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Numerical study of the north Adriatic circulation during two successive bora episodes

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The north Adriatic circulation during two successive bora episodes was studied using single point current measurements and results of the Princeton Ocean Model (POM). Surface currents recorded at the gas field Ivana positioned in the central part of the northern Adriatic were directed downwind during the bora episode of 8-11 February 1984, whereas during the next bora period of 12-16 February 1984 they were directed upwind. The observed current reversal was reproduced in the numerical experiment controlled by air-sea fluxes and river inflows. Atmospheric forcing for the POM model was estimated from high resolution Mesoscale Model 5 (MM5) surface fields, while river discharges were introduced in the simulations as source terms of zero salinity in the continuity equation. The baseline experiment with realistic forcings, atmospheric and riverine, related the current reversal to displacements of the bora induced gyres. Sensitivity studies revealed a dominant role of the wind stress curl for the vorticity in the current field and showed the relevance of the changing wind divergence for the cross-shore circulation variability and accompanied current reversal. Additional numerical experiments emphasized even more the role of the spatial wind variability for the recorded flow and also stressed the importance of the model domain size for the numerical results.

Key words: the northern Adriatic, bora, surface currents, POM, MM5

INTRODUCTION

The importance of the spatial wind variability for the sea circulation is recognized world wide, in the open ocean (SVERDRUP, 1947; STOMMEL, 1948; CHELTON, 2004) and coastal areas (NELSON, 1977; MUNCHOW, 2000; OKE *et al*., 2002; BEG PAKLAR *et al.,* 2001, 2005, 2008, 2009; KORAČIN *et al.,* 2004; BENCETIĆ KLAIĆ *et al.,* 2011). Unfortunately, estimates of spatial and temporal variability in the marine wind field are often limited by a lack of high quality wind observations over the sea, even in the coastal areas. Widely used satellite microwave measurements, although providing surface wind fields with wide space and time coverage, due to heavy filtering are not useful for investigations of the small-scale variability in air-sea interactions particularly in the coastal areas (KORAČIN *et al.,* 2004). Significant advances in understanding the structure of marine wind field came from direct measurements of the near-surface wind field using instrumented aircraft (ENRIQUEZ & FRIEHE, 1995, 1997; DORMAN et al., 1999; GRUBIŠIĆ, 2004). Over the Adriatic, open sea measurements, either in situ or aircraft are rare, satellite estimates are of limited accuracy and therefore many valuable information on wind variability over the Adriatic arrived from modelling studies in which ocean data were used as indirect verification of the atmospheric models (BEG PAKLAR *et al.,* 2001, 2008, VILIBIĆ *et al.,* 2008). However, there are several exceptions. Within environmental studies carried out in the northern Adriatic between 1978 and 1986 for the possible exploitation of the gas fields, continuous wind measurements were performed at two off-shore research platforms. Single point measurements were compared to the climatological wind characteristics at the coastal meteorological station Pula (LEDER & MOROVIĆ, 1996) and were used in several studies of the bora influence on the circulation and thermal front in the northern Adriatic (ORLIĆ *et al.,* 1986; ZORE-ARMANDA & GAČIĆ, 1987). Measurements presented and analysed here are also from that set of measurements but unfortunately wind data over the sea are missing. More comprehensive study of the atmospheric marine conditions in the northern Adriatic was made during oceanographic field campaign in 2003 when convergence/divergence areas were identified during several bora events (DORMAN *et al.,* 2007).

Many experimental and numerical investigations have revealed the importance of the bora wind for the Adriatic general circulation, its short-term variability and distribution of thermohaline properties. Resemblance between mean Adriatic circulation and bora-induced fields points to its possible contribution to current field vorticity through nonlinear interaction. Bora spatial variability, its strong vorticity and divergence determined by the orography of the mountain chains along the eastern Adriatic coast and synoptic conditions, respectively, generates series of cyclonic and anticyclonic gyres in the Adriatic current field with surface currents having intensities of up to 50 cm/s (ORLIĆ *et al.,* 1994). Alongshore bora variability is well known, as it can be determined from coastal meteorological stations and it is documented in many papers (e.g. ORLIĆ *et al.,* 1994). On the other hand, investigations of the bora cross-shore variability are limited to several empirical (POLLI, 1956; YOSHINO *et al.,* 1976, MAKJANIĆ, 1978, MILJAK, 1982) and theoretical studies (ENGER & GRISOGONO, 1998; BEG PAKLAR *et al.,* 2005). Moreover, bora plays significant role in dense water formation (HENDERSHOTT & RIZZOLI, 1976; SUPIĆ & VILIBIĆ, 2006). Bora brings cold and dry air above the Adriatic, decreases sea surface temperature, increases surface salinity and creates water mass, which due to its high density sinks in deep parts of the Adriatic. Bora is also responsible for the upwelling along the Albanian coast during summer (BERGAMASCO & GAČIĆ, 1996) while its frequency and intensity influence Adriatic-Ionian Sea water mass exchange (ORLIĆ *et al.,* 2007).

Success in the numerical modelling of the bora-driven currents crucially depends on the used wind fields which should have resolution capable to recognize bora complex spatial structure (BEG PAKLAR *et al.,* 2001). Many authors reported more or less successful numerically simulated bora-induced current fields, and recognized, besides prevailing importance of the spatial wind variability also the impact of topography (KUZMIĆ *et al.,* 1985; ORLIĆ *et al.,* 1986; MALAČIĆ *et al.,* 2012), parameterization of vertical eddy viscosity, open boundary conditions (KUZMIĆ & ORLIĆ, 1987) and more recently of the coupled air-sea interaction (LOGLISCI *et al.,* 2004; PULLEN et al., 2007; DJURDJEVIĆ & RAJKOVIĆ, 2008).

In this paper we have investigated the importance of the bora spatial variability for the current reversal recorded at the gas field Ivana in the northern Adriatic (Fig. 1). Influence of the same successive bora episodes on the north Adriatic circulation was studied also in BEG PAKLAR et al. (2005) using ocean model forced with climatological bora profiles. Besides schematized numerical experiments, BEG PAKLAR et al. (2005) provided detailed description of the prevailing synoptic conditions which revealed two distinct bora episodes with wind decrease between them. The main contribution here is made by realistic simulations with meteorological and ocean models which enabled us to test the hypothesis on space and time wind variability as the main cause of the recorded current reversal. Our paper besides being a contribution in understanding the role of the spatial variability of the bora wind field for the northern Adriatic currents is also an example of using numerical model results in elucidating somewhat unexpected results of the

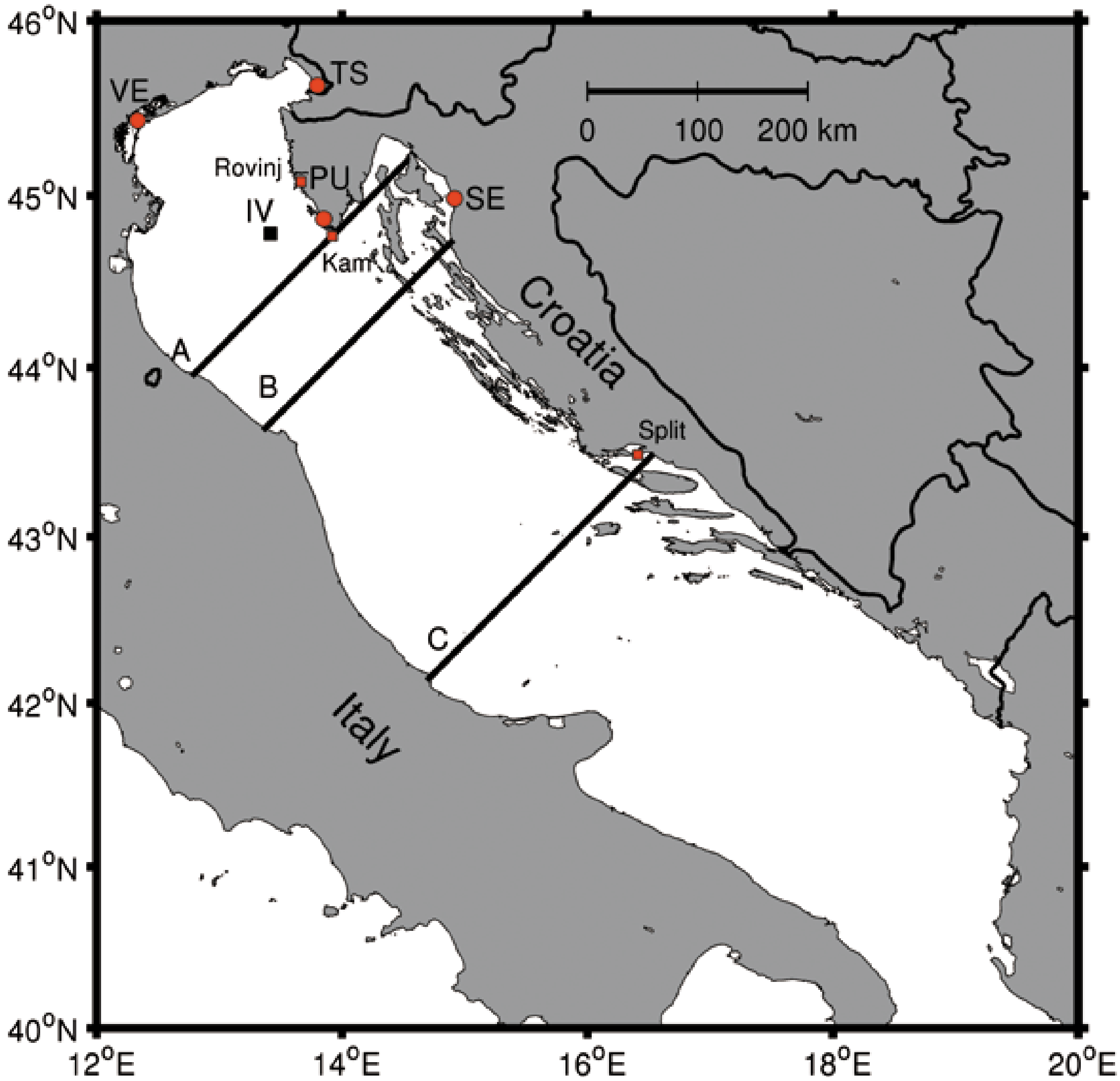

Fig. 1 Adriatic Sea map with locations of the meteorological stations Venice (VE), Trieste (TS), Pula (PU) and Senj (SE), the gas field Ivana (IV) and cape Kamenjak (Kam). Southern boundaries of three ocean model domains used are denoted with A, B and C

single point current measurements. Due to high expenses of the marine measurements, particularly current measurements, in situ data are often limited to few points (here only one), which is usually not enough for reliable conclusions. Therefore, several numerical experiments with Princeton Ocean Model (POM) were designed to reveal the origin of the current reversal recorded at the gas field Ivana (Fig. 1).

In the next section numerical models applied for two bora cases are described, as well as current measurements. Numerical model results are presented in the third section and are related to the wind and current measurements. A summary of the results and main conclusions are given in the fourth section.

CURRENT MEASUREMENTS AND SETUP OF NUMERICAL MODELS

Current measurements

Measurements at the gas field Ivana in the northern Adriatic (Fig. 1, 44^0 47'N, 13^0 25'E) presented and analysed in this paper were carried out by Aanderaa RCM4 current meters. This type of instrument is one of the most frequently used in Croatia during the 1970s and 1980s, and has been widely tested and compared with other types of instruments. Strong currents during studied period and special current meter deployment assure us that recorded reversal is realistic and not affected by some known RCM4 weakness (BEG PAKLAR *et al.,* 2005).

Atmospheric model – MM5

Mesoscale model 5 (MM5) was used to simulate atmospheric conditions during two bora wind cases. MM5 is a community atmospheric model that has been jointly developed by Pennsylvania State University and the National Center for Atmospheric Research in Boulder, Colorado. The physical parameterizations including the processes involving planetary boundary layer, cloud microphysics and radiation are described by GRELL *et al.* (1995). The MM5 has been successfully used worldwide in a variety of research and application studies. In particular it has been already used as a POM model driver in the studies of the circulation and density changes during winter and summer bora episodes (BEG PAKLAR *et al.,* 2001, 2008).

In this study MM5 model grid has horizontal resolution of 2 km and consists of 141x96 grid points and 35 terrain following sigma vertical layers. A vertical resolution is approximately 10 m for the first several hundred meters above the surface, expanding toward the top of the model domain. During numerical simulation MM5 results were stored with hourly intervals for period between 7 and 16 February 1984 and were used in the POM model simulations.

Ocean model – POM

Princeton Ocean Model (POM; BLUMBERG & MELLOR, 1987) was used in the numerical experiments to reveal the origin of the current reversal at gas field Ivana in the northern Adriatic. POM is three-dimensional primitive equation nonlinear model with complete thermo- and hydrodynamics. The equations which capture the model physics are the traditional equations for the conservation of mass, momentum, heat and salt coupled with the equation of state (MELLOR, 1991). The model contains a second order turbulence closure submodel 'Level 2 1/2' described in MELLOR & YAMADA (1982) review, which provides two prognostic differential equations for turbulence kinetic energy and turbulence macroscale. The horizontal viscosity and diffusivity coefficients are obtained using horizontal diffusion formulation following J. Smagorinsky, adapted to sigma coordinate system (MELLOR & BLUMBERG, 1985). The model employs a staggered C-grid according to Arakawa and bottom following sigma coordinate in the vertical direction.

In the simulations of bora influence on the northern Adriatic, rectangular grid with 2.5 km resolution in the horizontal plane (noted with B on Fig. 1) and 22 sigma layers in the vertical direction was used. The horizontal grid B consists of 92x63 equally spaced points, whereas the vertical spacing varies in order to achieve better resolution near surface and bottom. Two additional domains, A and C (Fig.1), with the same distribution of vertical layers but with different horizontal extensions were used to resolve the role of the domain size in the results. The first domain A extends to the southern tip of Istra (cape Kamenjak) whereas the second one C extends to the transect from Split to the opposite western coast. All three domains used in simulations have their x axes rotated by 45^0 from the east in anticlockwise direction. The POM model bathymetry was based on 7.5'' resolution objectively analyzed depth field derived from Naval Oceanographic Office database and nautical chart sounding [DYKES *et al.,* 2009; BURRAGE *et al.,* 2009]. Fine resolution data were bin averaged on 2.5 km POM grid and smoothed with SHAPIRO filter (1970). In the numerical experiments an external time step of 12 s and an internal time step of 120 s satisfied Courant-Friedrichs-Lewy stability criterion. The model was integrated for nine days in each experiment.

In the numerical experiments POM was forced with air-sea fluxes and river inflows. Atmospheric forcing, surface momentum and heat fluxes, were computed from the surface MM5 hourly fields – wind vector, air tempera-

Table 1. Discharge rates of the northern Adriatic rivers

RIVER	*Climatological discharges in February according to Raicich [1994]* [m^3s^{-1}]	*Discharges used in the numerical experiments during the bora wind episodes* [m^3s^{-1}]
Mirna	90	55
Dragonja	90	55
Soča	101	62
Stella	36	22
Tagliamento	20	12
Livenza	86	53
Sile	48	30
Brenta	30	18
Adige	135	83
Canal Bianco	20	12
Po	1220	750
Reno	86	53
Lamone to Savio	76	47
Marecchia to Tronto	272	167

ture and humidity - and instantaneous sea surface temperature (SST) from the POM using standard bulk formulae. LARGE & POND (1981) drag coefficient formulation was used to calculate the wind stress. Heat flux components were calculated using the REED (1977) formulation for shortwave radiation, MAY (1986) for longwave radiation, and KONDO (1975) for evaporative and sensible fluxes. The northern Adriatic rivers were introduced in the numerical simulations as source terms in the continuity equation (KOURAFALOU *et al.,* 1996) and, moreover, were assumed to have zero salinity. Discharges were imposed at three top model layers of the near coastal nodes that correspond to the position of the particular river mouth and the value of salinity in the immediate vicinity of the source was then determined by simulated mixing. All north Adriatic rivers, besides the Po River, were included in the simulations as point sources (Table 1). Po was defined at 16 points corresponding to the location of delta. Climatological mean February discharges for all rivers outflowing in the northern Adriatic were used in the initialisation experiment for salinity and were selected according to RAICICH (1994) (Table 1). River discharges during the bora episodes were determined by multiplying the monthly mean values for February with the ratio of the mean Po River discharge for the nine day bora interval (750 m^3s^{-1}) and corresponding mean value for February (1220 m^3s^{-1}).

All experiments started from the state of the rest, while temperature field was initialized with horizontally and vertically homogeneous field having value of 15^{0}C. Salinity field was initialized with the results of 10-day experiment in which north Adriatic rivers were the only forcing. In all of the experiments radiation condition was applied at the southern open boundary of the domain. As impact of the tidal forcing is of the secondary importance for the circulation during bora events (MIHANOVIĆ *et al.,* 2011), it was left out of the simulations.

List of the performed numerical experiments is given in Table 2. Besides baseline experiment (E1) with realistic atmospheric and river forcing, sensitivity experiments were made to elucidate the role of the wind stress curl and wind stress divergence. In the curl-free experiment (E2) wind components were determined in the following way:

$$\frac{\partial u}{\partial y} = 0 \quad \text{and} \quad \frac{\partial v}{\partial x} = 0 \qquad (1)$$

Table 2. List of the numerical experiments

experiment	wind stress	heat fluxes	domain
E1	calculated from surface MM5 fields	calculated from surface MM5 fields and POM SST	B
E2	curl-free wind stress	calculated from surface MM5 fields and POM SST	B
E3	divergence-free wind stress	calculated from surface MM5 fields and POM SST	B
E4	horizontally homogeneous with vector value modelled at gas field Ivana	horizontally homogeneous calculated from MM5 values at gas field Ivana and POM SST	B
E5	horizontally homogeneous with vector value modelled at meteorological station Pula	horizontally homogeneous calculated from MM5 values at meteorological station Pula and POM SST	B
E6	horizontally homogeneous with vector value measured at meteorological station Pula	horizontally homogeneous calculated from values measured at meteorological station Pula and POM SST	B
E7	horizontally homogeneous with vector value modelled at gas field Ivana	horizontally homogeneous calculated from MM5 values at gas field Ivana and POM SST	A
E8	horizontally homogeneous with vector value modelled at gas field Ivana	horizontally homogeneous calculated from MM5 values at gas field Ivana and POM SST	C
E9	calculated from surface MM5 fields	calculated from surface MM5 fields and POM SST	A

i.e. the northeastward wind component (u) for all 'j' indices was equal to the values along the southern boundary, while the northwestward component (v) for all 'i' indices was equal to the values along the western domain boundary (ENRIQUEZ & FRIEHE, 1995). Wind field in the divergence-free (E3) experiment was defined as:

$$\frac{\partial u}{\partial x} = 0 \quad \text{and} \quad \frac{\partial v}{\partial y} = 0 \qquad (2)$$

i.e. the northeastward wind component (u) for all 'i' indices was equal to the values along the western domain boundary, while the northwestward component (v) for all 'j' indices was equal to the values along the southern open boundary. In the next three experiments wind forcing was horizontally homogeneous and time-varying vectors were determined according to the modelled values at the gas field Ivana (E4) and meteorological station Pula (E5) and according to the measured wind at the Pula station (E6). Experiments with horizontally homogeneous wind were performed to stress the errors that could arrive from this approach which is sometimes used, particularly in the application studies. Experiments E7, E8 and E9 were performed to analyse the impact of the domain size for the obtained results. In E7 and E8 experiments horizontally homogeneous wind was determined according to time-varying vector modelled at the location of the gas field Ivana, while in E9 experiment wind field had realistic space and time variability determined by the MM5 model.

MODEL RESULTS AND COMPARISON WITH WIND AND CURRENT MEASUREMENTS

Atmospheric conditions

Detailed analysis of the surface wind and radiosounding measurements made by BEG PAKLAR *et al.*, 2005 revealed that surface currents changed direction for about 180^0 during two consecutive bora episodes. The crucial difference between the bora episodes were in their vertical atmospheric structure across the Dinaric Alps and Adriatic coast. The first bora episode (B1) from 8 to 11 February 1984 was characterized by cyclonic activity over the western Mediterranean and Genoa Bay and a deep bora layer, whereas the second episode (B2) lasting from 12 to 16 February was accompanied by a temperature inversion and a southwesterly tropospheric wind above a shallow bora layer. According to hydraulic theory developed by SMITH (1985) different vertical developments resulted in stronger acceleration in bora layer during B2 period. Wind measured at the meteorological station Pula, measured surface currents and currents modelled in the baseline experiment (E1) at the grid point corresponding to gas field Ivana are shown in Fig. 2. In order to analyse synoptic-scale variability, both wind and current hourly means, as well as modelled currents were low-pass filtered with a 24m214 filter (THOMPSON, 1983). The bora wind from 8 to 11 February, with a maximum low-pass filtered speed in Pula of about 6.5 ms^{-1}, induced downwind currents in the surface layer of the gas field Ivana reaching 20 cms^{-1} (Fig. 2). On the other hand, in the period from 12 to 16 February surface currents with pronounced upwind component dominated. Maximum current speed during period B2 was about 20 cms^{-1}, while corresponding maximum filtered wind speed at the Pula station was 8.5 ms^{-1} (Fig. 2).

Atmospheric conditions during B1 and B2 episodes were reproduced by MM5 model. Surface wind fields are shown in Fig. 3. MM5 model results reveal that during the first bora

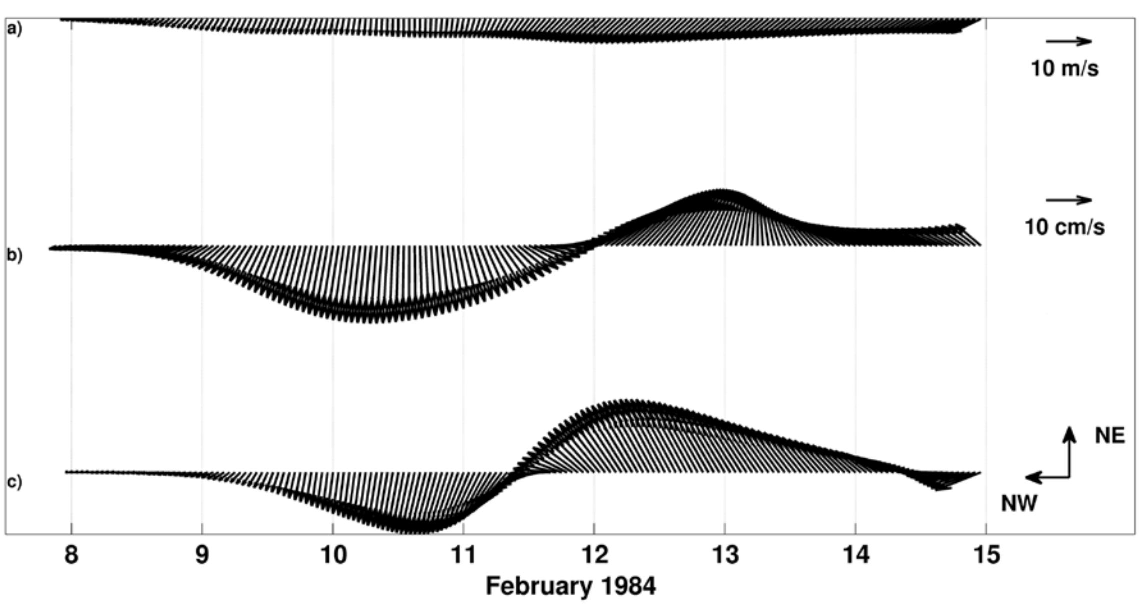

Fig. 2. Low-pass filtered wind measured at Pula meteorological station (a), low-pass surface current vectors measured at the gas field Ivana (b) and surface currents modelled at the model point corresponding to the gas field (c)

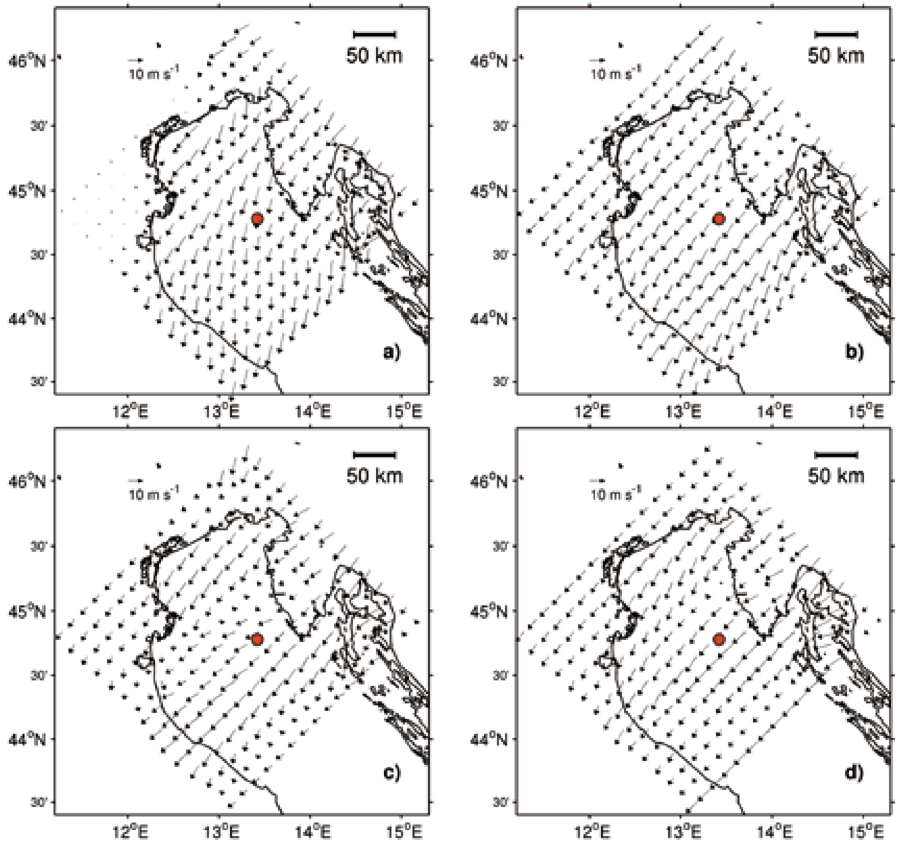

Fig. 3. Surface wind fields obtained from MM5 model: a) 11 February 12:00, b) 12 February 12:00, c) 14 February 0:00, and d) 15 February 12:00 1984

period NE wind was blowing mostly along the eastern coast, while N wind prevailed over the open sea. On 11 February NE wind started to blow also over the open sea but as can be noticed from Fig. 3 areas with maxima and minima wind intensities are not stationary, they are moving over the domain. On 11 February maximum is reproduced south of the Rovinj transect (Fig. 3a), whereas on 12 February the same area is characterized with weakest wind while maxima are placed further north and south (Fig. 3b). Modelled wind fields for 14 and 15 February are obviously influenced by surrounding orography and show characteristic maxima in front of Trieste and Senj with minimum in between. Wind data from coastal meteorological stations in the northern Adriatic (Pula, Senj, Trieste and Venice) were used to verify MM5 model results. Unfortunately wind measurements over the sea were not performed during February 1984 and offshore MM5 verification was not possible. The MM5 model reproduced well intensity and direction of the wind vectors at four stations, but with less temporal variations if compared with measurements (Fig. 4). Generally better agreement between model and measurements is obtained during second, stronger bora episode. Also wind modelled at the Italian stations (Trieste and Venice) agrees better with measurements than wind modelled at Pula and Senj. Wind measured at Pula meteorological station has more pronounced easterly component than corresponding modelled wind vector. ENE wind direction is obtained from both measurements and MM5 model for Senj meteorological station but some temporal variability is missing

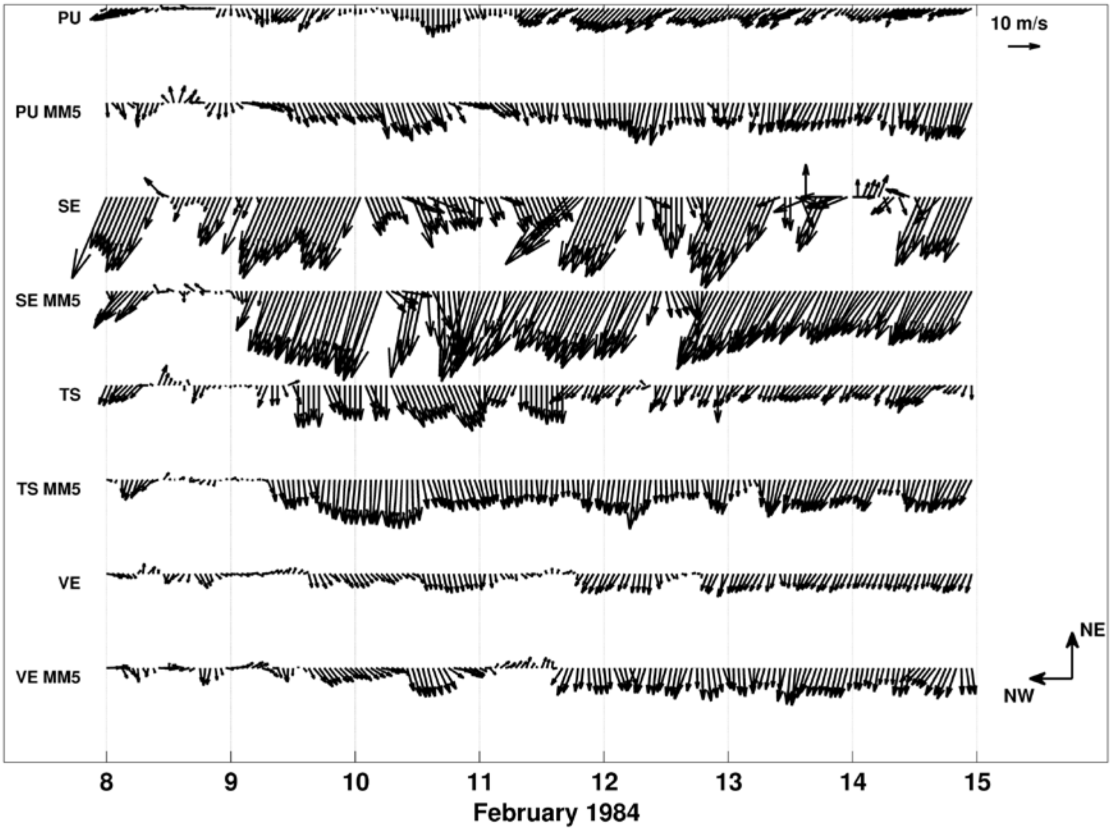

Fig. 4. Surface wind time series obtained at the coastal meteorological stations Pula (PU), Senj (SE), Trieste (TS) and Venice (VE) and modelled values at the corresponding points

in the model results particularly at the end of the studied period.

Ocean model experiments

Numerical experiments listed in Table 2 were conducted primarily to examine the influence of the bora wind spatial variability on the surface circulation in the northern Adriatic. Several additional experiments were made to estimate the proper domain in which selected artificial open boundary condition would not affect the result. In the baseline experiment (E1) POM model was forced with realistic wind stress and heat fluxes calculated from MM5 outputs and instantaneous SST from ocean model. River influence was also included in the experiment. Model domain extended up to the line B on Fig. 1 where radiation condition was applied. Surface current time series obtained at the model node corresponding to the gas field Ivana indicate downwind flow up to 11 February afternoon with significant currents started on 9 February (Fig. 2c). On 11 February afternoon surface currents changed direction for about 180^0 which is in agreement with current measurements, although POM model reproduced current reversal about 12 hours earlier than it occurred in measurements (Figs. 2b, 2c). Modelled current intensities of up to 20 cms^{-1} at the gas field Ivana are in agreement with measurements. Surface current field on 11 February 12:00 reveals cyclonic gyre south of transect Po-Rovinj (Fig. 5a) with gas field Ivana in its downwind branch. On 12 February cyclonic gyre moved toward north and gas field Ivana is now in its southern upwind branch (Fig. 5b). On 14 February two cyclonic gyres are present in the model domain and gas field Ivana is in the weak upwind flow (Fig. 5c). Next day on 15 February 12:00 gas field is in downwind branch of the southern cyclonic gyre which moved a

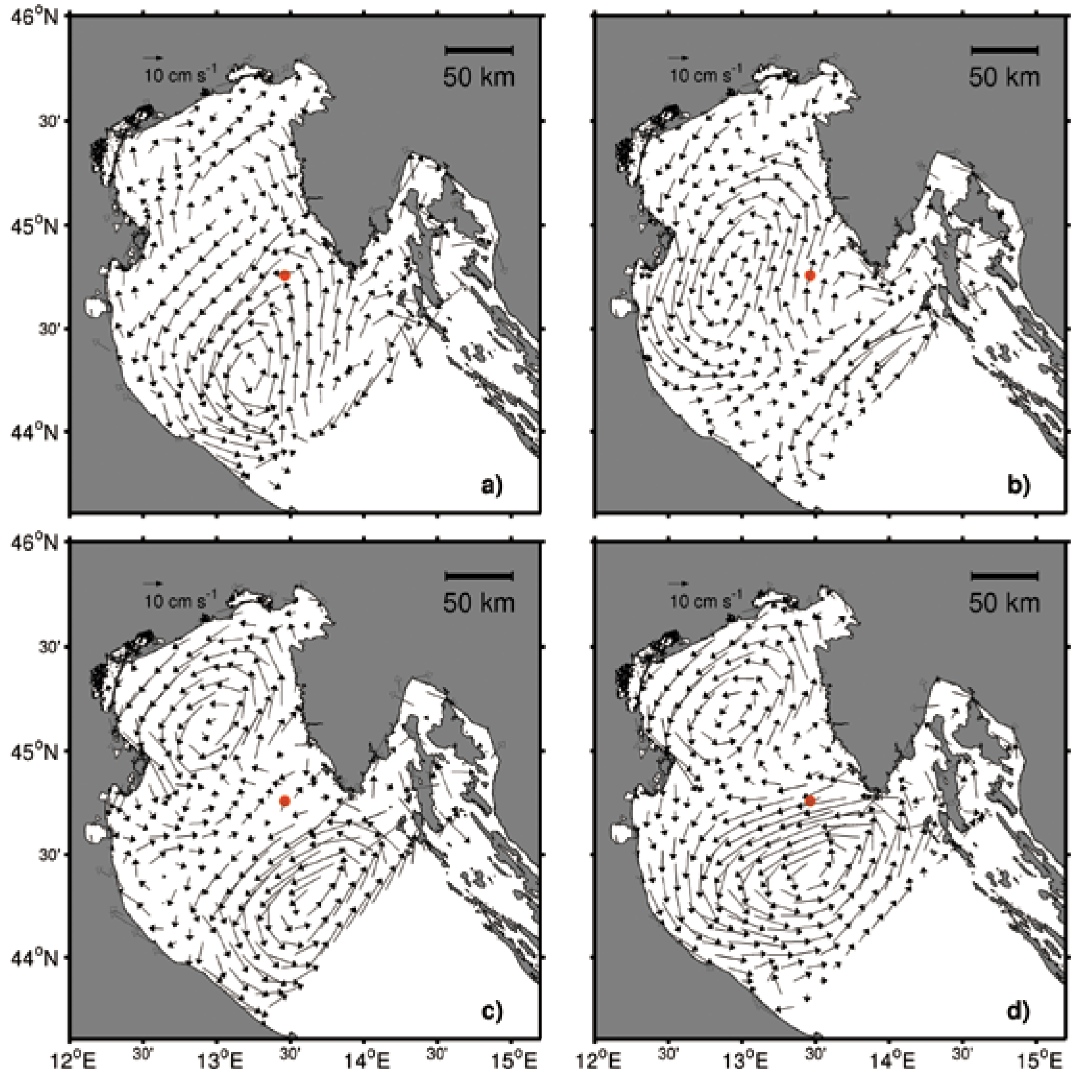

Fig. 5. Surface currents obtained in baseline experiment E1: a) 11 February 12:00, b) 12 February 12:00, c) 14 February 0:00, d) 15 February 12:00

little bit northward (Fig. 5d). Current speeds are up to 40 cms^{-1}. Surface fields during the last two days show characteristic flow patterns for bora events with two cyclonic gyres separated by small anticyclonic vortex along the western Istrian coast south of Rovinj (ORLIĆ *et al.*, 1994; KUZMIĆ *et al.*, 2007). Results of the baseline experiment identify cyclonic gyre movements as the main cause of the recorded current reversal at the gas field Ivana.

Fig. 6 shows curl-free wind field used in E2 experiment (Figs. 6a and 6c) and wind stress curl (Figs. 6b and 6d) during B1 and B2 periods. During the first bora episode (B1) significant values of curl are in the coastal areas, while during the second episode (B2) increased curl values are calculated also over the open sea. Surface currents obtained in the curl-free experiment at the model node corresponding to the gas field Ivana indicate slowly changing current direction from NW at the beginning of the first bora episode to N at the end of the second bora (Fig. 7). During E2 experiment no current reversal was reproduced as it was obtained from measurements and in the baseline experiment E1. Although being of the opposite direction, surface currents

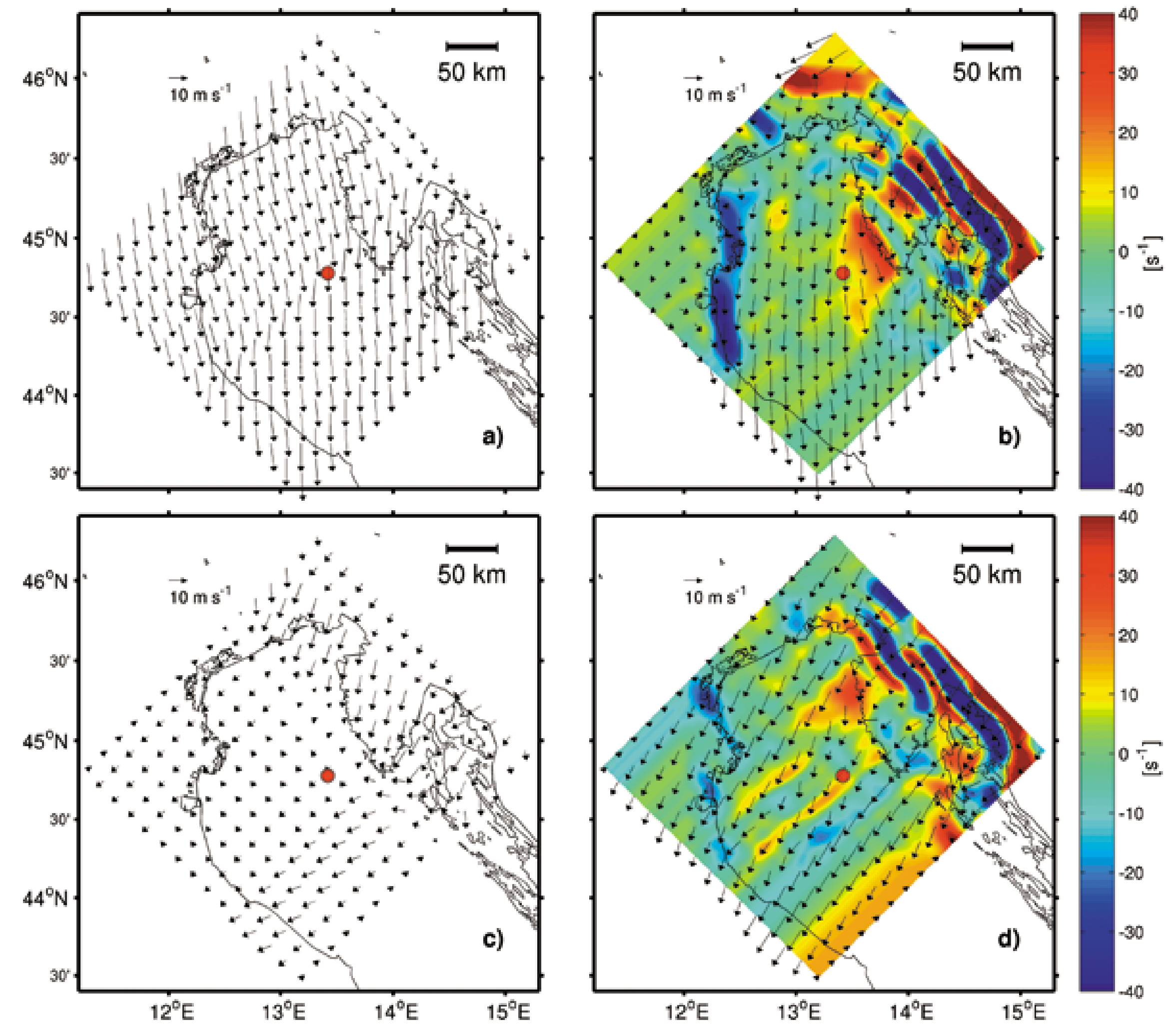

Fig. 6. Curl-free wind field on 11 February 12:00 (a) and 13 February 12:00 (c) used in E2 experiment and wind stress curl for the same dates overlaid on surface MM5 wind fields (b, d)

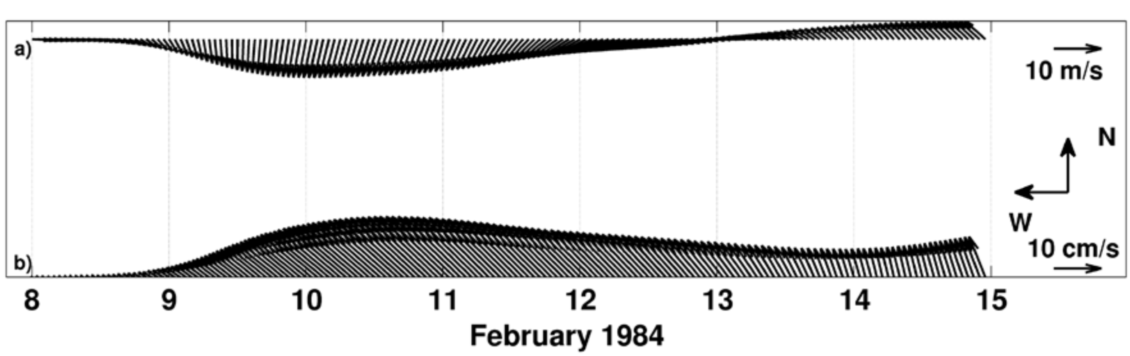

Fig. 7. Curl-free wind series at the model point corresponding to the gas field Ivana and surface current time series obtained in curl-free experiment E2 at the same point

are of the similar intensities as measurements during B1, whereas during B2 period surface currents obtained in E2 experiment are weaker than measured. Cyclonic vortex dominates the domain during the whole experiment and the gas field Ivana is mostly in its northwestward branch (Fig. 8). Cyclonic flow obtained in E2 experiment is topographically controlled and shows no significant displacements. Flow patterns typical during bora episodes, such as double cyclonic gyre with anticyclonic one between, are missing which reveals wind stress curl as a crucial source of vorticity during the studied period.

Fig. 9 in similar way as Fig. 6 shows divergence-free wind fields used in E3 experiment (Figs. 9a and 9c) and wind stress divergence during B1 and B2 periods (Figs. 9b and 9d). Increased values of wind stress divergence are obtained over the open sea in B2 period characterized by upwind currents at the gas field Ivana. During B1 period with measured downwind currents increased divergence is over the coastal areas, although maximum values during B1 period are lower than those calculated for B2 period. Modelled surface currents at the gas field Ivana during divergence-free experiment are dominantly downwind with varying intensities (Fig. 10). Two intensity peaks are at the beginning of 11 and 14 February. Modelled current intensities are comparable to the values from E1 experiment during B1 whereas during B2 currents are weaker and of the opposite direction to those from E1. Surface current patterns are changing significantly during E3 experiment but gas field Ivana is constantly in the downwind flow (Fig. 11). During the first part of the experiment gas field Ivana is in the southern branch of the anticyclonic flow (Fig. 11a), while during the next two days of the experiment anticyclonic gyre weakens, cyclonic one moves northward and the gas field is in the northern branch of the cyclonic gyre (Fig. 11b). Strong vorticity of positive and negative sign is present during the whole E3 experiment and establishes almost regular distribution of positive and negative vortices alongshore. Due to the absence of the wind stress divergence, vortices have low cross-shore variability. Identified importance of the changing divergence for the reversal is in agreement with previous study of the bora induced currents in the northern Adriatic (BEG PAKLAR *et al.*, 2005).

Atmospheric forcing in the experiments E4, E5 and E6 was characterized by time varying horizontally homogeneous wind stress and heat fluxes. Wind vector and heat exchange in the experiments E4 and E5 are determined according to the values modelled at the nodes corresponding to the gas field Ivana and meteorologi-

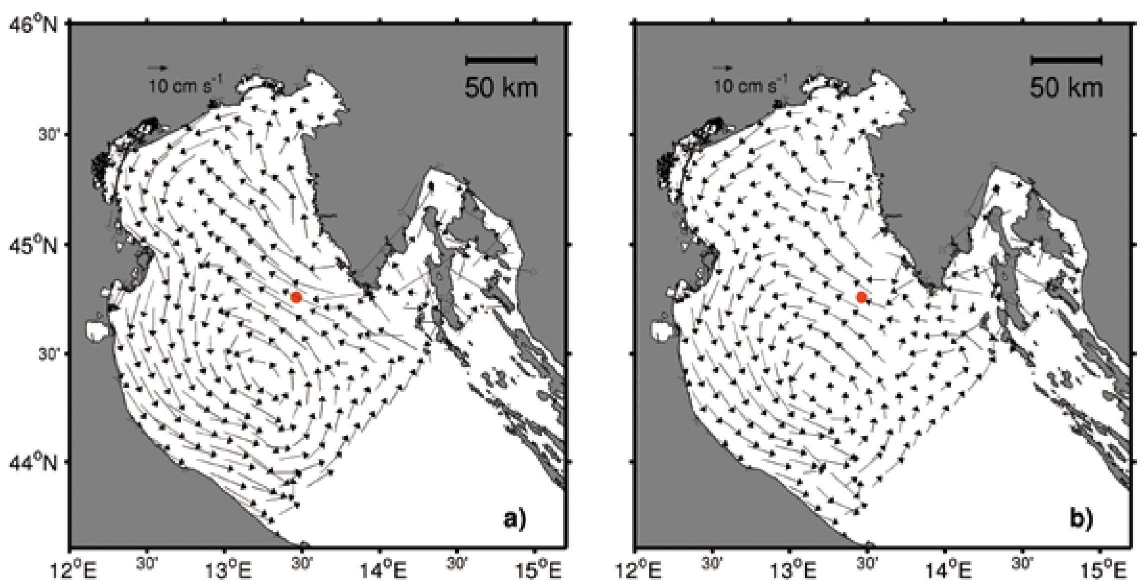

Fig. 8. Surface currents obtained in curl-free experiment E2 on: a) 11 February 12:00 and b) 12 February 12:00

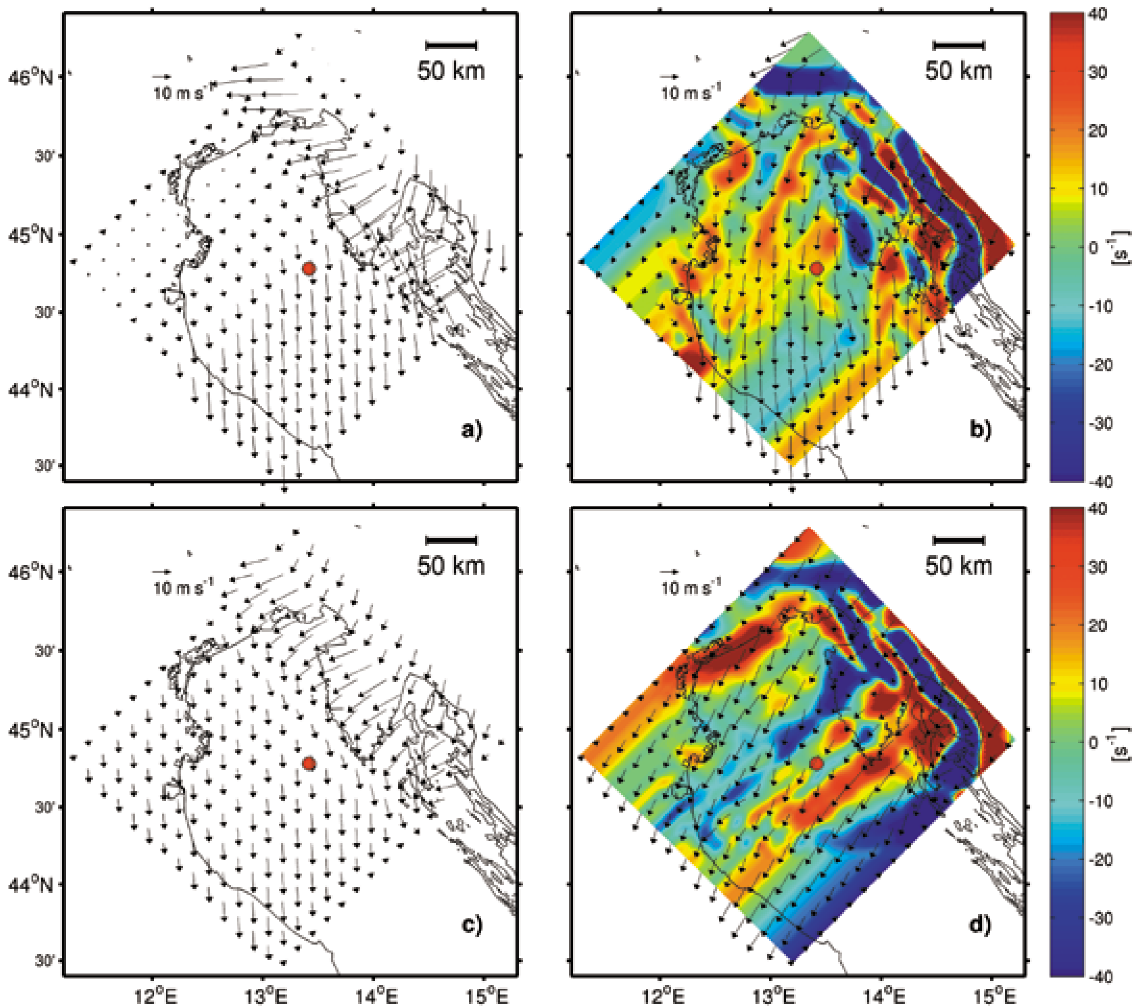

Fig. 9. Divergence-free wind field on 11 February 12:00 (a) and 13 February 12:00 (c) used in E3 experiment and divergence wind stress for the same dates overlaid on surface MM5 wind fields (b, d)

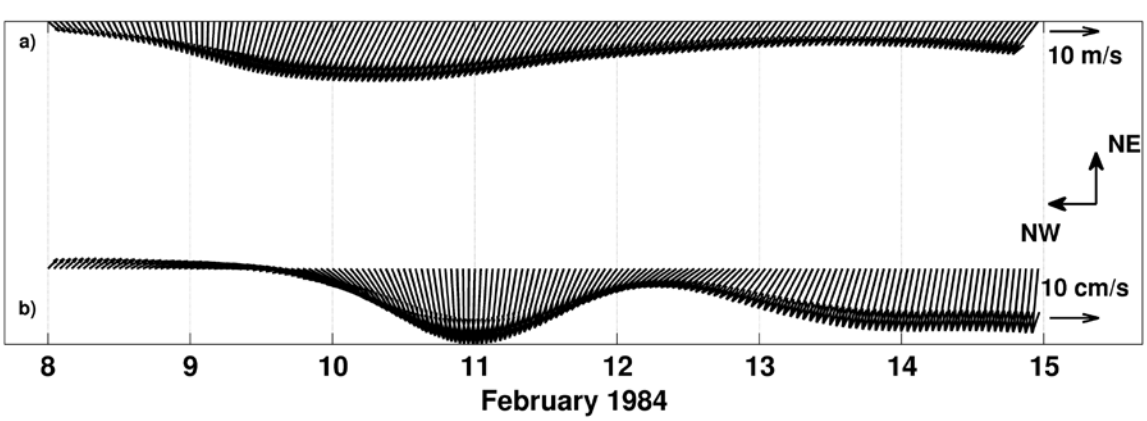

Fig. 10. Divergence-free wind series at the model point corresponding to the gas field Ivana and surface current time series obtained in divergence-free experiment E3 at the same point

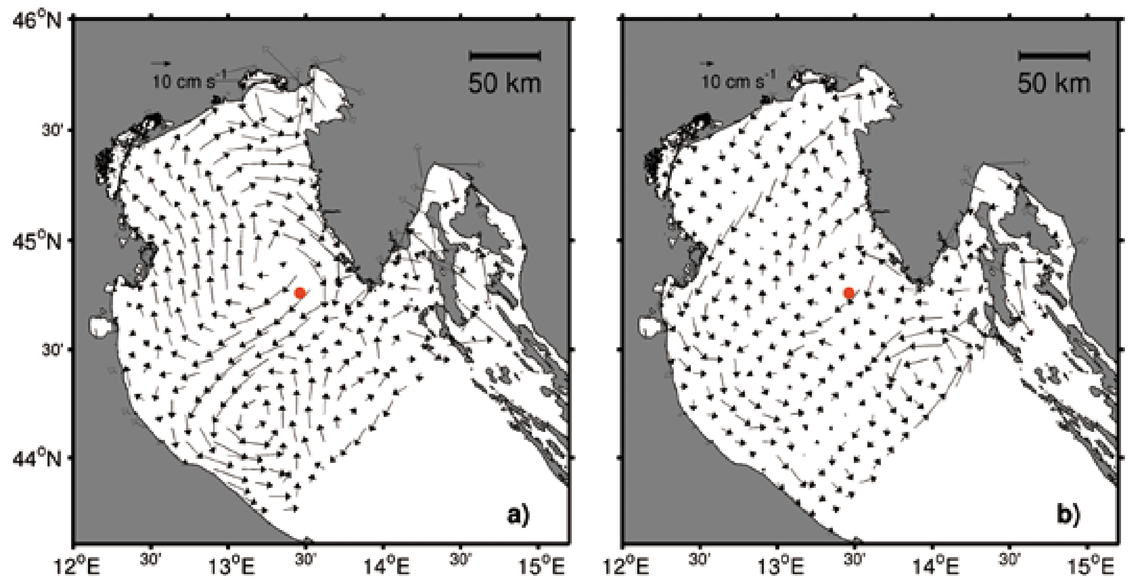

Fig. 11. Surface currents obtained in divergence-free experiment E3 on: a) 11 February 12:00 and b) 12 February 12:00

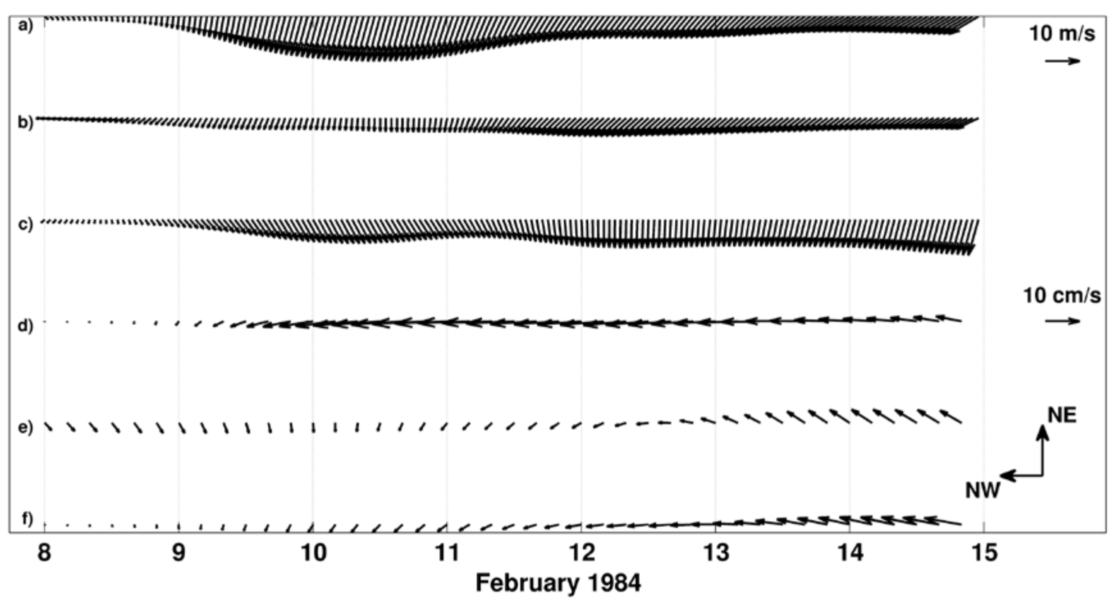

Fig. 12. Wind time series used in experiments E4, E5 and E6 and determined according to wind vector modelled at point corresponding to the gas field Ivana (a), to wind vector modelled at point corresponding to meteorological station Pula (b) and to wind vector measured at the meteorological station Pula (c), respectively. Below are surface current time series obtained in the experiments with horizontally homogeneous wind fields E4 (d), E5 (e) and E6 (f) at the model node corresponding to gas field Ivana

cal station Pula, respectively. In E6 experiment wind stress and heat exchange are determined according to the measurements at the meteorological station Pula. Wind modelled at the gas field Ivana has higher intensities if compared to the modelled and measured wind at Pula station, while wind modelled at the location of the meteorological station Pula has higher intensities than measured values (Fig. 12). Easterly winds dominate in the measurements, while wind modelled at Pula has more pronounced NE component. Surface currents obtained in E4 experiment at the grid point corresponding to the gas field Ivana have dominantly northwestward direction. E6 experiment started with weak southward currents, which gradually changed direction to northward at the end of experiment. Similar surface current variability is obtained in E5 experiment. Due to higher intensities of the wind vector used to force the POM model, surface currents are strongest in E4 experiment but even in E4 experiment intensities are almost twice weaker than those obtained by measurements. Careful inspection of the surface current fields reveals topographically controlled cyclonic gyre in all experiments with horizontally homogeneous wind (E4, E5, and E6) (Fig. 13). Even though results of E4 and E5 experiments are very similar, some differences in the circulation patterns can be related to different temporal variability in the forcing. Surface flow fields from E6 experiment show occasionally anticyclonic gyre along the western coast. Due to weak winds in E6 experiment, river forcing along the western coast prevails and induces clockwise circulation. SCHWING & BLANTON (1984) performed similar modelling experiments with horizontally homogeneous winds from coastal and open sea stations. Currents obtained in the experiment with coastal winds are significantly underestimated in comparison to those obtained using wind forcing from sea stations.

To ensure that obtained results did not come from artificial open boundary condition in the experiments E7 and E8 we used two different model domains (Fig. 1). Model domain in E7 experiment has open boundary extending from the southern tip of Istra (cape Kamenjak) towards western coast (noted with A on Fig. 1), while in E8 experiment the domain encompass the whole shelf and extends to the transect from Split towards western coast (C – Fig. 1). In both E7 and E8 experiments POM was forced with horizontally homogeneous wind stress deter-

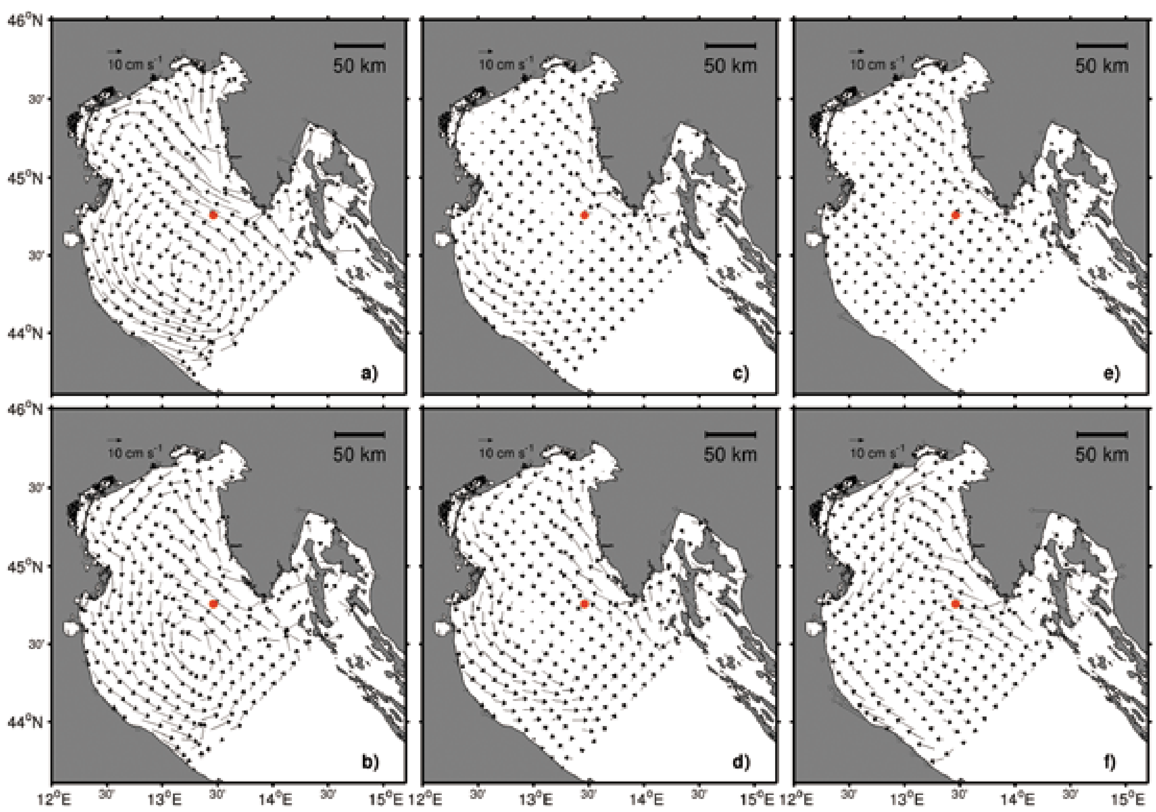

Fig. 13. Surface currents obtained for 11 February 12:00 and 12 February 12:00 in the experiments with horizontally homogeneous wind fields E4 (a and b), E5 (c and d) and E6 (e and f)

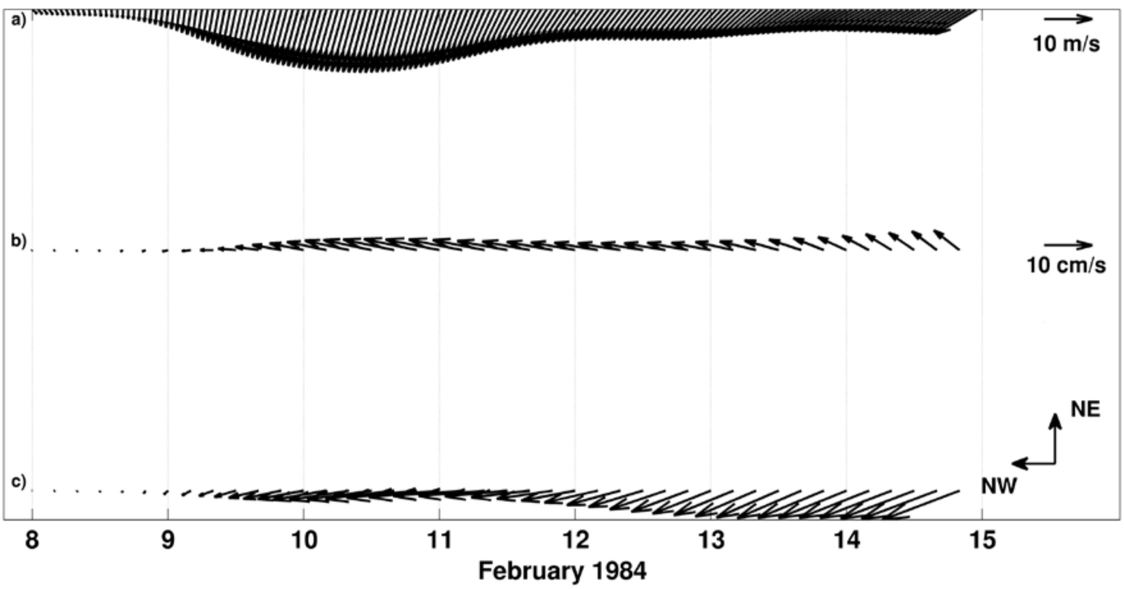

Fig. 14. Wind time series modelled at model point corresponding to the gas field Ivana (a), surface current time series obtained in the numerical experiments with horizontally homogeneous wind fields (E7 and E8) in the model domains A (b) and C (c) at the POM model node corresponding to gas field Ivana

mined according to modelled vector at the gas field Ivana. Surface currents obtained in E4, E7 and E8 experiments indicate the importance of the open boundary position for the surface current direction (Fig. 14). Surface current temporal variability is low in all experiments with dominant directions towards NW in B domain, WNW and W in C and NW and N directions in A domain. Maximum difference between surface currents is at the end of 14 February when modelled flows at the gas field Ivana in A and C domains are deflected for about 90^0. Cyclonic gyre is dominant in the northernmost part of all domains but with different extensions. In case of A domain, southern open boundary is too close to the location of the measurements, and the condition applied here obviously affects flow modelled at the gas field Ivana (Fig. 15). Simple radiation boundary condition is not suitable in this case and it should be replaced with more realistic one, like one obtained using nesting procedure. Intensity of the cyclonic gyre in C domain is affected by internal oscillations which occur in the periods with significant wind variability. An example is current field obtained for 11 February on 12:00 hours when surface flow is significantly reduced in C domain if compared to circulation pattern in A and B domains (Figs. 13a and 15a, c). Similar oscillations do not appear in A and B domains as they have almost flat bottom. In the periods with low wind variability surface flows in all domains are of similar intensity, while current direction at the gas field Ivana depends on the position of the open boundary. We assume that B domain is most suitable in this case as the area of measurements is not significantly affected by open boundary condition and it is not exposed to the internal oscillations due to slowly changing topography in the domain.

Comparison between sea surface currents obtained in experiments E1 and E9 at the position of the gas field Ivana indicates that in both domains main current reversal occurs about 12 hours earlier than in measurements (Fig. 16). Resemblance in the modelled time series is obvious during the whole simulation period except during last 12 hours when current vectors from two experiments are deflected for about 90^0 (Fig. 16). Careful analysis of the surface current fields obtained in two experiments revealed the reason for this discrepancy. In E1 experiment reoccurrence of downwind current resulted from southward movement of the cyclonic gyre

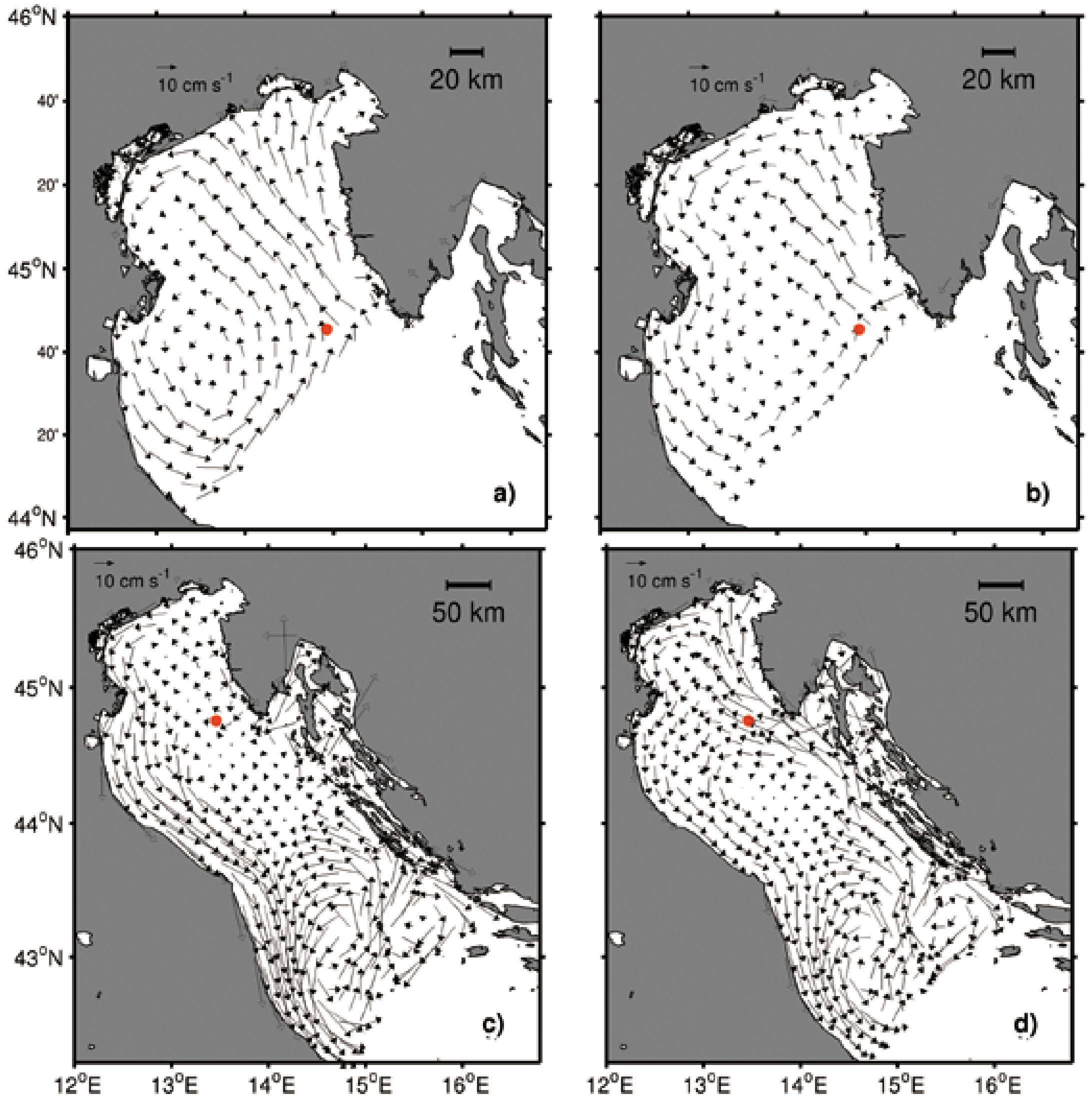

Fig. 15. Surface currents obtained in the numerical experiments with horizontally homogeneous wind field (modelled wind vector at gas field Ivana) (E7, E8) in the model domains A and C for 11 February 12:00 (a and c) and 12 February 12:00 (b and d)

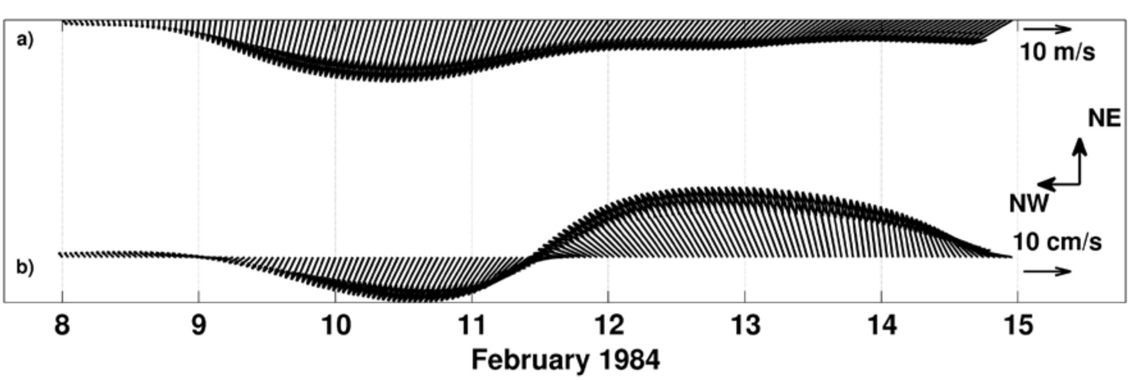

Fig. 16. Wind time series modelled at model point corresponding to the gas field Ivana (a) and surface current time series obtained in the numerical experiment with realistic atmospheric forcing (E9) in the model domain A at the same point (b)

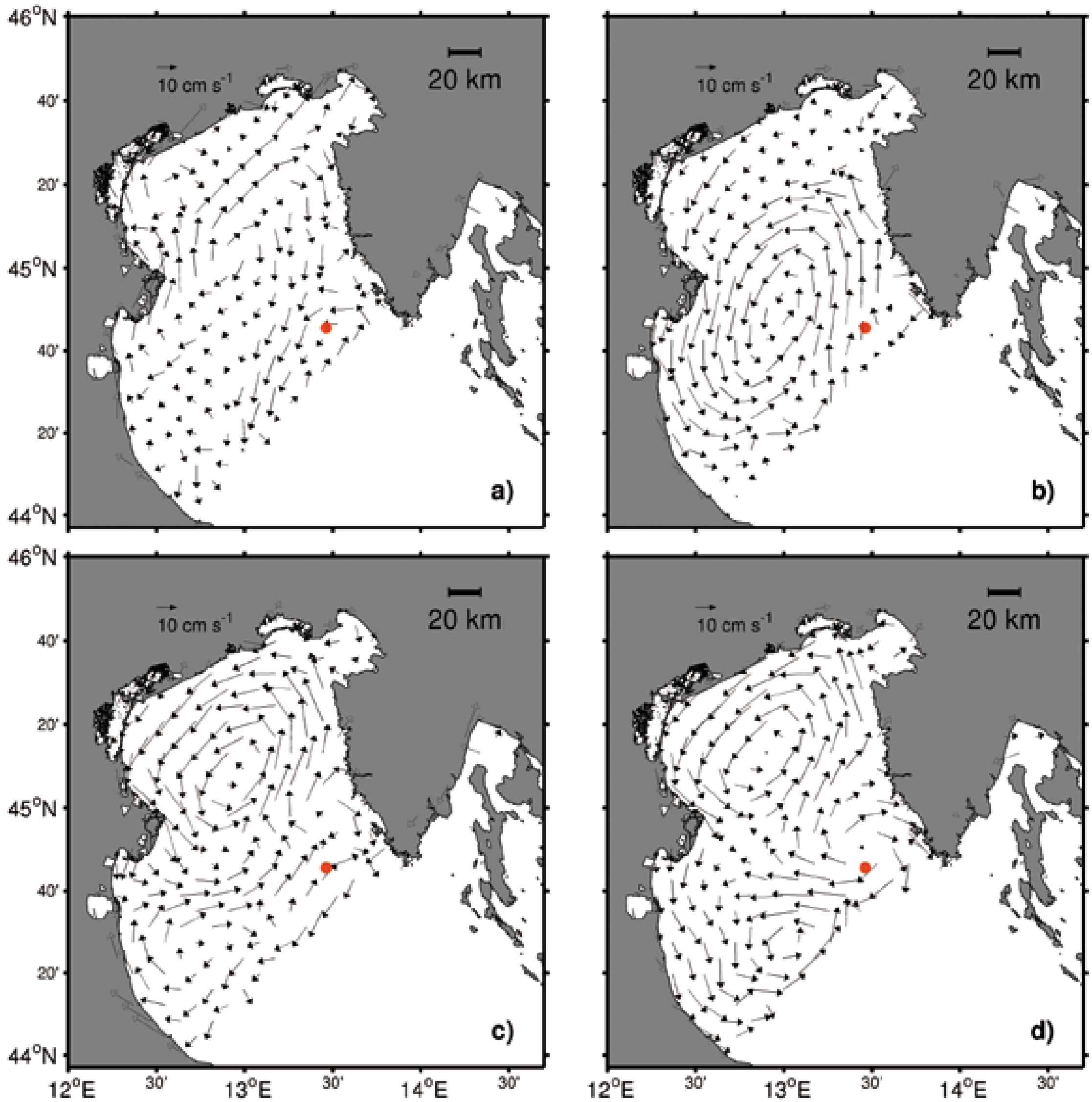

Fig. 17. Surface currents obtained in E9 experiment on: a) 11 February 12:00, b) 12 February 12:00, c) 14 February 0:00, d) 15 February 12:00

which positioned Ivana in its northern branch. In E9 experiment southward movement of the cyclonic gyre occurs about 12 hours later and therefore at the end 14 February Ivana is still in the anticyclonic gyre that occupies the south-eastern part of A domain. Fig. 17d shows that similar reversal as in B domain occurs also in A but about 12 hours later. In general surface current fields obtained in A domain are the same as in B, and the differences are in the location of the southern branch of the cyclonic flow (Fig. 17). Also during the last day of simulation distribution of gyres in the southern parts of A and B are different, again due to the location of the open boundary. In a small domain cyclonic and anticyclonic gyres are just north of the open boundary, while in B cyclonic gyre is placed more to the south and anticyclonic one is weaker and placed more towards north. Obviously location of the reproduced gyres is significantly influence by the position of the open boundary which should be defined out of the area with strong vorticity. It is interesting to notice that differences in realistic experiments performed in two domains are less significant than those obtained by simple horizontally homogeneous forcing. In experiment E9 with realistic forcings surface currents at the location of the current measurements are almost the same as in baseline experiment E1 but the differences become evident in the overall flow patterns.

SUMMARY AND CONCLUSIONS

Eulerian current measurements performed in the northern Adriatic during two consecutive bora episodes characterized by different synoptic conditions revealed oppositely directed surface currents. The main goal of our investigation was to resolve the role of the wind spatial variability for the current reversal. The northern Adriatic is particularly suitable for this kind of investigation since the current vorticity is primary induced by the wind stress curl as the bottom is rather smooth with no prominent features (KUZMIĆ & ORLIĆ, 1987), while on the other hand further south vorticity resulted from significant topography variations (ZORE-ARMANDA & BONE, 1987).

The occurrence of the oppositely directed surface currents at the gas field Ivana (positioned in the northern Adriatic) during bora episodes is explained by several numerical experiments in which ocean model was forced with the wind stress and surface heat fluxes calculated from the fine resolution meteorological model outputs and with river inflows. Results of the meteorological model are verified with wind data from coastal stations. Unfortunately measurements over the sea were not performed and direct off-shore verification was not possible. The ocean model setup enabled us to assess the impact of spatial and temporal variability in the wind field for the northern Adriatic circulation. Nine-day baseline experiment was carried out for period from 7 to 16 February 1984 together with eight more sensitivity experiments listed in Table 2.

Baseline experiment related current reversal with movements of the wind induced gyres. Additional calculations reveal that during the first bora episode B1 wind stress curl and wind stress divergence had higher values in the coastal areas. NE wind was blowing along the eastern coast, while N wind prevailed over the open sea. Absence of the typical circulation patterns for bora during B1 is result of low wind stress curl and divergence off-shore. During the second bora episode B2 wind stress curl and divergence had significant values over the open sea which induced two cyclonic gyres with an anticyclonic between them, i.e. typical flow for the northern Adriatic during bora (KUZMIĆ *et al*., 2007). Moreover results of the curl-free experiment reveal the dominant role of the curl for the vorticity in the surface current field since the only gyre during the whole E2 experiment was topographically induced cyclonic gyre. The cyclonic flow was more or less stationary and occupied the whole numerical domain. Introduction of the wind stress curl in the experiment induced positive and negative moving vortices. Results of E3 experiment reveal importance of the divergence for the circulation variability. In the divergence-free E3 experiment surface current field consists of series of cyclonic and anticyclonic gyres regularly distributed in the cross-shore direction. Introduction of the divergence in the wind stress field brings significant cross-shore variability in the distribution of the wind-induced vortices which turned out to be important for the current reversal during second B2 bora episode. From the obtained results we concluded that both curl and divergence in the wind stress fields had distinct roles for the reversal. It is particularly important that during second bora episode both wind stress curl and divergence had significant values over the open sea where current reversal was recorded. This result could be related to the conclusion obtained in BEG PAKLAR *et al.* (2005) where instead of the realistic wind fields calculated by MM5, schematic wind forcing was used. In those artificial wind fields determined according to the climatological wind profile, cross-shore fetch was variable. Results of the experiments with short fetch could be related to the first bora episode having higher values of the curl and divergence in the coastal areas, while increased values of fetch gave higher values of the curl and divergence over the whole northern Adriatic and finally resulted in the reversal of the surface flow at the gas field Ivana. In

BEG PAKLAR *et al.* (2005) wind stress divergence resulted from sharp discontinuity in the wind field. Realistic MM5 wind fields do not have such strong discontinuities, north and northeast winds are blowing during the whole studied period but characteristic flow pattern is present only during the second bora episode.

In experiments E4, E5 and E6 time-varying but horizontally homogeneous wind stress and heat fluxes were used to force the POM model. These experiments are performed to further stress the importance of the wind stress spatial variability for the north Adriatic circulation and also to detect the errors that could arrive from using horizontally homogeneous wind stress instead of realistic. In many marine modelling studies, particularly those with application character, homogeneous wind stress is used and therefore here we wanted to show some of the problems that could arrive from such approach. Results of the experiments performed here indicate that in the situations with complex wind structure as in the case of bora this approach is completely unacceptable. Realistic spatial variability is completely missing and current intensities are almost twice lower than measured values. SCHWING & BLANTON (1984) performed similar modelling experiments with horizontally homogeneous winds from coastal and open sea stations. Currents obtained in the experiment with coastal winds are significantly underestimated in comparison to those obtained using wind forcing from sea stations.

To be sure that numerically obtained current reversal is not influenced by the artificial open boundary conditions we performed several additional experiments (E7, E8 and E9). In E7 and E8 experiments two different model domains were used, while wind stress was horizontally homogeneous determined in the same way as in E4 experiment – from time-varying wind vector modelled at the gas field Ivana. Comparison of the results obtained in experiments E4, E7 and E8 due to simple wind forcing clearly showed the influence of the domain size for the modelled circulation. Results of E7 experiment revealed that open boundary in A domain is too close to the area with current measurements, while E8 experiment revealed occurrence of the oscillations due to the variable topography in C domain. Therefore we conclude that B domain is the most suitable for our investigation, since open boundary is far from the area of measurements and there are no oscillations related to the changing topography. And finally we performed an additional experiment in model domain extending to the southern tip of Istra (cape Kamenjak) using wind stress and heat fluxes simulated by MM5 model. At the location of the gas field Ivana E1 and E9 resulted almost in the some time series, except during last two days, while in the overall circulation patterns differences were more evident.

In terms of final remarks we believe that in spite of limited amount of in situ measurements, with the aid of numerical results, both atmospheric and marine, we resolved the question on current reversal at the gas field Ivana. Modelling results show that movements of bora induced gyres resulted in current reversal at the point of measurements. Moreover, current reversal reproduced in both baseline experiment E1 and E9 experiment confirmed reliability of the previous conclusion. Our study also shows why it is so important to use the outputs from fine resolution atmospheric models in the marine applications. Use of inappropriate wind fields, without realistic spatial variability could lead to errors in the ocean forecast and in many misunderstandings of the marine processes. Also it is highly recommendable to define the model domain open boundary out of the area with strong vorticity.

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Numerička analiza cirkulacije u sjevernom Jadranu za vrijeme dvije uzastopne epizode bure

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SAŽETAK

Površinsko strujanje u sjevernom Jadranu za vrijeme trajanja dvije uzastopne epizode bure analizirano je na temelju strujomjernih podatka i rezultata numeričkog modela Princeton Ocean Model (POM). Površinske struje zabilježene na plinskom polju Ivana smještenom u centralnom dijelu sjevernog Jadrana bile su u smjeru vjetra za vrijeme prve epizode bure od 8. do 11. veljače 1984., dok su za vrijeme slijedeće epizode bure od 12. do 16. veljače bile suprotnog smjera od vjetra. Zabilježeni obrat struje reproduciran je u numeričkom eksperimentu u kojem je oceanografski model kontroliran površinskom napetošću vjetra, protocima topline i riječnim dotocima. Atmosfersko prisilno djelovanje za POM model izračunato je na temelju prizemnih polja iz meteorološkog modela Mesoscale Model 5 (MM5), dok je djelovanje sjevernojadranskih rijeka uvedeno u numeričke eksperimente kao izvor slatke vode u jednadžbi kontinuiteta. Rezultati osnovnog eksperimenta s realističnim prisilnim djelovanjima, atmosferskim i riječnim, povezali su obrat površinske struje na plinskom polju Ivana s pomacima burom induciranih vrtloga. Analize osjetljivosti numeričkih rezultata ukazale su na dominantnu ulogu rotora vjetra za vrtložnost u strujnom polju, dok je promjenjiva divergencija u polju vjetra utjecala na varijabilnost struja u smjeru okomitom na obalu te tako dovela do obrata površinske cirkulacije na poziciji plinskog polja Ivana. Dodatni numerički eksperimenti još su više naglasili važnost prostorne varijabilnosti vjetra za zabilježeni obrat struje, a također su pokazali i važnost veličine modelske domene za dobivene rezultate.

Ključne riječi: sjeverni Jadran, bura, površinske struje, POM, MM5