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Formation of reversed lee flow over the north-eastern Adriatic during bora

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In-situ measurements indicate the existence of reversed near-surface airflow over the north-eastern Adriatic during the bora wind. Here we examine its structure and evolution by means of a numerical simulation. The studied phenomenon developed during typical summer frontal bora that is associated with a cold air advection from the north-east. It is characterized by a sudden increase in wind speed and a brief duration. Within a sheltered area near the town of Malinska on the island of Krk, onshore flow occurred as the bottom branch of the lee rotor-like circulation that was associated with the hydraulic jump. While the closed circulation somewhat resembles the hypothesized hydraulic-jump rotor, there are significant differences, particularly in the strength of the turbulence associated with the rotor formation.

Keywords: wake, hydraulic jump, lee rotor

1. Introduction

The bora wind is characterized by many jets and wakes alternating along the east Adriatic coast (e.g. Grubišić, 2004, Belušić and Klaić, 2006, Grisogono and Belušić, 2009). These flow features are primarily related to the local topography and are therefore rather persistent phenomena (e. g., Jeromel et al., 2009). However, certain differences in the lee flow structure may appear due to variations of the upstream incoming flow. For example, Belušić et al. (2007) and Gohm et al. (2008) report on the appearance of the mountain wave induced lee rotor for certain upstream conditions. Prtenjak et al. (2009) analyzed a summer frontal bora event (for details about the frontal bora type see e.g. Jurčec, 1988) and found several sheltered areas along the north-eastern Adriatic coast. They pointed out the formation of the lee flow reversal within the sheltered area near the town of Malinska (45.12° N, 14.53° E, numbered 23 in Fig. 1) and assigned it to the appearance of the hydraulic-jump rotor, although without a detailed analyses. Malinska is situated in a bay at the north-western coast of the island of Krk, surrounded by slightly hilly terrain. The area around Malinska is known by local inhabitants for its low wind

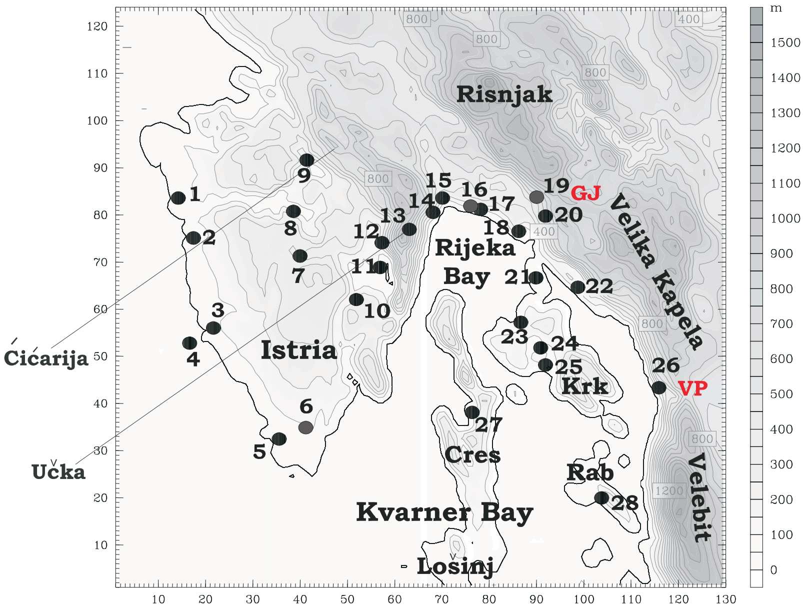

Figure 1. The innermost domain of the WRF model with the positions of measuring sites (black dots) along the northeastern Adriatic coast. Topography contours are given every 100 m at 1 km horizontal grid spacing. GJ stands for Gornje Jelenje and VP for Vratnik Pass. Stations numbered 23 and 26 are Malinska and Senj, respectively.

speeds during otherwise strong bora events in the close surroundings. Since the noted formation of the flow reversal might account for at least a part of the reason of this climatological bora wake, we concentrate on further analysis of this situation.

2. Model overview and its application

We use the Weather and Research Forecasting – Advanced Research WRF (WRF-ARW) model (version 2.2) (Skamarock et al., 2005). The WRF model consists of fully compressible nonhydrostatic equations on a staggered Arakawa C grid. WRF dynamics and physics options used for the simulation for all domains include: the Mellor-Yamada-Janjic scheme for the planetary boundary layer; the Rapid Radiative Transfer Model for the longwave radiation and the Dudhia scheme for shortwave radiation; the Single-Moment 3-class microphysics scheme with ice and snow processes; the Eta surface layer scheme based on Monin-Obukhov similarity theory and the five-layer thermal diffusion scheme for the soil temperature. The Betts-Miller-Janjic cumulus parameterization scheme is used only for the coarsest domain. Sixty-five terrain-influenced coordinate levels are used, with the lowest half-sigma level at about 25 m. Spacing between levels ranges from about 60 m near the surface to 300 m in the middle and upper troposphere and 400 m near the model top at 50 hPa. Initial and boundary conditions are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses, available at a 0.25 degree resolution every 6 h. The simulation was performed from 06 UTC on 28 June 2004 until 00 UTC on 1 July 2004.

Two inner domains are two-way nested in the coarse 9 km domain, which has 72 × 72 grid points and covers the wider Adriatic region. The first nested domain has 106 × 106 grid points with 3 km horizontal mesh size covering Croatia. The innermost domain has 130 × 124 grid points, covering the north-eastern Adriatic with 1 km horizontal grid spacing (Fig. 1). The results presented here are based on the finest model domain.

3. Results

The frontal bora case that occurred on 28 – 30 June 2004 is chosen for the study of the reversed flow appearance. A shallow cold front crossed over the Alps towards the east, while its eastern part bended and approached the Dinaric Alps from the northeast. It was followed by a cold air outbreak in the lowermost 2 km along the north-eastern Adriatic coast. The sudden bora onset occurred at 21 UTC on 28 June, continuously lasting for 30 hours. Bora speed reached its maximum at 11 UTC on 29 June 2004.

3.1. Validation of the model results

First, we compare the model simulation with the available surface wind measurements at two sites: the most famous bora station, Senj, and Malinska (Fig. 1). Otherwise, high-quality wind measurements in the area of interest are sparse because the majority of wind data (Fig. 2) is available from observations performed only three times per day.

The wind measurements in Senj (44.99° N, 14.90° E) were performed by the WindMaster ultrasonic Gill anemometer placed at the coast (Orlić et al., 2005). The model satisfactorily reproduced the wind speed, although with a slight overestimation during bora compared to the measurements (Fig. 3). The wind direction is reproduced very well, successfully predicting the timing of the bora breakthrough near the coast. In Malinska, the wind speed was recorded by an automatic weather station, while the wind direction was obtained from observations performed three times a day. The wind speed is simulated less accurately than in Senj, particularly during stronger winds in the surroundings when the model occasionally overestimates the wind speed. Nevertheless, the speeds in Malinska are low during the entire bora episode which is reproduced by the model. The wind direction agrees rather well with the sparse observations, except at 13 UTC on 29 June when the observed winds are south-westerly, while model gives easterly winds. This is the case of the re-

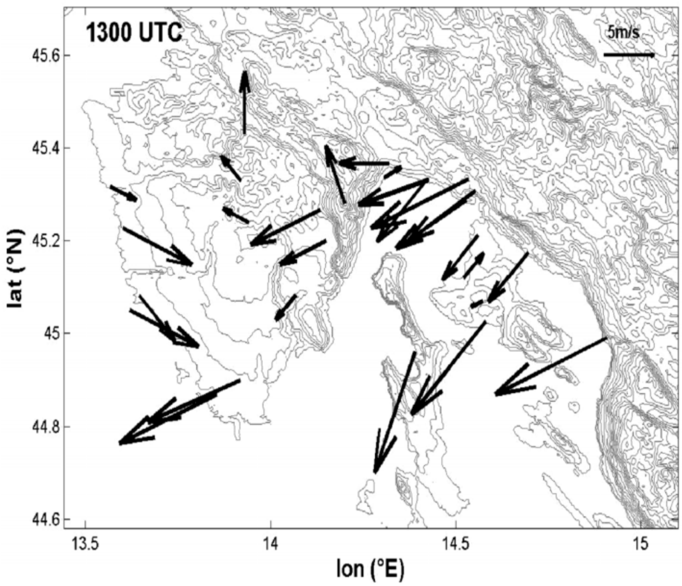

Figure 2. Hourly 10-m wind from meteorological and climatological stations at 13 UTC on 29 June 2004. The reference vector is near the upper right-hand corner. Topography contours are given every 100 m at 300 m horizontal grid spacing.

versed flow in Malinska that the model does not fully reproduce and it will be examined in the next section.

The comparison with the soundings launched from Zadar-airport (44.12° N, 15.38° E) and Zagreb (45.82° N, 16.03° E) is shown in Fig. 4. The model reasonably well agrees with the measured vertical structure at both stations, apart from some smaller-scale deviations that are probably due to either too low model vertical resolution, or to the instantaneous nature of radiosonde data.

The overall correspondence between the measurements and the model encourages us to continue with the analysis. Concerning the occasional lower performance in terms of the point-to-point comparison, we have to bear in mind that the observations are not always representative of the regions studied, and that the agreement between the model and certain measurements, e.g. those made in the most complex topographical region of the domain, can be less precise albeit the wind characteristics in the majority of the domain are still accurately represented.

3.2. Characteristics of the flow reversal

We chose two modeled situations with the lee reversed flow for detailed examination. The first case occurred at 00 UTC on 29 June and was related to the onset stage of the bora. Figure 5 shows the flow development from 21 UTC

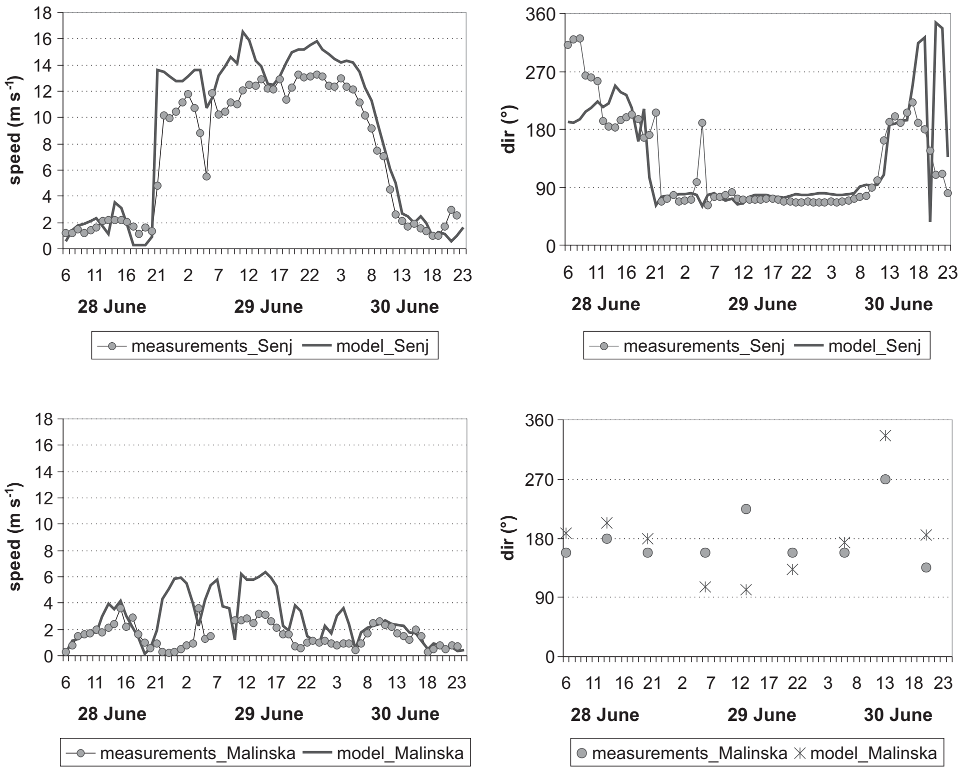

Figure 3. Modeled versus measured surface winds (10 m above ground) from 06 UTC on 28 June, until midnight 30 June 2004 for Senj (up) and Malinska (down). The positions of the measuring sites are indicated in Fig 1. The observations of wind direction in Malinska were performed only three times per day (6, 13 and 20 UTC).

on 28 June to 00 UTC on 29 June, where the transient nature of the onset stage is evident. During the three hours, the strength and extension of bora jets change significantly. The bora is first developed only relatively close to the coast, with jets related to the well-known mountain gaps (Gornje Jelenje and Vratnik Pass in Fig. 1). Later on, the prominent jet from the Vratnik Pass extends over the island of Cres. At the same time, the other local wind speed maximum over the land north of the island of Krk weakens, while the flow reversal appears over the sea northward of Malinska. The dimensions of the reversed flow are about 10 km × 10 km in the horizontal and about 200 m in the vertical. The corresponding vertical cross-sections reveal the reason for the change in the flow dynamics. The depth of the incoming flow layer, depicted by the thick white line in Fig. 5, increases from about 1300 m at 21 UTC on 28 June to over 2300 m three hours later (see the most north-eastern point on vertical cross-sections in Fig. 5c,d). This would theoretically correspond to

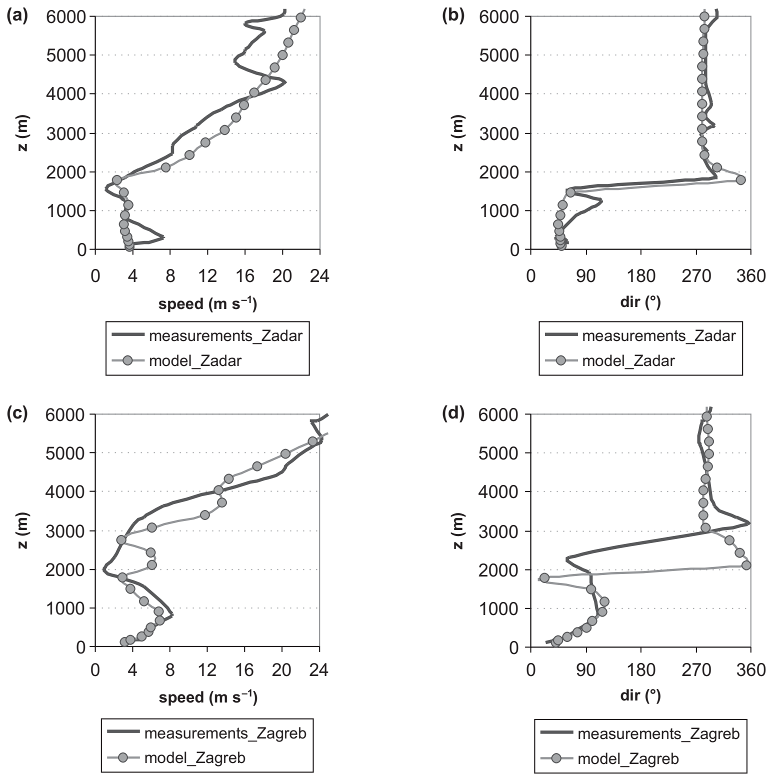

Figure 4. Modeled versus measured vertical profiles of (a, c) the wind speed and (b, d) the wind direction at Zadar-airport (44.12° N, 15.38° E) and at Zagreb (45.82° N, 16.03° E) from the soundings launched at 12 UTC on 29 June 2004.

lowering of the shallow-water Froude number and consequent transition of the flow structure from more spread or even propagating hydraulic jump to the stationary lee hydraulic jump (e.g. Durran, 1986; Baines, 1995). The latter statement is based on the hydraulic-like look at downslope winds and is more a conceptual view here, because the flow is not characterized by constant stability and wind speed, and the layer is delimited with a mean-state critical level which induces additional processes in formation of the shooting flow in the lee. Nevertheless, it is clear that with the layer deepening the hydraulic jump becomes confined to the lee, which is in agreement with the theory, while simultaneously farther from the mountain the reversed flow develops. The flow appearance is conceptually similar to 3D simulations of Sheridan and Vosper (2006). The close-up of the flow reversal (Fig. 5e) shows the existence of a vortex with a horizontal along-mountain axis, resembling a lee rotor circulation. Since it is related to the hydraulic jump, the closed circulation might be

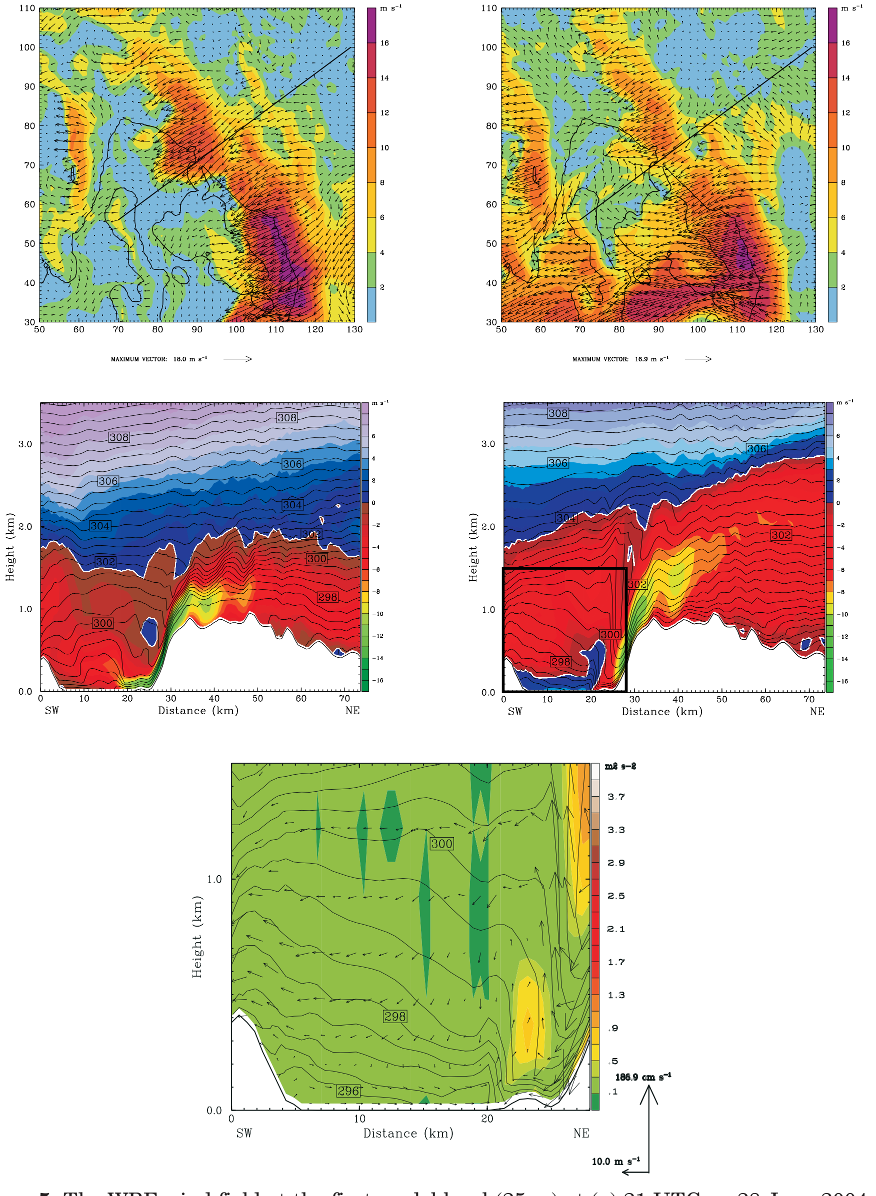

Figure 5. The WRF wind field at the first model level (25 m) at (a) 21 UTC on 28 June 2004 and (b) 00 UTC on 29 June 2004. The wind vectors are given every 2 km. The thick black line denotes the base of vertical cross-sections shown in the bottom panels. Vertical cross-sections of the horizontal wind parallel to the cross-section (filled) and potential temperature (contours, 0.5 K interval) at (c) 21 UTC on 28 June 2004 and (d) 00 UTC on 29 June 2004. (e) A close-up of the reversed flow structure within the lowermost 1.5 km of the atmosphere at 00 UTC on 29 June 2004 (see black rectangle in Fig. 5d). Shown are isentropes with 0.5 K contour increment, wind vectors and TKE (m^2 s^{-2}; filled).

a sign of the hydraulic-jump rotor (the type 2 rotor from Hertenstein and Kuettner, 2005). However, relatively low turbulent kinetic energy (TKE) values within the circulation pattern (up to 0.5 m^2 s^{-2}) do not seem to agree with the 2D and conceptual view of the type 2 rotor.

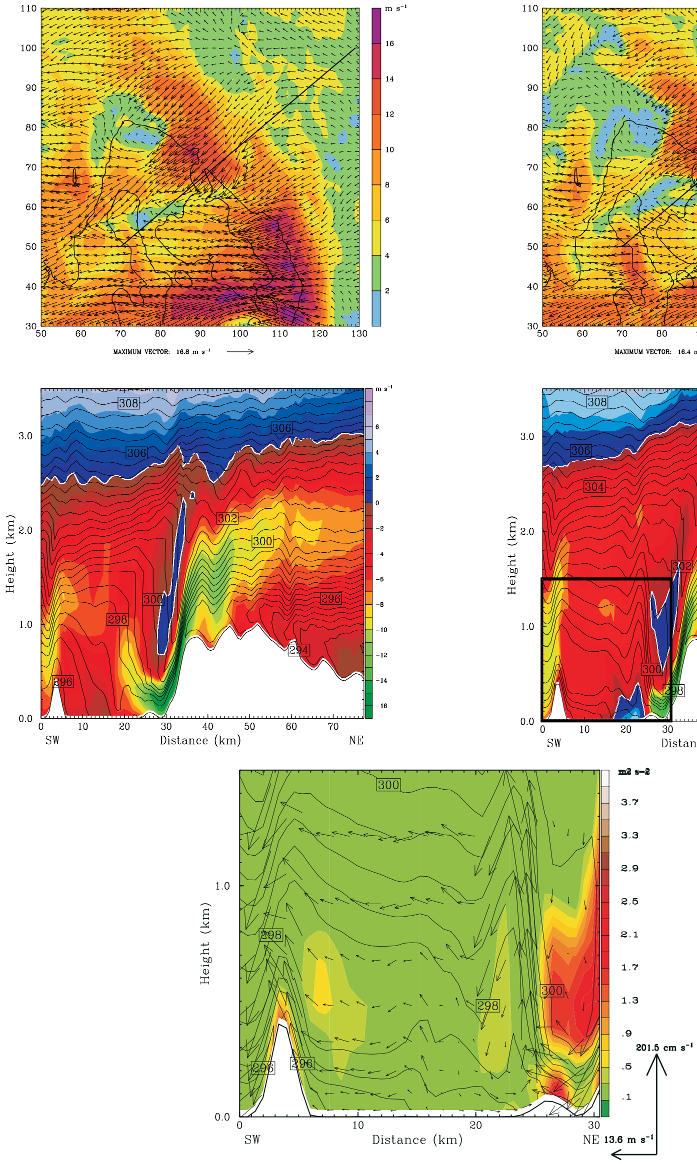

Figure 6. As in Fig. 5, but for the second case with reversed flow: (a, c) 14 UTC and (b, d, e) 16 UTC on 29 June 2004.

The second case occurred later in the bora episode, around 16 UTC on 29 June. During the day, the measurements indicate the existence of the reversed flow in Malinska at 13 UTC (Fig. 2). Since the wind speeds are somewhat overestimated by the model, the reversed flow forms later than in the measurements, i.e. around 15 UTC, and lasts for four consecutive hours. At 16 UTC, the most pronounced reversed flow appearance is found above approximately the same region as before (Fig. 6) covering about 11 km × 7 km in horizontal and the lowermost 300 m in vertical. Here the difference between the situation without and with the reversed flow is not in the along-shore structure of the flow, but primarily in its strength. Compared to the situation without the reversed flow at 14 UTC, during the flow reversal at 16 UTC the wind speed in the core of the bora jet north of the island of Krk is reduced by about 2 m s^{-1}. The vertical cross-sections show that then the incoming flow slightly deepens, but is also characterized by a significant drop of wind speed of about 40 %. Both factors act to reduce the Froude number, thus again leading the flow to a more confined, stationary lee hydraulic jump. The close-up of the vertical cross-section (Fig. 6e) shows the recirculation in the near-surface flow related to the flow separation occurring at the hydraulic jump, similar to the first case (Fig. 5e). The near-surface speeds of the reversed flow are about 4 m s^{-1}.

It should be noted that in neither case does the model reproduce the reversal in Malinska, but only northward of it.

4. Conclusions

The lee reversed flow appearing north of Malinska on the island of Krk during bora has been examined. The closed circulation structure and the relation of the flow reversal to the stationary lee hydraulic jump resemble the type 2 (or hydraulic-jump) rotor. The formation of the rotor-like reversed flow is related to the increase of the depth of the incoming flow layer and/or decrease of its speed. Both phenomena reduce the Froude number, thus supporting the formation of the stationary lee hydraulic jump. However, there are significant differences compared to the type 2 rotors obtained from idealized 2D studies (e.g., Hertenstein and Kuettner, 2005; Hertenstein, 2009). First of all, there is significantly less rotor-associated turbulence in our case. Furthermore, the phenomenon discussed here is characterized by a shallow layer of reversed flow close to the surface, whereas in the type 2 rotor from Hertenstein and Kuettner (2005) and Hertenstein (2009), the reversed flow occurs above a near-surface jet.

Other flow/terrain features might also play a role in the formation of the flow reversal; e.g. vortices with a *vertical* axis formed between the two gap jets of Gornje Jelenje and Vratnik Pass and/or the effects of the islands (Krk and Cres). Also, Malinska is located below a hill whose height is about 120 m in the upstream direction. Farther to the south-east, the hill height grows to about

250 m. Local effects induced by this hill might be at least partially responsible for the wind reversal observed in Malinska. In that respect, the reversed flow simulated over the Kvarner Bay could be a phenomenon that is related to, but not necessarily responsible for, the observed Malinska reversal. With regard to the sparsity of measurements in the area, it would be required to perform numerical simulations with quite small grid box size (~ 100 m) in order to obtain conclusive results. On the other hand, recent studies depicting the wind velocities over the sea derived from the synthetic aperture radar point to a well-defined wake in the Kvarner Bay during bora (Alpers et al., 2009). While these winds have a 180° ambiguity in wind direction (e.g., Koch and Feser, 2006) and thus cannot be used here to verify the flow reversal over the sea, they do confirm the existence of a wake covering the sea from Malinska northwards (Alpers et al., 2009; their Fig. 1), similar to the one obtained here. The wake area is larger than the local hill effect would induce, and since it extends from the coast of Malinska, it indicates that even the reversal in Malinska might have a larger-scale origin.

Despite the limitations of both high-quality wind measurements and the model setup (e.g., horizontal and vertical grid spacing, mixing length parameterization), this study allows us to draw some first conclusions. Future work will be dedicated to idealized numerical simulations to isolate e.g., the effect of the lee-side islands of the bora flow varying the topography (with or without Krk and Cres in the domain) and to the improvement of the mixing length parameterization in the model.

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References

Alpers, W., Ivanov, A. and Horstmann, J. (2009): Observations of bora events over the Adriatic Sea and Black Sea by spaceborne synthetic aperture radar. *Mon. Weather. Rev.*, **137**, 1150–1161.

Baines, P. G. (1995): *Topographic Effects in Stratified Flows*. Cambridge University Press, Cambridge, United Kingdom, 482 pp.

Belušić, D. and Klaić, Z. B. (2006): Mesoscale dynamics, structure and predictability of a severe Adriatic bora case. *Meteorol. Z.,* **15**, 157–168.

Belušić, D., Žagar, M. and Grisogono, B. (2007): Numerical simulation of pulsations in the bora wind. *Q. J. Roy. Meteor. Soc*., **133**, 1371–1388.

Durran, D. R. (1986): Another look at downslope windstorms. Part I: the development of analogs to supercritical flow in an infinitely deep, continuously stratified fluid. *J. Atmos. Sci*., **43**, 2527–2543.

Gohm, A., Mayr, G. J., Fix, A. and Giez, A. (2008): On the onset of bora and the formation of rotors and jumps near a mountain gap. *Q. J. Roy. Meteor. Soc*., **134**, 21–46.

Grisogono, B. and Belušić, D. (2009): A review of recent advances in understanding the meso- and microscale properties of the severe Bora wind. *Tellus,* **61A**, 1–16.

Grubišić, V. (2004): Bora-driven potential vorticity banners over the Adriatic. *Q. J. Roy. Meteor. Soc.*, **130**, 2571–2603.

Hertenstein, R. F. and Kuettner, J. P. (2005): Rotor types associated with steep lee topography: influence of the wind profile. *Tellus,* **57A**, 117–135.

Hertenstein, R. F. (2009): The influence of inversions on rotors. *Mon. Weather Rev.,* **137**, 433–446.

Jeromel, M., Malačić, V. and Rakovec, J. (2009): Weibull distribution of bora and sirocco winds in the northern Adriatic Sea, *Geofizika*, **26**, 85–100.

Jurčec, V. (1988): The Adriatic frontal bora type. *Papers* **23**: 13–25.

Koch, W. and Feser, F. (2006): Relationship between sar-derived wind vectors and wind at 10-m height represented by a mesoscale model.. *Weather Rev.,* **134**, 1505–1517.

Orlić, M., Belušić, D., Pasarić, Z. (2005): First measurements of bura wind at Senj with a three--axis anemometer. *Cro. Meteorol. J.,* Đuričić, Vesna (ed.). Zagreb: Hrvatsko meteorološko društvo, 308–311.

Prtenjak, M. T., Viher, M. and Jurković, J. (2009): Sea/land breeze development during a summer bora event along the north-eastern Adriatic coast. *Q. J. Roy. Meteor. Soc.* (accepted).

Sheridan P. F. and Vosper, S. B. (2006): A flow regime diagram for forecasting lee waves, rotors and downslope winds. *Meteorol. Appl.*, **13**, 179–195.

Skamarock, W. C., Klemp J. B., Dudhia J., Gill D. O., Barker D. M., Wang W. and Powers J. G. (2005): A description of the Advanced Research WRF Version 2, NCAR/TN–468+STR, NCAR, Boulder, Colo.

SAŽETAK

Formiranje povratnog zavjetrinskog strujanja nad sjeveroistočnim Jadranom tijekom bure

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Površinska mjerenja upućuju na postojanje povratnog površinskog strujanja na sjeveroistočnom Jadranu tijekom bure. Stoga ovdje ispitujemo njegovu strukturu i razvoj pomoću numeričkih simulacija. Proučavana se pojava razvila tijekom jednog tipičnog događaja ljetne frontalne bure koju karakterizira iznenadno povećanje brzine vjetra. U blizini Malinske, unutar zaklonjenog dijela tijekom bure, strujanje prema obali je nastalo kao donja grana zavjetrinske cirkulacije slične rotoru koja je povezana s hidrauličkim skokom. Iako zatvorena cirkulacija sliči hipotetskom rotoru uslijed hidrauličkog skoka, postoje značajne razlike, osobito u snazi turbulencije koja je povezana s nastankom rotora.

Ključne riječi: predjel zavjetrinske tišine; hidraulički skok; zavjetrinsko vrtloženje

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