using the observations at Melina and Trieste against the MM5 simulated wind fields showed a relatively good agreement with the observed timing although it is less successful than ALADIN. MM5 simulated rather pronounced northerly winds at Trieste if compared to the observations and significantly stronger winds at this location than ALADIN (Figure 5 as compared to Figure 3).

In this particular study, even though MM5 simulations were conducted using a fine, 3 km resolution in the horizontal direction, it was seen that the finer horizontal grid resolution did not ensure a better accuracy of the simulated winds. Furthermore, the 3-km grid results significantly influenced its parent nest results on 9-km grid through two-way nesting strategy. Various numerical experiments conducted to explore the alternative choice of initial conditions (ECMWF) led to an apparent early inference that the initialization in ALADIN is superior to the initial conditions used in MM5. The study also provides evidence on the importance of the representation of orography in the atmospheric model when forcing marginal seas such as the Adriatic, surrounded by the land with strong orographic features. The orography used in the ALADIN overcame its coarser resolution and provided more suitable forcing fields than the one used in the MM5.

### 3.2. Process-Oriented Oceanographic Studies

Trajectories of two drifters present in the Adriatic shelf area during the bora episode of 22–25 June 1995 are shown in Figure 6. The maximal current speed of 70 cm s\(^{-1}\) was deduced from the drifter movements in the Italian coastal area. This was also the maximal current speed of the entire drifter data set and it significantly affected the calculated residual circulation [Poulain, 1999].

To answer the question on the principal forcing mechanism for the drifter movements a number of numerical experiments with different combinations of three external forces (wind stress, heat fluxes and river discharges) were carried out. In the process-oriented studies the oceanographic model was forced by the atmospheric fields obtained by the ALADIN model as these experiments provided more realistic prediction of the surface transport in comparison with results obtained using the MM5 forcing. Performed experiments are listed in Table 2, where SW denotes experiments with wind forcing, SR are experiments...
with river discharge control, SF are experiments with heat flux forcing, SWR are experiments with combined action of winds and rivers, etc. First we studied the influence of single forcings, then the effects of paired influences and finally we studied the effect of the combined action of all three factors.

All experiments were initialized with satellite sea surface temperature field obtained for 20 June 1995, as it was the last day without clouds before the bora started to blow, and with the vertical structure according to the summer climatological values [Artegiani et al., 1997]. Summer climatological profile was imposed on satellite sea surface temperatures interpolated on the ocean model grid and at each grid point vertical temperature profile had the same slope as the climatological one. Initial salinity fields for the experiments including river influences were obtained by the results of 10-day experiments with river discharges being the only forcing, as explained in subsection 2.3., whereas experiments without rivers were initialized with homogeneous salinity field of value 38. We assumed that the state of the rest was suitable initial condition for the current field mostly because of the nature of our investigation that was oriented toward the processes.

In the numerical experiments movements of ten drifters were simulated. Six were used for the open sea area; only one of them had initial position that exactly coincided with the real drifter position while the others were displaced from the real initial position to the neighboring grid points. Selected positions gave the best results in comparison to use of the other grid points as initial. Since the drifter initially positioned north of the Po River delta at a grid point that coincided with real position of the drifter quickly collided with the coast in most of experiments, four drifters were initially placed a little bit south of the real position and were used for the qualitative comparison with the observed drifter trajectories. Observed movements indicate that the drifter in front of the Po River delta was too close to the coast for the oceanographic model with 5 km resolution and 10 m minimum coastal depth to reproduce its path realistically.

In all the experiments with the wind stress being the only external forcing the drifters in the northern part of the domain quickly collided with the coast. The drifters in the open sea area moved with increased speed as the drag coefficient increased (Figure 7). When the drag coefficient according to Large and Pond [1981] was applied, drifter movements were

---

**Figure 3.** Hourly wind vector time series from meteorological stations Trieste and Melina and corresponding model nodes during the bora episode of 22–25 June 1995.

---
much weaker than the observed (Figure 7a, experiment SW1). Trajectories comparable with the observed ones were obtained in the experiments SW4 in which the drag coefficient has been increased by factor 3.5 (Figure 7c), while lower and higher values resulted in either an underestimation (SW1, SW2, SW3) or an overestimation of the movements (SW5).

It is interesting here to note that the introduction of the dependence of the wind stress on the atmospheric instability according to Behringer et al. [1979] caused unrealistically intensified movements of the drifters in the open sea, particularly during 25 June (Figure 7d). With the effect of the air-sea temperature difference introduced, the absence of the interaction between the air and sea through the surface heat flux resulted in the unrealistic temperature difference, too strong wind stress and consequently unrealistic drifter movements. In the described experiments two values were actually used for the factor \( e \) in equation (2) which determines the strength of the wind stress dependence on the air-sea temperature difference. The first one \( (e = 0) \) in experiments SW1, SW2, SW3 and SW4 was chosen to illustrate the case without thermal effect on the wind stress, whereas the second one \( (e = 0.3) \) in SW5 experiment was selected according to the study of Behringer et al. [1979] for the Gulf Stream and simulations by Beg Paklar et al. [2001] for the offshore Po River spreading under the influence of the bora.

Surface current fields obtained in the experiment SW4 show strong spatiotemporal variability, more pronounced during the last 2 days. On 24 June 0000 UTC surface currents were dominantly of NNW direction in the northern part of the domain with intensification in front of the Istrian coast (Figure 8b). Further south flow became of SW direction. On 25 June 0000 UTC a cyclonic eddy formed in the middle part of the northern Adriatic was embedded in the basin-wide cyclonic circulation (Figure 8c). A basin-wide cyclonic circulation dominated 24 hours later, while the small eddy disappeared (Figure 8d). Predicted maximal velocities along the western coast, where velocity of 70 cm s\(^{-1}\) was deduced from drifter movements, range from 40 cm s\(^{-1}\) in SW1 experiment to 80 cm s\(^{-1}\) in SW5 experiment. The wind stress dependence on the atmospheric instability included in the experiment SW5 did not influence the directions in the current field, only its intensities.

In the experiments SR1 and SR2 with Po River discharge and river discharges from all Adriatic shelf rivers, respectively, acting as the only forcing, drifters in the open sea were almost still. On the other hand drifters in front of Venice had unrealistic trajectories that follow baroclinic

Figure 4. Same as Figure 2 but for the MM5 model having horizontal resolution of 9 km.
currents induced by river discharges (Figure 9). In the experiment with only the Po River discharge (SR1) drifters moved toward south (Figure 9a), whereas introduction of the other rivers (SR2) resulted in cyclonic current on the whole shelf and thus influenced the drifters to move first parallel with the Italian coast and then southeastward (Figure 9b). Initial position of the drifter in the coastal area was at the outer edge of Po River bulge, i.e., at the northern part of the plume [Kourafalou et al., 1996]. Inside bulge currents are initially northward and then turn anticyclonically because of the Coriolis force and proximity of the north coast [Kourafalou, 1999]. At the beginning of SR1 (Po River only) experiment drifter was at the edge of the bulge and was carried by its southward flow as can be seen on Figure 10. In the presence of the other Adriatic shelf rivers (SR2 experiment) offshore extension of the Po plume was reduced (Figure 10), and the initial drifter position was out of it. But because of buoyant influence of other rivers, a baroclinic current was developed and dragged the drifter again toward river bulge (Figure 10). Therefore, the drifter first moved along the north coast because of buoyancy induced flow and then started to move southward similarly as in SR1 experiment (Figure 9). Velocity and salinity fields from Figure 10 elucidate more clearly drifter paths in the experiments SR1 and SR2.

[39] Surface heat fluxes alone in experiment SF could not induce drifter movements neither along the north Adriatic coast nor in the open sea. Also in the combination with river discharges in experiments SRF1 and SRF2 they had no effect on the current field (not shown).

[40] A comparison of the drifter trajectories in the experiments with two forcings including wind stress is presented in Figure 11. A combination of the wind stress and heat fluxes in SWF experiment produced satisfactory trajectories for the drifters in the open sea area, while drifters north of the Po River delta collided with the coast. Although the drifters returned to the wet grid point after the collision with the coast, wind-induced currents toward the coast inhibited their further movements. On the other hand, combination of the wind stress and river discharges (experiments SWR1 and SWR2) resulted in successful reproduction of the drifter movements in the northern part of the domain, especially with action of all rivers on the shelf, while too intensive movements were obtained for the drifters in the open sea, particularly on 25 June. Too strong movements in the open sea area, especially during the last day of simulation, resulted from the effect of atmospheric instability on the

Figure 5. Same as Figure 3 but for the MM5 model having horizontal resolution of 9 km.
wind stress, similarly as in the SW5 experiment. In both SWR1 and SWR2 experiments, the heat flux between the sea surface and atmosphere above was missing and therefore there were no changes in the sea surface temperature field due to the atmospheric influence. During this bora event air temperatures at the coast decreased about 10–15°C and similar behavior (with lower amplitudes) is expected to occur also above the sea. Without heat exchange the differences between the air and sea surface temperatures were increasing during the simulation and resulted in the unrealistically increased wind stress, surface currents and consequently drifter movements. In case of using parameter $\varepsilon$ equals to 0, i.e., using the wind stress without thermal dependence, drifter trajectories would be shorter and closer to the realistic ones, but we used the same parameters in all experiments with multiple forcings in order to make experiments comparable to the final result.

Low-salinity river-influenced water extended further south and offshore in SWR2 experiment than in SWR1, as can be seen on Figure 12. Differences in the area under the river influence resulted in different drifter trajectories in the open sea obtained in these two experiments (Figure 11). Open sea trajectories, calculated in the experiment SWR2 at

Table 2. List of the Process-Oriented Experiments for the Bora Episode Lasting From 22 to 25 June 1995

<table>
<thead>
<tr>
<th>Experiment</th>
<th>External Forcing</th>
<th>Initialization</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1</td>
<td>1 0.0</td>
<td>AVHRR, VS 37</td>
</tr>
<tr>
<td>SW2</td>
<td>2 0.0</td>
<td>AVHRR, VS 37</td>
</tr>
<tr>
<td>SW3</td>
<td>3 0.0</td>
<td>AVHRR, VS 37</td>
</tr>
<tr>
<td>SW4</td>
<td>3.5 0.0</td>
<td>AVHRR, VS 37</td>
</tr>
<tr>
<td>SW5</td>
<td>3.5 0.3</td>
<td>AVHRR, VS 37</td>
</tr>
<tr>
<td>SR1</td>
<td>0 0 PO</td>
<td>AVHRR, VS 10 D. PO</td>
</tr>
<tr>
<td>SR2</td>
<td>0 0 ALL</td>
<td>AVHRR, VS 10 D. ALL</td>
</tr>
<tr>
<td>SF</td>
<td>0 0 Q</td>
<td>AVHRR, VS 37</td>
</tr>
<tr>
<td>SRF1</td>
<td>0 0 PO Q</td>
<td>AVHRR, VS 10 D. PO</td>
</tr>
<tr>
<td>SRF2</td>
<td>0 0 ALL Q</td>
<td>AVHRR, VS 10 D. ALL</td>
</tr>
<tr>
<td>SWR1</td>
<td>3.5 0.3 PO</td>
<td>AVHRR, VS 10 D. PO</td>
</tr>
<tr>
<td>SWR2</td>
<td>3.5 0.3 ALL</td>
<td>AVHRR, VS 10 D. ALL</td>
</tr>
<tr>
<td>SWF</td>
<td>3.5 0.3 Q</td>
<td>AVHRR, VS 37</td>
</tr>
<tr>
<td>SWRF1</td>
<td>3.5 0.3 PO Q</td>
<td>AVHRR, VS 10 D. PO</td>
</tr>
<tr>
<td>SWRF2</td>
<td>3.5 0.3 ALL Q</td>
<td>AVHRR, VS 10 D. ALL</td>
</tr>
</tbody>
</table>

$\varepsilon$, nondimensional parameter from equation (2); AVHRR, sea surface structure according to the Advanced Very High Resolution Radiometer satellite estimates; VS, vertical stratification according to climatological data; ALL, all Adriatic shelf rivers; Q, four components of heat flux; 10 D. PO, initialization with 10 days Po discharge; 10 D. ALL, initialization with 10 days discharge from all Adriatic shelf rivers.
the end of bora episode, were in the area of lower salinities that increased stratification, and according to Pollard et al. [1973] reduced mixed layer depth and consequently increased surface currents.

The best results for both drifters were obtained in the experiments with all three forcings considered, denoted SWRF1 and SWRF2 and shown in Figure 13. Wind affects the drifter movements in the open sea south of the Istran Peninsula, and for the correct estimate of the trajectories the

---

**Figure 7.** Drifter trajectories obtained from the experiment with the wind stress being the only forcing with (a) drag coefficient dependent on wind velocity according to Large and Pond [1981] (SW1), (b) drag coefficient 2 times larger than in Figure 7a (SW2), (c) drag coefficient 3.5 times larger than in Figure 7a (SW4), and (d) drag coefficient 3.5 times larger than in Figure 7a and allowing for its dependence on the atmospheric instability (SW5). Asterisks denote the drifter initial position on 22 June 1995, whereas circles denote their positions at the end of each day. Realistic drifter trajectories are represented by thicker lines.
drag coefficient and heat flux exchange between the sea surface and the air above need to be carefully parameterized. On the basis of the results of many experiments we found that the parameter $\varepsilon$ from equation (2) with value of 0.3 provided the best agreement with observed trajectories in these final experiments. The drifter initially placed north of the Po River delta moved because of the combined effect of the wind and the coastal buoyancy flux, while the heat fluxes did not have significant influence.

[43] Time evolution of the current field in the experiment with all the external forcings included (SWRF2) is depicted in Figure 14. Variable cyclonic eddies are present in the area of the northern and middle Adriatic during almost the entire episode. Surface currents on 25 June 0000 UTC indicate a wind-induced cyclonic eddy embedded in the basin-wide cyclonic circulation (Figure 14c). The small eddy was obviously responsible for the accurately reproduced shape of the drifter trajectory in the open sea. Similar structure as in the sea south of the Istrian Peninsula can be also observed in the surface winds simulated by the ALADIN model (Figure 2). By comparing results from SWRF2 experiment with results from SW4 (Figure 8) it can be seen that the barotropic component of the current field dominated in the open sea area during the whole bora episode, while its influence spread over the whole basin during the periods with particularly strong wind (24 June). It is interesting to note that wind fields on 24 and 25 June (Figures 2 and 4) had alongshore component which induced currents in the same direction as buoyancy induced Western Adriatic Current. Therefore, during these dates wind-induced current field resembled one from the final experiment, although it was of the lower strength. In the final experiment western coastal current increased because of superposition of the wind and buoyancy induced component. The baroclinic component induced by the coastal buoyancy fluxes had dominant role along the northern and western Adriatic coasts and it was responsible for preventing the drifter tracked there to move too close to the shore. A maximal current of 60 cm s$^{-1}$ was predicted in the western coastal area.

3.3. Sensitivity of the Drifter Movements to the Atmospheric Forcing

[44] Here we would like to address the sensitivity of the reproduced sea circulation and drifter trajectories that arise from forcing the oceanographic model by different mesoscale meteorological models. The differences between the
ALADIN and MM5 model results in the present case can occur for a number of reasons and their exact identification is beyond the scope of this paper. By adding simulations with the MM5 model, we simply illustrate the difference in the drifter movements as a function of the wind forcing in the case of bora which is often a dominant forcing of the Adriatic Sea. In this study commonly used setups for ALADIN and MM5 are applied, as described in subsection 2.2.

Drifter trajectories obtained in two numerical experiments in which POM model used 9 km MM5 outputs are shown on Figure 15. Results obtained in the case of forcing POM by 3 km MM5 were almost the same as those using 9 km MM5, possibly indicating insufficiencies in the model’s subgrid-scale parameterizations. In both experiments shown the ocean model was forced with the wind stress, surface heat fluxes and rivers discharging along the Adriatic shelf coasts. In the first experiment (Figure 15a) the drag coefficient was increased by a factor of two with respect to the value predicted by Large and Pond [1981] formulation, whereas in the second one (Figure 15b) the drag coefficient was increased by a factor 3.5, i.e., by the same value used in the similar experiment (SWRF2) with the ALADIN forcing. In the first case drifters in the northern part of the domain collided with the coast, while the movements in the open sea were overpredicted (Figure 15a). In the second experiment drifters in front of Venice had realistic trajectories, whereas movements in the open sea were stronger than in the previous case (Figure 15b). In this experiment, the drifter, which in reality stayed in the open sea, was displaced toward the western coastal area.

Differences in drifter movements on Figures 15 and 13 illustrate the importance of a careful model tuning before its application and need for more field experiments in data sparse areas such as the Adriatic. Presented example also shows how oceanographic measurements and modeling can be used for an indirect verification of the wind fields predicted by meteorological models. Usually, meteorological measurements above the open sea do not exist and if they do exist they do not have a necessary density and therefore it is hardly possible to verify the model results. Process-oriented studies for this bora case showed that the drifter in the open sea area was moving solely because of the wind-induced currents, or more precisely it was captured by a wind-induced cyclonic eddy formed in the middle part of the northern Adriatic. Since the position of this eddy was not well reproduced by MM5, related surface transport differed from the observed trajectories (Figure 15) suggesting a need for improving the MM5 simulations for the present case.

4. Discussion

The effect of the bora wind on the Adriatic circulation during winter is well studied [Orlić et al., 1994], but studies of the bora influence in the summer season are rare [Bergamasco and Gačić, 1996]. This fact makes our investigation of the bora event of 22–25 June 1995 interesting from the oceanographic point of view. The presence of two satellite-tracked drifters, one in the open sea area south of the Istran Peninsula and the other one in the western coastal strip, enable direct evidence of the sea surface circulation during this rare event to be obtained. Moreover, the maximal current of the entire drifter data set, collected between 1990 and 1999, of 70 cm s⁻¹ was calculated by Poulain [1999] from the movements of drifter tracked along the western...
coast during this particular bora. The selected bora episode was intriguing also from the meteorological point of view, since it was characterized by strong and sudden winds accompanied with air temperature decrease of about 10–15°C at most meteorological stations in the area in a short time period (24 hours). Furthermore, it is interesting to note that the double-vortex system usually observed in the northern Adriatic during the bora episodes, with cyclonic gyre in the northernmost part and anticyclonic one further south [Zore-Armanda and Gačić, 1987], was absent during this bora case. Double vortex system is related to the variable bora wind field, with alternating areas of positive and negative vorticity along the eastern Adriatic coast. Such bora variability is common in the colder part of the year, being related to the synoptic-scale atmospheric disturbances and strong modifying influence of the Dinaric mountain range along the eastern coast. The presented summer situation was different, since it happened on the mesoscale and was characterized by a strong cyclonic vorticity in the wind field, with the orographic effects being of secondary importance.

[48] Numerical simulations of the effect of the bora episode of 22–25 June 1995 on the Adriatic were performed with the oceanographic model forced by the outputs of two meteorological models, ALADIN and MM5. Calculations of the drifters' trajectories showed large drifter movements in the strong wind-induced current fields. Large space- and time-variability of the sea surface current field would be impossible to reproduce without time variable atmospheric forcing fields calculated with fine spatial resolution. The main goal of our investigation was to resolve the dominant forcing for the drifters launched in two different areas and to achieve it we performed a number of process-oriented studies using the ALADIN outputs. The ALADIN model results were chosen to force the POM as this setup provided more realistic trajectories as compared to those obtained by using the MM5 forcing. Also wind time series from the meteorological stations along the Adriatic coast showed better agreement with the corresponding time series simulated by the ALADIN model than with those obtained from MM5. Process-oriented experiments showed that maximal current obtained along the western coast was a result of a combined influence of the wind stress and rivers discharging along the Adriatic shelf coast. The wind was responsible for the strong drifter movements, whereas the baroclinic current in front of the Po River delta due to the coastal buoyancy fluxes prevented the drifter from moving too close to the shore and from colliding with the coast. In the experiments with no river influence the drifter initially placed north of the Po River delta very soon approached the coast. By introducing the rivers along the Adriatic shelf coasts, the buoyancy current was generated and the drifter stayed offshore. The
current variability south of the Po River delta was under the combined influence of winds and rivers. Experiments with the Adriatic river discharges and idealized wind field performed by Kourafalou [1999] showed increased southward movements of the Po influenced waters in case of NE bora wind. Realistic wind fields obtained by ALADIN indicated the alongshore component which created corresponding surface transport in the western coastal area even in experiments with only wind action. This current was further enhanced by the alongshore river induced current with which it had the same alongshore direction in all experiments having wind stress and rivers as driving mechanisms, as can be seen in comparison of the current fields from Figures 8 and 14. The southward buoyancy current intensification was stronger in our study than in the case of idealized NE wind from Kourafalou [1999].

Because of the importance of the rivers for the coastal drifter movements, the salinity initialization experiment was particularly important. The 10-day duration of the initialization for the experiments with the river influence was selected because of the initial position of the drifters and character of the Po River plume. The drifter trajectory in the open sea area was out of the reach of the river influence, whereas the other drifter moved dominantly in the area of Po River plume. Although the 10-day experiment is not adequate for the full development of baroclinic circulation generated by all the Adriatic rivers, it is sufficient for the development of the Po plume which is crucial for the coastal drifter [Kourafalou, 1999]. Even though Po offshore extension was reduced during the 10-day experiment with all river discharges along the northern Adriatic coast, partially developed baroclinic current dragged the...
Figure 12. Surface salinity fields from (a, b) SWR1 (wind stress and Po River) and (c, d) SWR2 (wind stress and all Adriatic shelf rivers) experiments for 0000 UTC on 24 June 1995 (Figures 12a and 12c) and 0000 UTC on 26 June 1995 (Figures 12b and 12d).

Figure 13. Same as Figure 7 but with (a) a combined action of the wind stress, Po River discharge, and surface heat fluxes (SWRF1) and (b) a combined action of the wind stress, discharges from all Adriatic shelf rivers, and surface heat fluxes (SWRF2).
drifter again in the Po plume. Since the Po River plume, according to Kourafalou [1999], is surface advected, which means that the buoyancy dominates over the mixing tendency, the density vertical structure does not change significantly during numerical experiments as the offshore plume range. Therefore, the 10-day initial experiment enabled successful simulation of the surface trajectory in the plume area.

Figure 14. Surface current fields obtained from the experiment with a combined action of the wind stress, discharges from all Adriatic shelf rivers, and surface heat fluxes (SWRF2) on (a) 0000 UTC 23 June 1995, (b) 0000 UTC 24 June 1995, (c) 0000 UTC 25 June 1995, and (d) 0000 UTC on 26 June 1995.

Drifter movements in the open sea area resulted from the wind action solely. Different surface velocities in the two Adriatic areas were not result only of the different wind stresses, they were also influenced by the different stratifications in the two areas (Figure 16). Increased stratification amplified the Brunt-Vaisala frequency and decreased mixed layer depth [Pollard et al., 1973]. Since the wind-induced surface velocity is proportional to the ratio of the Ekman transport to the mixed layer depth, its value is significantly higher in the coastal area. Stronger density stratification in the coastal area was the result of river discharges, while in the open sea the density was determined by the vertical temperature structure dominantly and had lower vertical gradient (Figure 16). Mixed layer depths in two Adriatic areas were different for almost factor of three: in the coastal strip the mixed layer depth was approximately 10 m, whereas in the open sea it was about 30 m. That was the main reason for such significant differences in the surface currents of the two areas (20 versus 70 cm s\(^{-1}\)) with very similar wind velocities.

The comparison of drifter movements before and during bora episode indicates much stronger movements during bora (Figure 6), which is in correspondence with the increased Ekman transport. The bora event probably also influenced geostrophic component of the current field through its influence on the extent of the river plume, but this space limited effect was not crucial for the drifter movements. Namely, the wind-induced component of the current field was much stronger than the geostrophic one, and both of the drifters were outside of the regions with significant salinity changes: the first one was inside the river plume most of the time, whereas the other was constantly outside of the plume.

Experiments showed that the proper formulation of the drag coefficient was crucial for the correct simulations of drifter trajectories. Classical theoretical values of the drag coefficient according to Large and Pond [1981] did not produce acceptable results. The dependence of the drag
coefficient on the wind wavefield and on the atmospheric instability, with both processes increasing the value of the drag coefficient, should be allowed for this and similar synoptic situations.

The drag coefficient dependence on the wavefield was recognized in some investigations in the northern Adriatic as well as in the other areas. The estimation of the Reynolds stress in the northern Adriatic during the bora event indicates a value 5 times larger than the expected theoretical value for the same wind speed [Cavaleri and Zecchetto, 1987]. Empirical and numerical considerations of the wind stress during the bora in the northern Adriatic by Lionello et al. [1998] resulted in 2 times stronger wind stress during the bora when considering the effect of wind wavefield than without this effect. Toba et al. [1990] showed that the drag coefficient depends on the sea state and that under stormy conditions it can exceed usual theoretical predictions [Charnock, 1955] by a factor of two to three. The short bora duration, its short fetch and the shallowness of the sea probably also increase the wind stress, as it was found in some other regions during similar conditions [Smith, 1980; Geernaert et al., 1986; Donelan et al., 1993].

Although the sea surface is usually colder than the air above it during the summer season, in this particular case large reduction of the air temperature (10–15°C) in a short period (24 hours) caused a strong atmospheric instability above the sea, thus increasing turbulent momentum exchange between the sea and the atmosphere. Figure 17 shows that air/sea temperature differences in the Adriatic Sea area during bora were up to 12°C and the strongest temperature differences coincided with areas of the strongest wind. Therefore the thermal influence had positive feedback effect on the wind stress. As a result, the intense sea surface currents were generated in the open sea as well as in the coastal areas. The obtained result indicates the importance of the knowledge of the detailed sea surface temperature structure, which along with the air temperature determines the drag coefficient, in all synoptic situations with significant air/sea temperature differences. Parameterization of the surface heat exchange also played an important role here since its introduction in the experiments decreased air-sea temperature difference and consequently the wind stress and accompanied sea surface transport. Similar result was obtained by Pullen et al. [2007] by comparison of the two-way interaction in the coupled atmosphere-ocean model with a simple one-way interaction. The two-way coupling during a bora episode resulted in 12% reduction of surface current speeds in comparison with simulations having one-way interaction. Although here we did not use full two-way interaction, by calculating the wind stress and surface heat fluxes using atmospheric fields from mesoscale models and using instantaneous sea surface temperatures from the POM model, a step toward a full integration of the atmospheric and oceanographic models was made. These results, as well as similar results by other authors [Loglisci et al. 2004; Pullen et al., 2006, 2007] showing improved simulations of bora-induced response in comparison with simple one-way interaction, confirm a need for further investigations of the complex air-sea interaction with coupled models.

Figure 15. Drifter trajectories obtained from the experiment with a combined action of the wind stress, surface heat fluxes, and discharges from all Adriatic shelf rivers. Atmospheric forcing was obtained from MM5 results and drag coefficient was (a) 2 and (b) 3.5 times larger than coefficient according to Large and Pond [1981] formulation. Asterisks denote the drifter initial position on 22 June 1995, whereas circles denote their positions at the end of each day. Realistic drifter trajectories are represented by thicker lines.
Figure 16. Cross-shore (NE–SW) density sections for (a, b) 0000 UTC on 23 June 1995 and (c, d) 0000 UTC on 26 June 1995. The left section (Figures 16a and 16b) is placed in front of the southern tip of the Istrian Peninsula, whereas the right one (Figures 16b and 16d) is placed in front of Trieste Bay. Cross section positions are denoted in Figure 1.

Figure 17. Air/sea temperature differences for (a) 0000 UTC on 23 June 1995, (b) 0000 UTC on 24 June 1995, (c) 0000 UTC on 25 June 1995, and (d) 0000 UTC on 26 June 1995.
The drag coefficient formulation that takes into account effect of the surface roughness and atmospheric instability used here and by Beg Paklar et al. [2001] gave good results in reproducing drifter trajectories as well as in simulating AVHRR sea surface temperature changes during bora events. In both cases, parameters used in wind stress formulation (CD and ε from Table 2) were selected on the basis of the final experiments and the best results achieved there.

A need for an increase of the drag coefficient in the numerical experiments remains an intriguing open issue and should be a subject of further experimental and modeling research efforts. Another possible reason for this intervention in the POM model, beside mentioned mechanisms, could be unrealistically strong mixing in the periods of strong winds, noticed also by Orlić et al. [2006].

5. Conclusions

Despite some open questions we can conclude that our numerical simulations successfully reproduced the surface transport during the summertime bora event and pointed to the main forcing mechanisms. The successful simulations of drifter movements, when all forcing mechanisms were combined (plus the stepwise improvement in drifter simulations), demonstrated different dynamic regimes in the western Adriatic shelf and in the interior. Although the studied wind episode was of the unusual strength for the summer period, the drifter movements could not be explained only by the strong wind-induced currents. The influence of rivers was also important as they generate basin-wide cyclonic current, particularly strong along the northern and western coasts where they prevented the drifter to move too close to the shore. Furthermore, the river influence was also reflected in the reduction of surface salinity that substantially increased the ambient stratification and according to Pollard et al. [1973] decreased the mixed layer depth. This effect produced significant differences in the surface currents in the two studied areas, the coastal one under the river influence and the open sea from the influence of buoyancy fluxes. The heat fluxes were important as their introduction provided heat transfer between the sea surface and the atmosphere above it, which decreased the differences between the air and the sea temperature and consequently the atmospheric instability, crucial for the determination of the wind stress. The sensitivity study with two sets of atmospheric forcings indicated that differences in the predicted wind fields may result in the errors of the ocean transport, which can have significant impact during the hazardous weather conditions such as the one considered here, when accurate prediction can save time and effort.

Acknowledgments. Wind data from Croatian meteorological stations were provided by Hydrometeorological Institute of the Republic of Croatia. We wish to thank Fabio Raisch from Istituto Tassilografico Sperimentale, Trieste, Italy for providing us wind data from Trieste. The work was partly supported by the Ministry of Science, Education, and Sports of the Republic of Croatia through grants 001-0013077-1122, 001-0013077-1118, and 119-1155063-3085. Pierre-Marie Poulin was supported by the Office of Naval Research under grants N0001499WR30015 and NW0001400WR20193. We thank two anonymous reviewers for their helpful and constructive comments. Darko Koracini and Ramesh Vellore were supported in part by the National Science Foundation through grant OCE-9907884, the Office of Naval Research (ONR) through grant N000140010518, and the DOD-DURIP-ONR grant N00014010801.

References


Beg Paklar, G., A. Bajic, V. Dadić, B. Grbec, and M. Orlic (2005), Bora-induced currents corresponding to different synoptic conditions above the Adriatic, Ann. Geophys., 23, 1083–1091.


