Evolution and Structure of Two Severe Cyclonic Bora Events: Contrast between the Northern and Southern Adriatic

KRISTIAN HORVATH, STJEPAN IVATEK-ŠAHDAN, AND BRANKA IVANČAN-PICEK

Meteorological and Hydrological Service, Zagreb, Croatia

VANDA GRUBIŠIĆ

Desert Research Institute, Reno, Nevada

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ABSTRACT

While statistical analyses and observations show that severe bora with maximum gusts exceeding 40 m s^{-1} can occur in all parts of the Adriatic, the bora research to date has been mainly focused on the dynamics and structure of severe bora in the northern Adriatic. Examined to a significantly lesser degree is a less predictable counterpart in the southern Adriatic, where the Dinaric Alps are higher, broader, and steeper, and where the upwind bora layer is generally less well defined. Identification of the main differences in the sequence of mesoscale and macroscale events leading to the onset of bora in the northern and southern parts of the eastern Adriatic is of fundamental importance for its forecasting. To this end, presented here is a comparative analysis of the evolution and structure of two typical severe cyclonic bora events—one ''northern'' (7–8 November 1999) and one ''southern'' (6–7 May 2005) event. The analysis utilizes airborne, radiosonde, and ground-based observations, as well as the hydrostatic Aire Limitée Adaptation Dynamique Developement International (ALADIN/HR) mesoscale model simulations.

It is shown that the development of a severe bora in both the northern and southern Adriatic is critically dependent on the synoptic setting to create an optimal set of environmental conditions. For severe bora in the northern Adriatic, these conditions include a strong forcing of the northeasterly low-level jet and pronounced discontinuities in the upstreamflow structure that promote layering, such as lower- to midtropospheric inversions and environmental critical levels. The development of severe bora in the southern Adriatic is crucially dependent on the establishment of a considerably deeper upstream layer that is able to overcome the strong blocking potential of the southern Dinaric Alps. While the upstream layering is less pronounced, it is closely tied to the presence of a cyclone in the southern Adriatic or over the southern Balkan peninsula.

The upstream atmospheric layering is shown to strongly modulate bora behavior, and different phases of severe bora, related to the presence or absence of upstream layering, are shown to occur within a single bora episode. Furthermore, the presence of a mountain-parallel upper-level jet aloft appears to impede severe bora development in both the northern and southern Adriatic.

1. Introduction

A bora is a gusty northeasterly downslope wind along the eastern Adriatic that is strongly influenced by local processes and orography. The severity of bora is well known and exemplified by its gusts, which can exceed 60 m s^{-1}. Because of their severity and very frequent occurrence, in particular during the cold season, bora substantially influence the way of life of the local people. As a statistical analysis over a 30-yr period (1958–87) shows, severe bora with maximum gusts exceeding 40 m s^{-1} may appear along the entire Adriatic coast, but their durations and frequencies decrease from north to south (Bajić 1989). Despite the climatological preference for the northern Adriatic as the locus of strong bora, events do occur in which bora gain greater strength in the southern Adriatic.

Most of the bora research to date has focused on the severe bora in the northern Adriatic (e.g., Smith 1987; Klemp and Durran 1987; Bajić 1991; Grubišić 2004; Belušić et al. 2007; Göhm et al. 2008; see recent review paper by Grisogono and Belušić 2008), in particular that

Corresponding author address: Kristian Horvath, Gric 3, 10000 Zagreb, Croatia.
E-mail: horvath@cirus.dhz.hr

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at the locus of the climatological maximum near Senj, at the northern end of the Velebit range, where hydraulic theory appears to capture the dynamical essence of the bora phenomenon (Smith 1985; Smith and Sun 1987). Less studied and less predictable are the bora in the southern Adriatic, south of the Velebit range, where the Dinaric Alps are higher, broader, and steeper, and where the upwind bora layer, from the perspective of hydraulic theory, is less well defined. The few studies to date that have explicitly addressed the bora in the southern Adriatic challenge the traditional view of bora as a local small-scale phenomenon and reveal the multiscale nature of the bora-related airflow (e.g., Ivančan-Picek and Tutiš 1996).

The main aim of this study is to identify differences in the evolution of mesoscale and large-scale features favorable for the generation of severe cyclonic bora in the southern and northern Adriatic. It is well known that the synoptic pressure pattern over Europe can be used to distinguish between an anticyclonic and a cyclonic bora (e.g., Defant 1951; Yoshino; 1976; Heinmann 2001; Pandžić and Likso 2005). The *anticyclonic* bora develops under the influence of a high pressure system over central Europe (upstream of the Dinaric Alps). The *cyclonic* bora, on the other hand, is associated with the existence of a low pressure area over the central Mediterranean (e.g., Horvath et al. 2008). Clouds and precipitation together with strong winds typically characterize a cyclonic bora. The local population has always distinguished "dark bora" (cyclonic), with cloudy skies and precipitation, from a cloudless or "clear bora" (anticyclonic).

The identification of key differences in the mesoscale structure and evolution of airflow over the northern and southern parts of the eastern Adriatic shore in this study is based on a comparative analysis of two severe cyclonic bora events, one "northern" and one "southern." As the knowledge of mesoscale flow features generally leads to an increase in forecasting skill for surface winds, especially in hazardous situations, we pay particular attention to the generally less explored upstream bora conditions. The analysis is based on the numerical model simulations with the operational Air Limitée Adaptation Dynamique Development International (ALADIN/HR) hydrostatic model run at 8-km horizontal resolution and available airborne, radiosonde, and ground-based observations.

The paper is organized as follows. Section 2 delivers a description of the ALADIN/HR model and the numerical simulations. In section 3, we present the synoptic environments during the two chosen severe bora events. A comparison of the mesoscale model results with observations is given in section 4. The spatial structures of the upstream, downstream, and cross-mountain flows during these bora events are examined in section 5. Section 6 summarizes our findings and concludes the paper.

2. ALADIN/HR simulations

The ALADIN model is a limited-area model built on top of the Action de Recherche Petite Echelle Grande Echelle–Integrated Forecast System (ARPEGE–IFS) global model, which uses spectral representation of predicted fields (Bubnova et al. 1995). The physical parameterization package includes the vertical diffusion parameterization (Louis et al. 1982), shallow convection (Geleyn 1987), and modified Kuo-type deep convection (Bougeault and Geleyn 1989) schemes, as well as a Kessler-type large-scale precipitation parameterization (Kessler 1969) for the treatment of stratiform cloud processes. The vertical transport of moisture and heat in the soil is represented with a two-layer parameterization scheme (Giard and Bazile 2000).

ALADIN was one of the limited-area models used operationally at the Mesoscale Alpine Programme (MAP) Operational Centre (MOC) during the MAP Special Observation Period (SOP). At the Meteorological and Hydrological Service of Croatia, ALADIN/HR is run operationally at 8-km horizontal resolution with 37 vertical levels twice daily at 0000 and 1200 UTC using a 72-h integration of the ALADIN full-physics package (e.g., Ivatek-Šahdan and Tudor 2004). The initial and boundary conditions are taken from the ARPEGE global atmospheric model with horizontal resolution of approximately 40 km over the forecast target area. The above operational setup was also used in this study. The ALADIN/HR domain with the model representation for orography is shown in Fig. 1.

3. Synoptic conditions

a. Northern bora event

The northern cyclonic bora event selected for this study is that documented during MAP Intensive Observing Period (IOP) 15 (7–8 November 1999). An in-depth analysis of this case is presented in Grubišić (2004), where the dynamics and structure of the leeside and cross-mountain flows were investigated using the aircraft and other in situ data.

The synoptic situation during MAP IOP 15 (7–8 November 1999), as inferred by the European Centre for Medium-Range Weather Forecasts (ECMWF) T511 (~40 km horizontal resolution in the region) reanalysis (Fig. 2), was characterized by rapid lee cyclogenesis over the Gulf of Genoa and the Tyrrhenian Sea (Fig. 2a). The Alpine low-level blocking, deflection of airflow by the Alps, and appearance of the Genoa lee

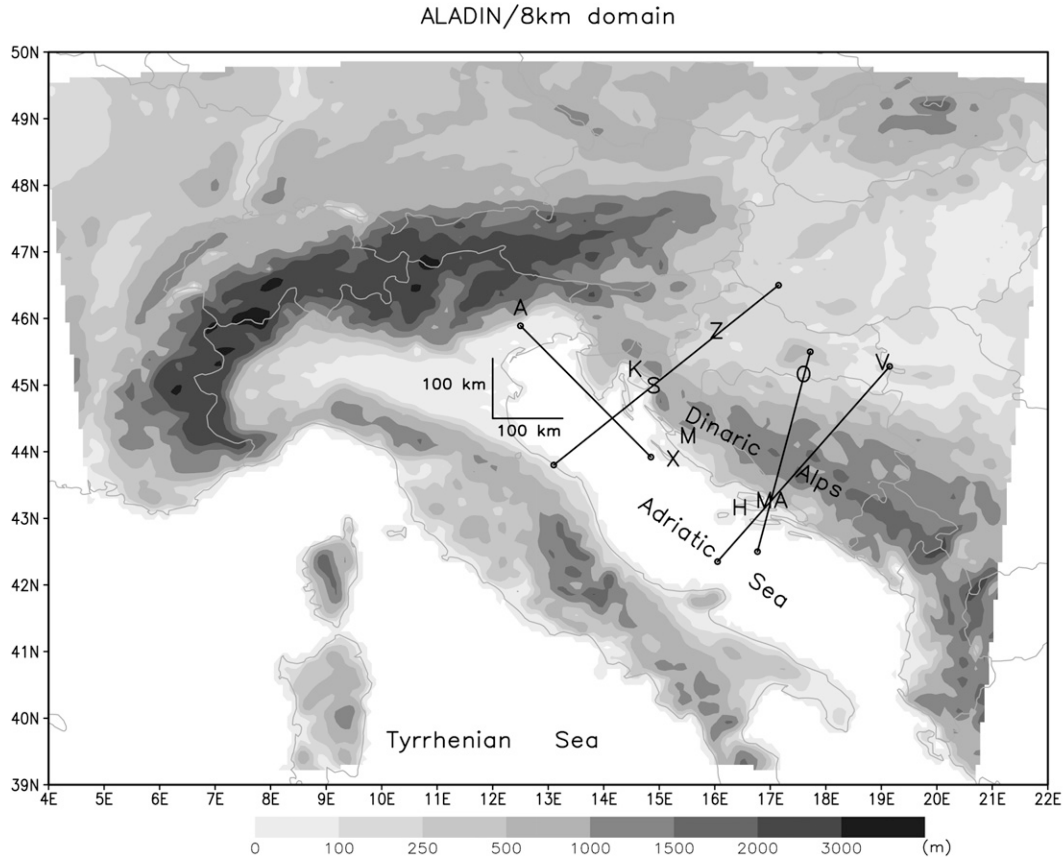

FIG. 1. The ALADIN/HR domain with sites of interest mentioned in the text. Solid black line AX denotes the NCAR Electra flight track and Z, K, V, MA, M, H, and O are the locations of Zagreb, Krk Bridge, Vukovar, Makarska, Maslenica Bridge, Hvar, and the model grid point of interest, respectively. Locations of vertical cross sections (used in Figs. 11 and 14) are indicated with gray solid lines.

cyclogenesis at the beginning of 7 November 1999 were associated with a primary cyclone north to the Alps and the related cold front traversing the Alpine range. At the upper levels, a deep trough extending from the North Sea to the central Mediterranean developed into an upper-level cutoff low with two circulation nuclei (Figs. 2b and 2d). With a strong anticyclone over northwestern Europe, and the cyclone over the Tyrrhenian Sea, the situation was characterized by strong low-level pressure gradients across the Alps as well as the Dinaric Alps (Fig. 2c).

The onset of this bora was in the northern Adriatic during the morning hours of 7 November 1999. At that time, strong Jugo[1] was still present over the southern part of the Adriatic. Later that day, a jugo was displaced by the bora that gradually extended to the middle and the southern Adriatic. This bora was significantly stronger in the northern Adriatic (wind gusts of over 45 m s^{-1}) than farther south, where wind gusts were approximately half as strong.

b. Southern bora event

The ‘‘southern’’ bora event selected for this study is that of 6–7 May 2005. The synoptic situation for the period 6–7 May 2005 was characterized by a cyclone development over the central Mediterranean and an anticyclone over the eastern Atlantic and central Europe (Fig. 3). At 0600 UTC 6 May 2005, the center of the surface cyclone was located in the southern Mediterranean and moving toward the northeast (Fig. 3a). At the same time, the upper-level trough was situated southwest of the Alps, slowly moving toward the east (Fig. 3b). By 0000 UTC 7 May 2005, the surface cyclone experienced a rapid deepening above the southern Adriatic and southeastern Europe and the central pressure fell

[1] A jugo is a local warm and humid southeasterly wind that belongs to the family of sirocco winds but that is channeled along the Adriatic basin by the Dinaric Alps (e.g., Jurčec et al. 1996).

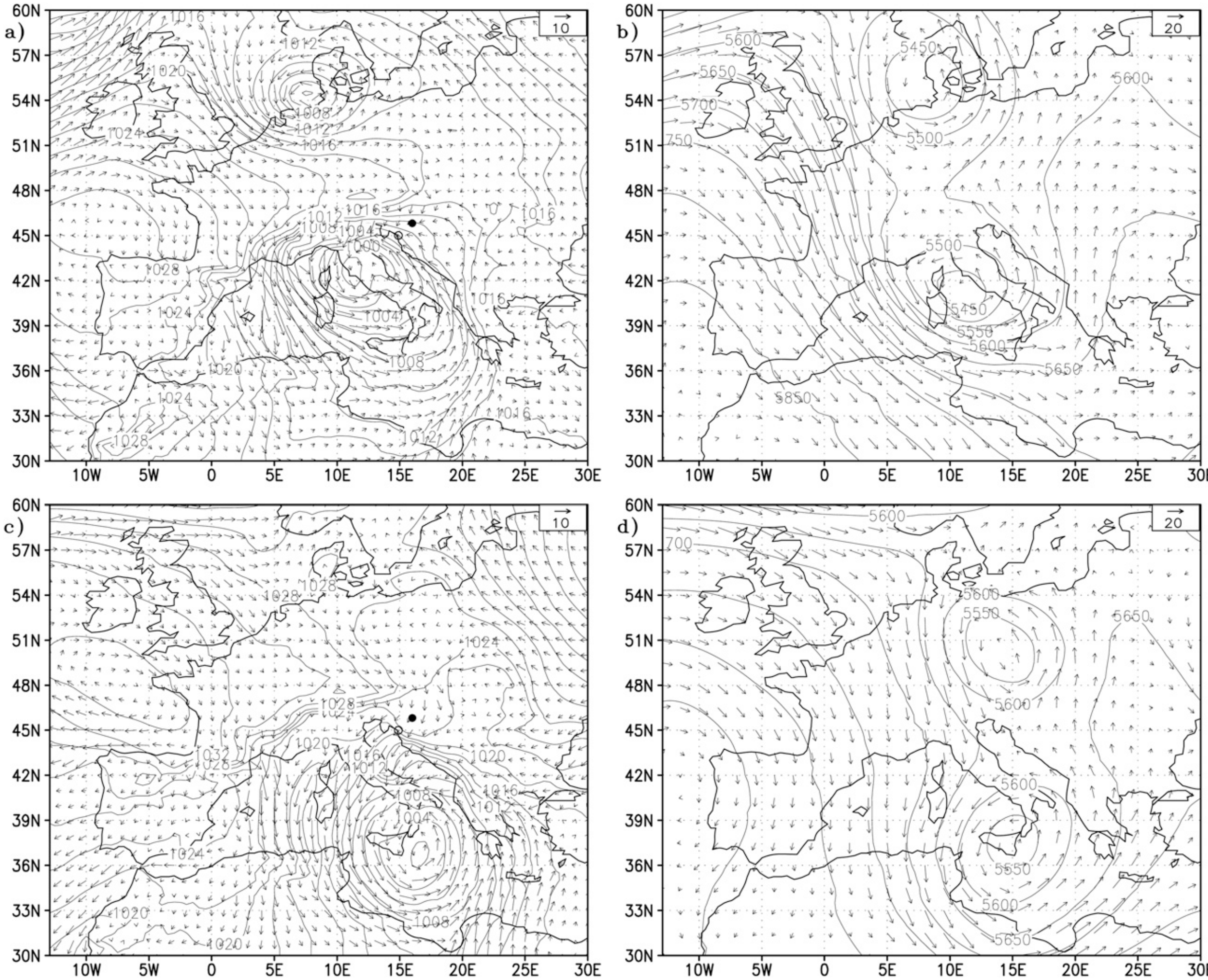

FIG. 2. The ECMWF reanalysis for the northern bora event: (left) MSLP and 10-m wind field and (right) geopotential height and wind field at 500 hPa on (a),(b) 0000 UTC 7 Nov and (c),(d) 1200 UTC 8 Nov 1999. In (a) and (c) Zagreb is denoted by a closed circle and Senj by an open circle.

below 996 hPa, as inferred from the ECMWF analysis (Fig. 3c). At that time, the center of the upper-level trough was positioned above the center of the surface cyclone and the trough axis acquired a negative tilt (Fig. 3d).

This synoptic setting had created a nonuniform pressure gradient across the Dinaric Alps that increased in strength from north to south, favorable for the generation of severe bora in the southern Adriatic. From the outset in the northern Adriatic, this bora gradually spread southward, too, but was not preceded by the jugo. The winds were significantly stronger in the southern Adriatic, causing a significant amount of infrastructural damage there. During this event, the highest values of the 10-min averaged wind speed and wind gusts in the southern Adriatic exceeded by a factor of 3 the respective values in the northern Adriatic.

Despite the absence of a primary cyclone and the associated cold front impinging on the Alps (such as in the MAP IOP 15 case), a strong NW flow was present north of the Alpine range. A pronounced low-level splitting of this NW flow produced rather sheltered conditions in the northern Adriatic. As the northern branch of this split flow turned around the eastern end of the Alps, the flow with a component perpendicular to the southern portion of the Dinaric Alps developed. While this flow splitting around the Alps bears some resemblance to that in MAP IOP 15, the thermal properties of these flows were quite different, as is discussed further below. By the end of 7 May 2005, the center of the surface low moved eastward and was positioned over the Black Sea, resulting in weakening of the pressure gradients across the Dinaric Alps.

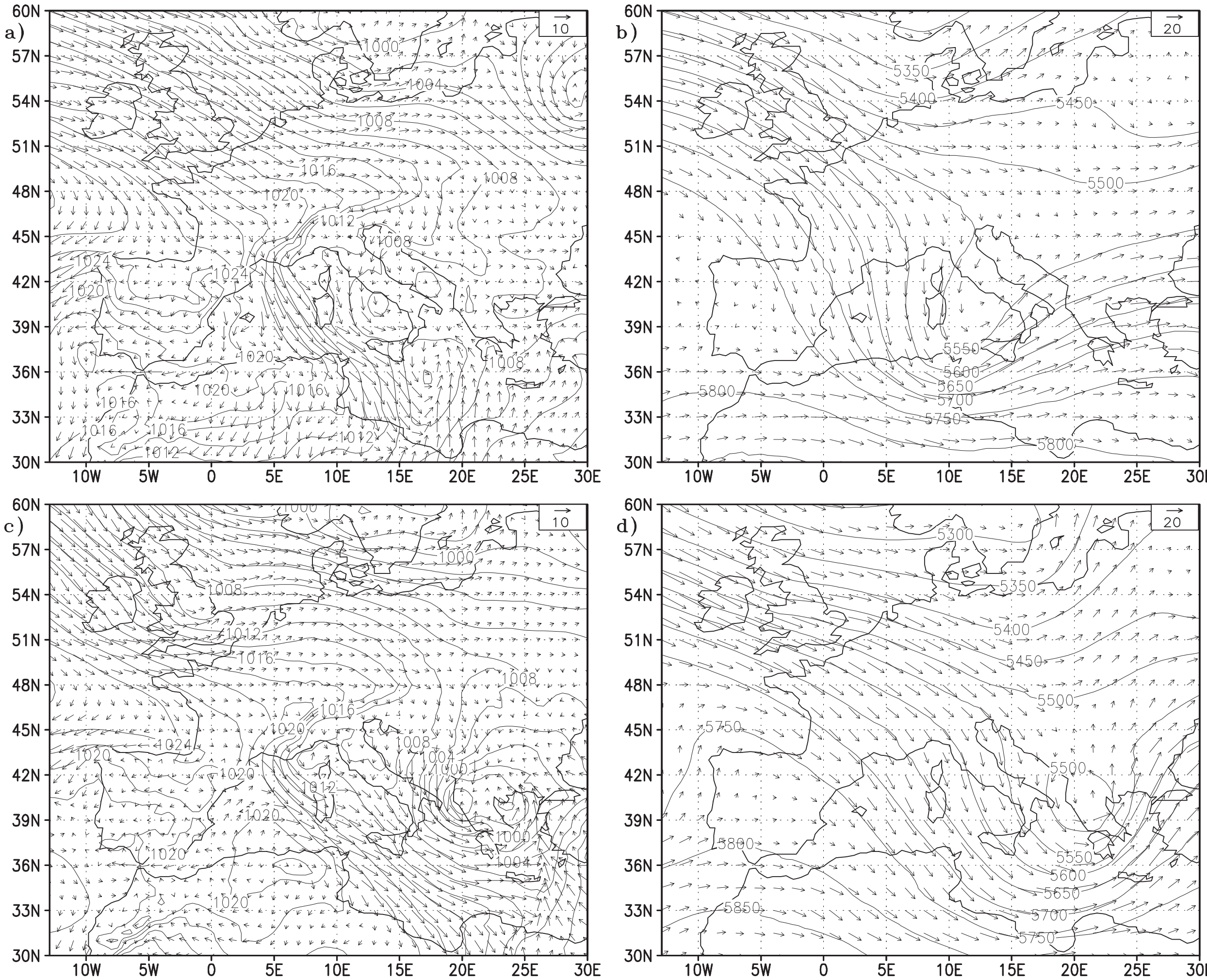

FIG. 3. The ECMWF reanalysis for the southern bora event: (left) MSLP and 10-m wind field and (right) geopotential height and wind field at 500 hPa at (a),(b) 0600 UTC 6 May and (c),(d) 0000 UTC 7 May 2005.

The northern and southern cases analyzed in this study are fairly typical cases of cyclonic bora in the northern and southern Adriatic. Based on Yoshino's (1976) classification, which identifies two types of cyclonic bora in the Adriatic, the southern event corresponds to a type A cyclonic bora, with a cyclone center near southern Italy and the Ionian Sea, whereas the northern event corresponds to a type B event, characterized by the presence of a cyclone in the Gulf of Genoa and the Tyrrhenian Sea. More recently, based on the analysis of synoptic situations in the 20 strongest southern Adriatic bora events during the period 1991–2000 using the ECWMF analyses, Večenaj (2005) demonstrated that a cyclone presence in the vicinity of southern Italy (type A in the Yoshino classification) is a fundamental synoptic ingredient of the most severe bora events in the southern Adriatic. As pointed out by Grisogono and Belušić (2008), however, the existing bora classifications lack detail regarding the bora's strength (weak, moderate, severe) and the associated synoptic settings, leading to some uncertainties with respect to this generalization.

4. Comparison of observations and model simulations

During these two selected bora cases, standard surface wind measurements were available at several coastal stations (Krk Bridge, Maslenica Bridge, Hvar, and Makarska). For the upstream conditions, we have utilized the radiosonde data from the Zagreb-Maksimir station. The locations of all these measuring sites are shown in Fig. 1. In addition to the routine operational data, for the validation of the model simulations we

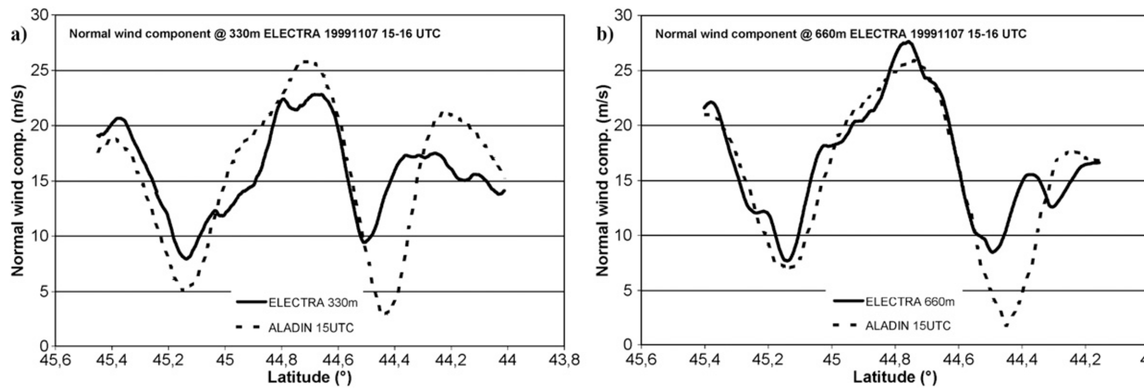

FIG. 4. Comparison of ALADIN/HR model predictions and flight data for the 10-min wind speed component normal to the flight track AX (cf. Fig. 1) at (a) 330 and (b) 660 m MSL at 1500 UTC 7 Nov 1999.

have used the aircraft data collected during MAP IOP 15.

a. Flight-level data

The observed flow structure derived from the flight-level data from a coast-parallel track of the National Center for Atmospheric Research (NCAR) Electra at 1500–1600 UTC 7 November 1999 is compared here with the results from the ALADIN/HR simulation. Figures 4a and 4b show the magnitude of the 10-min wind speed component normal to the flight track AX (cf. Fig. 1) at 330 and 660 m MSL as a function of latitude.[2] The main feature in these diagrams is a strong and relatively wide NE jet between 44.6° and 45.0°N. As discussed in Grubišić (2004), this jet is a downwind extension of the leeside maximum associated with the strong outflow through Vratnik Pass (near Senj in Fig. 1). Two weaker low-level jets are also visible to the north and south of the main jet, owing their origin to Postojna Pass and Oštarije Pass, respectively. In between the jets, wakes (weak wind regions) associated with peaks in the coastal range are detected. The main low-level jet is 5 m s^{-1} stronger at 660 m than at 330 m MSL and displaced ~10 km to the northwest, suggesting a vertical tilt of the low-level jet and an increase in its intensity with height.

The model predictions and flight-level data at these two altitudes show reasonably good agreement. The spatial structure of the observed flow and the strength of the low-level jets are predicted quite well, but the winds within the wake zone north of the main low-level jet (centered at 44.5°N) are underestimated. At 660 m MSL, the agreement is better than at 330 m MSL, where the underestimation in the wakes is more pronounced and the intensity of the low-level jets seems to be weakly overestimated. A comparison with results in Grubišić (2004), which are based on the nonhydrostatic Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) simulations at a horizontal resolution of 3 km (cf. Fig. 9a in Grubišić 2004), reveals that the two model predictions show only slight differences in the predicted spatial flow structure and the degree of agreement with the observations. While the ALADIN/HR results lack the finescale detail that is better captured by the COAMPS simulation, in particular at 330 m MSL, the overall spatial structure of the bora flow is accurately represented in the ALADIN/HR simulation results.

b. Surface data

Comparisons of the time series of the observed and simulated surface wind direction, wind speed, and gusts (from 1-Hz data) from four coastal weather stations for the selected northern and southern bora events are shown in Fig. 5. The model fields are obtained from the lowest model level at 10 m.

Figures 5a–d show the data for the northern bora event, for the period 0000 UTC 7 November–0000 UTC 9 November 1999. The bora breakthrough, marked by a rapid increase in wind speed in the northern Adriatic, occurred in the early morning hours of 7 November 1999. Throughout that day, the bora intensity at Krk Bridge was highly variable, ranging between the maxima (~22 m s^{-1}) at 0700 and 1700 UTC, and the minimum (2 m s^{-1}) at 1100 UTC. In contrast, shortly after 1900 UTC 7 November 1999 and until the end of the episode (~2100 UTC 8 November 1999), the wind intensity at this site was rather constant

[2] The right orthogonal coordinate frame has a positive x axis aligned with the flight track and directed toward the NW.

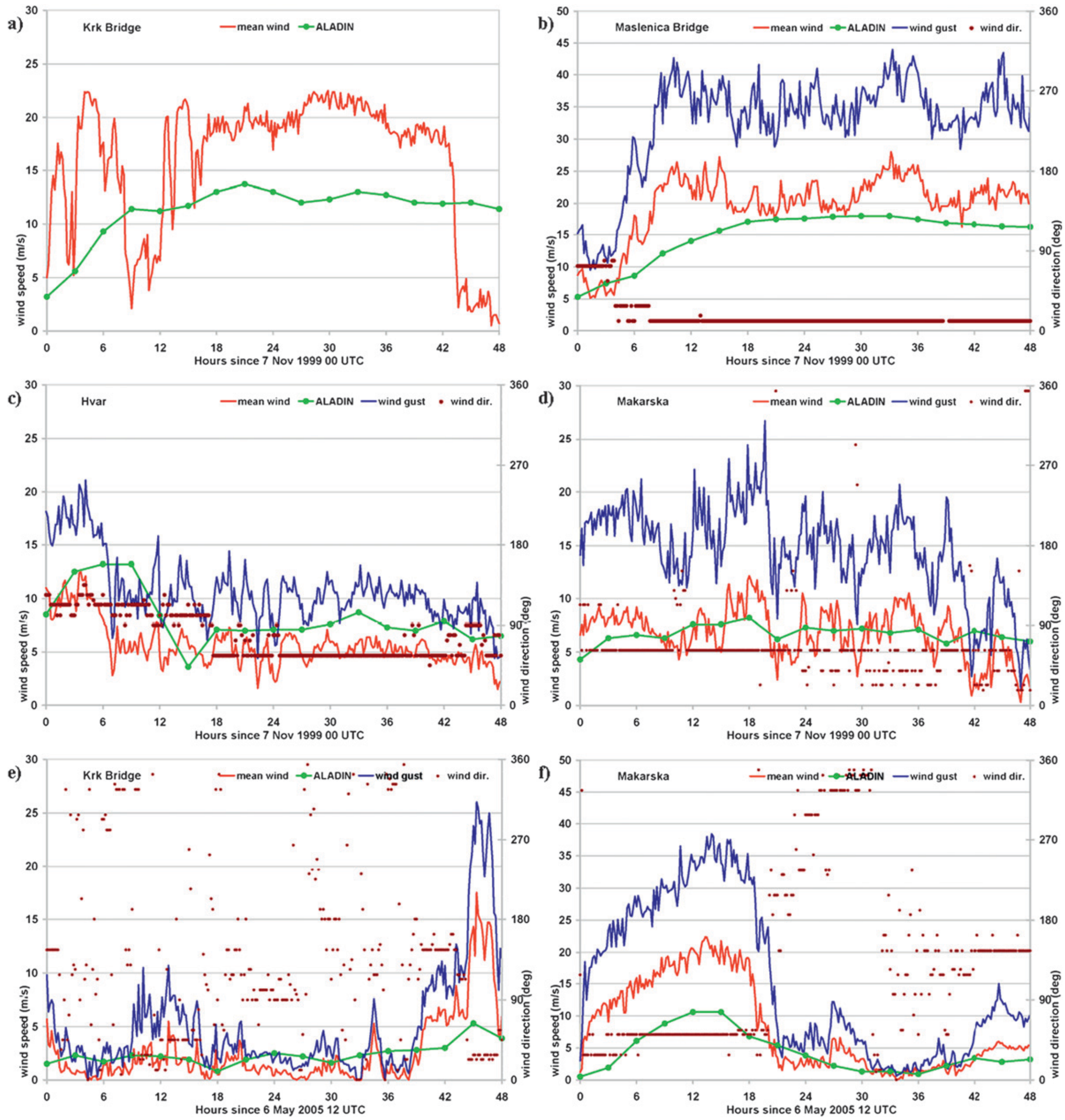

FIG. 5. Time series of surface wind speed (m s^{-1}), wind direction (°), and maximum gusts (m s^{-1}) at (a) Krk Bridge (wind direction and maximum gusts not available), (b) Maslenica Bridge, (c) Hvar, and (d) Makarska during the northern event (7–8 Nov 1999), and at (e) Krk and (f) Makarska during the southern event (6–7 May 2005). ALADIN/HR model prediction of the mean wind speed at 10 m level is shown with the green solid line.

($\sim$18–22 m s^{-1}). Based on the leeside wind speed at Krk Bridge, two phases of this bora seem evident: (i) the initial, variable wind speed, phase and (ii) the subsequent, sustained wind speed, phase. The gradual southward spread of this bora is revealed by a time delay (of a few hours) in the onset of the bora between the Krk and Maslenica Bridge sites (Figs. 5a and 5b). The highest mean hourly wind speeds measured at those two bridge sites exceeded 20 m s^{-1}, with gusts reaching close to 45 m s^{-1} (available at Maslenica Bridge only).

While the bora was already quite strong at the Krk Bridge site in the early morning hours of 7 November 1999, a strong jugo (10-min mean wind over 12 m s^{-1} with gusts over 20 m s^{-1}) was measured simultaneously at the island of Hvar (Fig. 5c), much stronger than the subsequent bora at the same location. After the onset of the bora in the afternoon of

7 November 1999, wind gusts at Hvar and Makarska,[3] the latter being a favorable site for severe bora in the southern Adriatic, barely exceeded 10 and 20 m s^{-1}, respectively. The noted simultaneous existence of a bora in the northern Adriatic and a jugo in the southern Adriatic is quite common in the case of surface lows over southern Italy (Jurčec et al. 1996; Brzović 1999; Pasarić et al. 2007). The ALADIN/HR model prediction of the mean wind speed agrees well with the observed except for the Krk Bridge site, where the model underestimates the mean wind speed by about 30%. In addition, the model predictions did not capture a short-lived cessation of the bora around 1200 UTC 7 November 1999, likely caused by a missed prediction of the weakened intensity of a low-level jet upstream of the coastal mountains (cf. section 4c).

During the southern event on 6–7 May 2005, the 10-min wind speed maximum of 22 m s^{-1} (with gusts reaching up to 40 m s^{-1}) was measured in Makarska, in the southern Adriatic. These maxima significantly exceed the maximum 10-min wind and gust measured in the north at the Krk Bridge site (7 and 11 m s^{-1}, respectively) (Figs. 5e and 5f). The initial phase of this bora was not preceded by the jugo since there was no cyclone over the Tyrrhenian Sea, which is the usual driver of this type of wind in the Adriatic. The model simulation captures the onset, timing, and cessation of this bora well. However, the maximum wind intensity was underestimated by roughly 50%. There is likely more than one contributing reason for this significant underestimation. The first is the model representation of the southern Dinaric Alps, which reduces their height as well as the marked steepness of the lee side, the latter being the most important mountain shape parameter that controls the strength of downslope windstorms (Miller and Durran 1991). For example, for the Biokovo section of the Dinaric Alps (Makarska station lying in its foothills), the mountaintop height in the ALADIN/HR simulation is 668 m, in contrast to 1762 m in reality. Second, given the higher steepness of the southern Dinaric Alps, nonhydrostatic effects likely play a more significant role in the dynamics of the southern Adriatic bora. Third, as recently indicated by Horvath and Ivančan-Picek (2009), the prediction of the Mediterranean cyclones and the bora in the southern Adriatic are strongly correlated. Though in both events the upper-level dynamical features were simulated with reasonable accuracy, the simulated cyclone intensity in this event was underestimated, as inferred from the ECMWF analyses (center low of 993 hPa at 0000 UTC 7 May 2005; Fig. 3c) and ALADIN/HR predictions [center low of 995 (997) hPa at 2100 (0300) UTC 6 (7) May 2005; Figs. 12a and 12b], which led to a weaker simulated background flow and contributed to weaker bora winds in the model prediction. Another possible reason for the underestimation of the bora intensity at Makarska is discussed in section 5b(3).

c. *Radiosonde data*

To determine the accuracy of the simulated upwind conditions leading to and throughout the selected bora events, we have examined the radiosonde data from Zagreb-Maksimir, located about 125 km upstream of the northern part of the coastal mountain range. Figure 6 shows a comparison of the observed upstream flow profile in Zagreb and the simulated profiles at the closest model grid point. The interval between the individual soundings at Zagreb was 6 h during MAP IOP 15 and 12 h during the May 2005 case.

The appearance of a shallow layer (<1000 m) of cold NE flow at 0000 UTC 7 November 1999 marks the beginning of this bora event (Fig. 6a). A few hours later, the northern Adriatic coastal stations show the onset and gradual increase of the bora flow (cf. Fig. 5). At 1800 UTC 7 November 1999, a marked environmental critical level[4] (see, e.g., Baines 1995) became evident at ~5 km MSL and, gradually, descended with time. This type of wind reversal or inversion formation is an important part of the bora dynamics (Smith 1987; Glasnović and Jurčec 1990). Throughout the mature phase, the upstream bora layer above Zagreb increased in depth (to ~3–4 km) and was characterized by a maximum of tropospheric wind speeds at 1–1.5-km altitude and a wind shear (synoptic wind veering to toward the mountain-parallel wind direction) aloft. The ALADIN/HR model seems to capture these features well (Fig. 6a), although the very initial phase of the low-level jet creation and the later short-lived decrease of the jet intensity at 1200 UTC 7 November 1999 (with a coincident strong reduction in bora intensity at Krk Bridge) appear to be forecasted with reduced accuracy.

The vertical wind structure from the Zagreb sounding data and the ALADIN/HR simulations during the

[3] The backward trajectory analysis shows that NE winds prior to 1500 UTC 7 Nov 1999 at Makarska did not pass over the southern Dinaric Alps and thus do not represent bora winds. This NE direction is associated with cyclonic circulation in the Mediterranean and originates from air parcels that moved along the coastal slope of the Dinaric Alps that backed (turned anticlockwise) to the NE direction near the land–sea border.

[4] An environmental (synoptically induced or mean-flow) critical level will refer to the location above the surface on the windward side of the mountain where the cross-barrier northeasterly wind component becomes zero within the incoming flow.

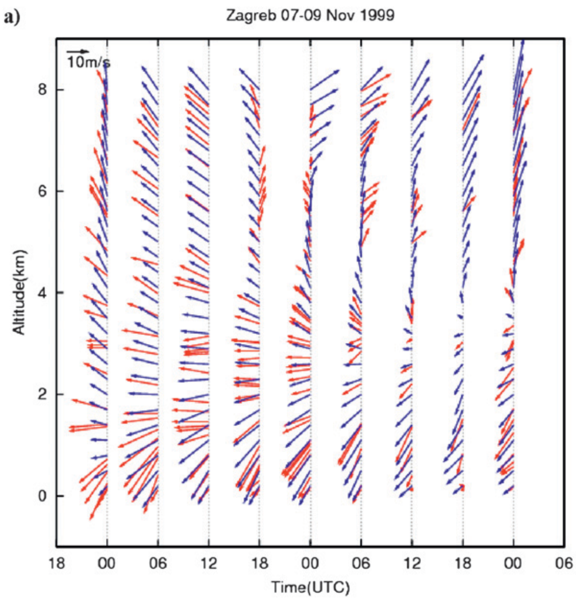

FIG. 6. Comparison of the vertical wind profiles above Zagreb as inferred from radiosonde data (red arrows) and ALADIN model simulations (blue arrows) for (a) the northern and (b) southern bora events.

southern bora event are presented in Fig. 6b. The NE low-level jet, present in the Zagreb sounding during the northern event, was absent in this case. The rather calm near-surface conditions, as well as a gradual intensification of the upper-tropospheric NW winds, were simulated with reasonable accuracy with more significant discrepancies after the end of the bora event by midday on 7 May 2005. This whole bora episode was marked by a strong wind shear in the lowest 4 km that extended throughout the depth of the troposphere toward the end of the episode.

In summary, the above verification shows that the operational version of the ALADIN/HR model captures the onset and cessation of the Adriatic bora, as well as its spatial structure with reasonable accuracy. The modeled results are less accurate in the lee of the southern Dinaric Alps near the Makarska station. For the most part, the discrepancies between the observed and simulated wind speed magnitudes are likely related to the local differences between the height of the terrain and its representation in the model at the chosen horizontal resolution (8 km). In addition, the hydrostatic approximation (and its influence on the mountain-induced pressure perturbation) constrains the ALADIN/HR model in its ability to reproduce the finer-scale details of the bora flow, such as pulsations, rotors, internal boundary layers, and the leeside flow separation. Nevertheless, these nonhydrostatic effects are not of primary importance for simulations of the basic dynamics of severe bora (Klemp and Durran 1987; Grisogono and Belušić 2008). In addition, the analysis in this section indicates that the ''bulk'' properties of the bora were simulated reasonably well in both the northern and southern Adriatic to aid us in examining the main differences in the temporal evolution and mesocale structure of severe bora as well as environmental factors favorable for its generation.

5. Temporal evolution and spatial structure of the bora flow

a. Northern bora event

1) SURFACE WIND AND PRESSURE GRADIENT FIELDS

The spatial structure of the ALADIN/HR simulated horizontal wind fields at 10 m AGL on the regional scale during 7–8 November 1999 is shown in Fig. 7. The left branch of the blocked NW flow that impinged on the Alps turned from NW to NE over northern Croatia. It is the crossing over the coastal mountain range of this layer of well-defined NE winds that gave rise to the development of a strong bora in the northern Adriatic. The region of increased surface winds in the upstream environment was confined to a narrow (~50 km wide) zone over central Croatia, including the Zagreb-Maksimir radiosonde site. Surface winds over eastern Croatia, approximately 400 km east of Zagreb, were significantly weaker. On the lee side, bora winds extended over the Adriatic, downstream of the northern

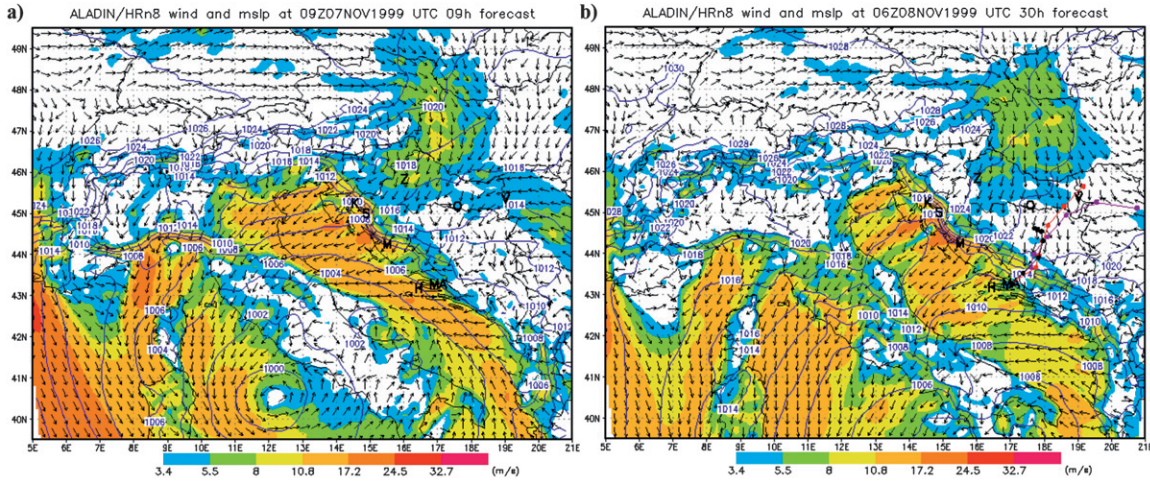

FIG. 7. ALADIN/HR model prediction of 10-m wind and surface pressure (hPa, blue solid lines) at (a) 0900 UTC 7 Nov 1999 and (b) 0600 UTC 8 Nov 1999. Backward trajectories with 3-h frequencies at 1000 (black), 950 (red), and 900 (purple) from Makarska starting at 1200 UTC 8 Nov 1999 for the 18-h period are shown in (b).

coastal mountains and the Velebit range, during both days of this event. As previously discussed in section 4b, in the initial phase, the bora was met by strong a jugo farther south, creating a shear zone across the central Adriatic.

The cross-mountain pressure gradient is typically a very good indicator of the leeside bora wind speed in the northern Adriatic [correlation coefficient r ~ 0.95–0.98; e.g., Ivančan-Picek and Tutiš (1995)], and somewhat less so in the southern Adriatic [r ~ 0.8; Horvath and Ivančan-Picek (2009)]. As inferred from the mesoscale model results (cf. Fig. 7b), the pressure gradient in this event increased from south to north to its maximum of $\sim$10 hPa $(100\ \mathrm{km})^{-1}$ at the ZS section (cf. Fig. 1) during the morning hours of 7 November 1999. However, it will be shown in the next section that the differences in the upstream conditions for the northern and southern parts of the Dinaric Alps have additionally contributed to less than optimal conditions for the bora development in the southern Adriatic.

2) UPSTREAM VERTICAL FLOW STRUCTURE

The Zagreb-Maksimir sounding is traditionally used for the study of bora winds in the northern Adriatic due to its optimal location upwind of the narrower and more regular northern Dinaric Alps as well as unidirectional low-level background flow at this site during bora episodes. However, this site is not necessarily representative of the wider southern Dinaric Alps, where 1) a more significant change in wind direction occurs in the upstream environment and 2) the impinging flow might be considerably modified over the mountains, before encountering a final set of mountain peaks in its descent toward the Adriatic coast. To account for the latter possibility requires a very high-resolution numerical model and a highly accurate representation of the terrain; here, we focus on the former.

To identify a more appropriate upstream site for the southern portion of the Dinaric Alps, we computed backward trajectories that were originated at the Makarska site at 1000, 950, and 900 hPa. The trajectories were initialized at 1200 UTC 8 November 1999 and calculated for an 18-h period with 3-h time frequency (Fig. 7b). This analysis reveals that the optimal upstream site for the southern Dinaric Alps in this case is located in eastern Croatia, near Vukovar (site V in Fig. 1). As there is no radiosounding site there, we used the model sounding instead.

Whereas a strong and sustained NE low-level jet was the characteristic feature of the background flow in the northern event over Zagreb (cf. Fig. 6a), the lower-tropospheric winds over Vukovar were weaker and mostly easterly, shifting between SE and NE during this event (Fig. 8a). In contrast to the Zagreb-Maksimir sounding, a shallow upstream NE flow of only 1–2-km depth was present upstream of the high and wide southern Dinaric Alps in the mature phase of this event.

Looking at the thermal structure of the upstream flow, the buoyancy (Brunt–Väisälä) frequency profiles for both the Zagreb and Vukovar soundings show the high static stability of the low-level tropospheric air (Fig. 9a). The shallow layer of very high stability in the lowest 1 km of the atmosphere, having its origin in shallow inversions, was clearly deeper in the Vukovar sounding. Together with lower wind speeds and higher mountain heights, this enhanced stability led to a smaller

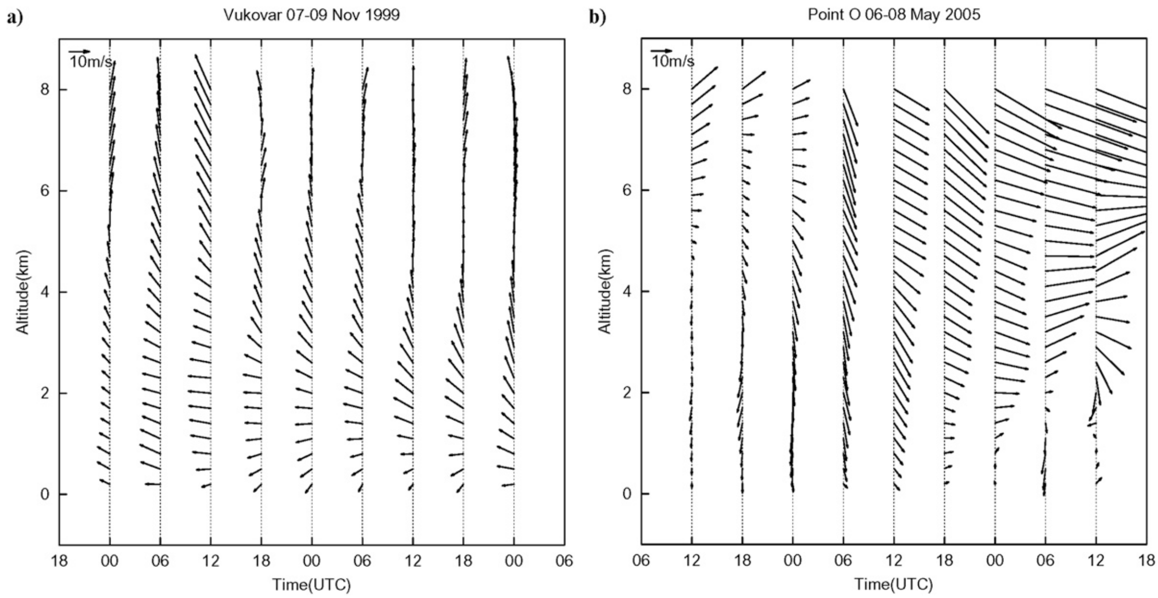

FIG. 8. ALADIN/HR model simulations of the vertical wind profiles on (a) 7–8 Nov 1999 during the northern event over Vukovar and (b) 6–8 May 2005 during the southern bora event over model gridpoint O.

integral low-level Froude[5] number (see, e.g., Baines 1995) and potential for stronger blocking upstream of the southern part of the Dinaric Alps. For example, taking average values of the horizontal wind speed (U) and static stability (N) in the lowest 2 km at 0600 UTC 8 November 1999 yields Fr ~ 0.87 for the background flow over Zagreb ($U \sim 13.2$ m s^{-1}, $N \sim 0.015$ s^{-1}, and $h \sim 1000$ m) and Fr ~ 0.3 ($U \sim 7.2$ m s^{-1}, $N \sim 0.016$ s^{-1}, and $h \sim 1500$ m) for the background flow over Vukovar.

On the other hand, the elevated zone of enhanced stability at 3 km MSL, which after the initial bora breakthrough gradually strengthened over time, was more pronounced in the Zagreb sounding. The layering of the background flow is further examined through the temporal evolution of the vertical profile of the Scorer parameter[6] (Scorer 1949) (Fig. 10a). The vertical profiles of the Scorer parameter above Zagreb clearly show two distinct phases of this bora event (Fig. 10a). In the first (initial) phase, until approximately 1800 UTC 7 November 1999, the Scorer parameter profile was rather uniform with height. At subsequent times, the profile is characterized by the presence of a local maximum near 3 km MSL, owing its existence primarily to the aforementioned layer of enhanced stability (cf. Fig. 2d). This sharp peak in the Scorer parameter defines the top of the bora layer in the mature phase of this event, and is a good indicator of the potential for the layered behavior of the atmosphere, that is, the uncoupling of the lower- and upper-tropospheric flows upstream of the northern part of the Dinaric Alps. In contrast, the Scorer parameter profile for Vukovar does not change significantly over time during this event (Fig. 10b). Additionally, its gradual decrease with height is conducive neither to wave energy trapping at low levels nor the amplification of vertically propagating internal gravity waves with height.

3) CROSS-MOUNTAIN FLOW STRUCTURE

Vertical cross sections of the potential temperature and airflow in the initial and mature stages of this bora event are shown in Fig. 11. The initial phase was characterized by the leeside wave activity in both the northern and southern parts of the Dinaric Alps. In the north, strong mountain waves and considerable wave steepening were indicated together with the strong NE

[5] The integral Froude number (Fr) is the nondimensional measure of the ratio of the inertial force to the buoyancy force for the background flow, defined as Fr = U/Nh, where U and N are the horizontal wind speed and the buoyancy frequency of the background flow averaged over the lowest 2-km layer AGL (hence "integral" Fr), and h is the maximum mountain height.

[6] The Scorer parameter was approximated by $l^2(z) = N^2(z)/U^2(z)$, where $N(z)$ is the buoyancy frequency and $U(z)$ is the vertical profile of the horizontal wind, both upstream of the Dinaric Alps. The shear vorticity term is neglected, since the value of that term is small for the given profiles after the small-scale shear variations average out. It should be noted that in the above calculation we used the total horizontal wind, since the flow upstream of the southern Dinaric Alps is not unidirectional due to the pronounced three-dimensional flow effects there.

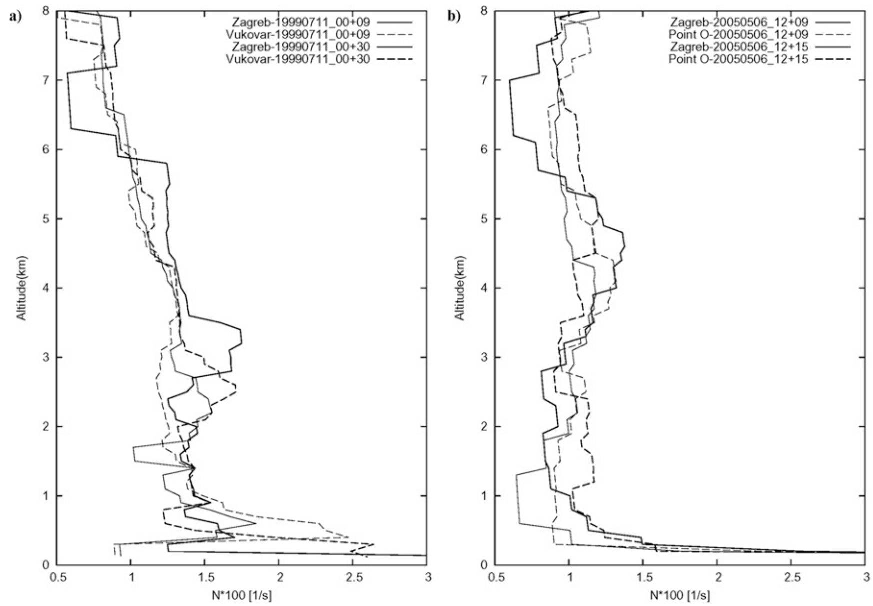

FIG. 9. Simulated buoyancy frequency for (a) the northern bora event for upstream locations of Zagreb and Vukovar at 0900 UTC 7 Nov 1999 and 0600 UTC 8 Nov 1999 and (b) the southern event for upstream locations of Zagreb and model gridpoint O at 2100 UTC 6 May and 0300 UTC 7 May 2005.

low-level jet below 2 km (Fig. 11a). In the south, only weak wave activity was present due to a much weaker NE low-level flow there, being in large part blocked by the 1.5-km-high mountains, leading to only a shallow layer of the lower atmosphere being involved in the mountain wave dynamics and downslope flow (Fig. 11b). The absence of the bora coincided with the presence of a rather weak (~25 m s^{-1}) SE mountain-parallel upper-level jet stream over the Adriatic Sea above 9 km MSL.

In the mature phase of this event, the northern cross section reveals the presence of a layer of increased stability[7] at 3 km MSL upstream of the coastal mountains, which together with the stagnant overturned region above the lee slope and the mean-flow critical level completely defines the bora layer (Fig. 11c). The hydraulic character of the flow is evident, resembling that from theoretical studies (e.g., Smith 1985). In the south, weak NE winds in the lower troposphere were again almost completely blocked by the higher southern Dinaric Alps (Fig. 11d). Nonlinear gravity waves are nevertheless evident over the lee slopes, coincident with the absence of a mountain-parallel upper-level jet over the Adriatic. Thus, it seems plausible that the upper-level jet may play some role in enhancing the linearity of the downstream wave response. The relationship between this upper-level jet and the surface bora winds will be further exemplified within the context of the southern bora event, during which a somewhat stronger upper-level jet affected both the upstream and downstream sides of the northern Dinaric Alps.

The initial absence of tropospheric layering in the first stage of this bora (up to 1800 UTC 7 November 1999) and a strong layering, with an inversion and a mean-flow critical level, in the subsequent phase point again to the existence of two distinct phases of bora behavior within a single bora episode. The timing of the transition between the two phases derived from the vertical flow structure is in good agreement with the surface observations at Krk Bridge (cf. section 4b). Therefore, uncertainties in the numerical prediction of the environmental layering and related transitions in the bora behavior (timing, intensity) can significantly impact the quality of the leeside wind prediction.

b. Southern bora event

1) SURFACE WIND AND PRESSURE GRADIENT FIELDS

During the southern event, the eastern branch of the low-level Alpine split flow was weaker compared to that in the northern event (Figs. 12a and 12b). Also, the NW direction of the surface winds changed only

[7] This increased stability is due to an isothermal layer, which is the model representation of the inversion evident in the radiosonde data.

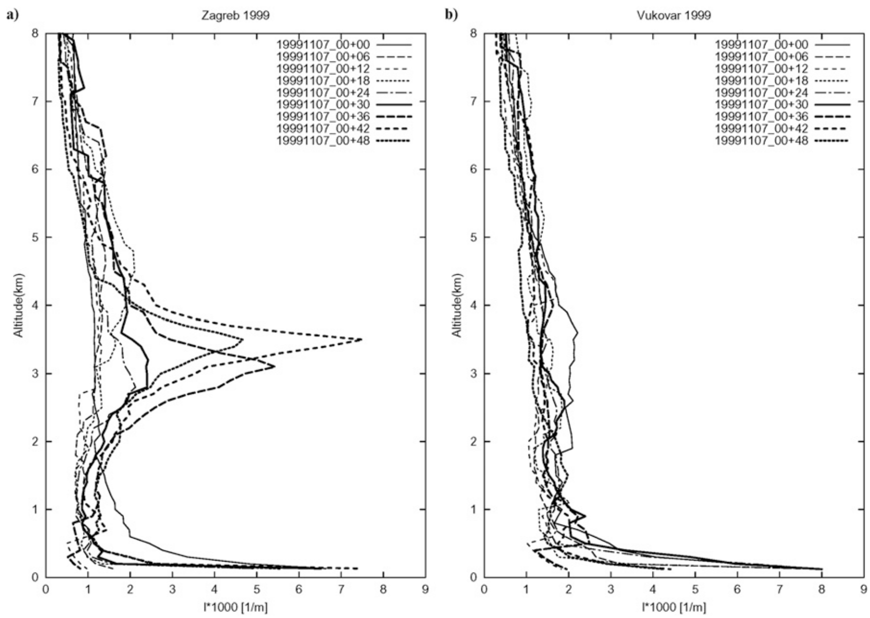

FIG. 10. Time evolution of the vertical profiles of the Scorer parameter above (a) Zagreb and (b) Vukovar derived from the ALADIN/HR model simulation of the northern event.

weakly over northern Croatia, resulting in a weak northerly flow upstream of the Dinaric Alps. A stronger low-level cross-mountain flow was present only over the windward side of the southern Dinaric Alps, seemingly aided by the cyclone presence over the southern Adriatic and southeastern Europe. This synoptic situation produced negligible mean sea level pressure gradients in the northern Adriatic. In the southern Adriatic, the inland–seaside cross-mountain mean sea level pressure gradient near Makarska was 5.4 hPa $(70\ \text{km})^{-1}$. As nearly the same pressure gradient of 5.9 hPa $(70\ \text{km})^{-1}$ was detected there during the MAP IOP 15 case, in which the bora strength was almost cut in half, the cross-mountain pressure gradient appears to be a less reliable indicator of bora strength in the southern Adriatic despite a solid climatological correlation [cf. section 5a(1)]. Nevertheless, it should be noted here that the regression between the cross-mountain pressure gradient and the bora magnitude in the lee of the southern Dinaric Alps is heavily constrained by (i) considerable changes in the wind direction that take place over the southern mountain transect and (ii) the spatial variability (in the cross-mountain direction) of the pressure gradient across a more complex and wider southern mountain profile (e.g., due to individual mountain peaks and valleys).

2) Upstream vertical flow structure

The backward trajectory analysis for the southern event points to the location just west of the town of Slavonski Brod (denoted "O" in Fig. 12b, also cf. Fig. 1) as the upstream location relevant for the southern Dinaric Alps in this case. The lower-tropospheric winds over the identified background site show the prevalence of the northerly and northwesterly directions, the latter being nearly parallel to the coastal mountains (Fig. 8b). The upstream wind magnitude increased with height throughout the troposphere, with some degree of backing from NW to SW farther aloft. Starting in the early hours of 7 May 2005, the wind profiles became more uniform with height, shifting to NW throughout the depth of the troposphere (cf. Fig. 6).

The lower troposphere over continental Croatia was less statically stable in this event due to the lack of a parent cyclone and the associated cold front impinging on the Alps. To some degree the weaker low-level static stability can also be attributed to the warmer season in which this event occurred (Fig. 9b). However, the vertical profile of the buoyancy frequency shows an increase in the low-level static stability during the later phase of this event, though the values are not as high as in the northern event. Also, a layer of enhanced stability is evident between 4 and 5 km MSL at site O but again it is not nearly as strong as during the northern event. At the onset of this bora (1200 UTC 6 May 2005), the Scorer parameter profiles show moderate peaks between, respectively, 4 and 5 km MSL over point O and at 5 and 6 km MSL above Zagreb, indicating some degree of layering in the troposphere. Whereas over point O these profiles retain a weak

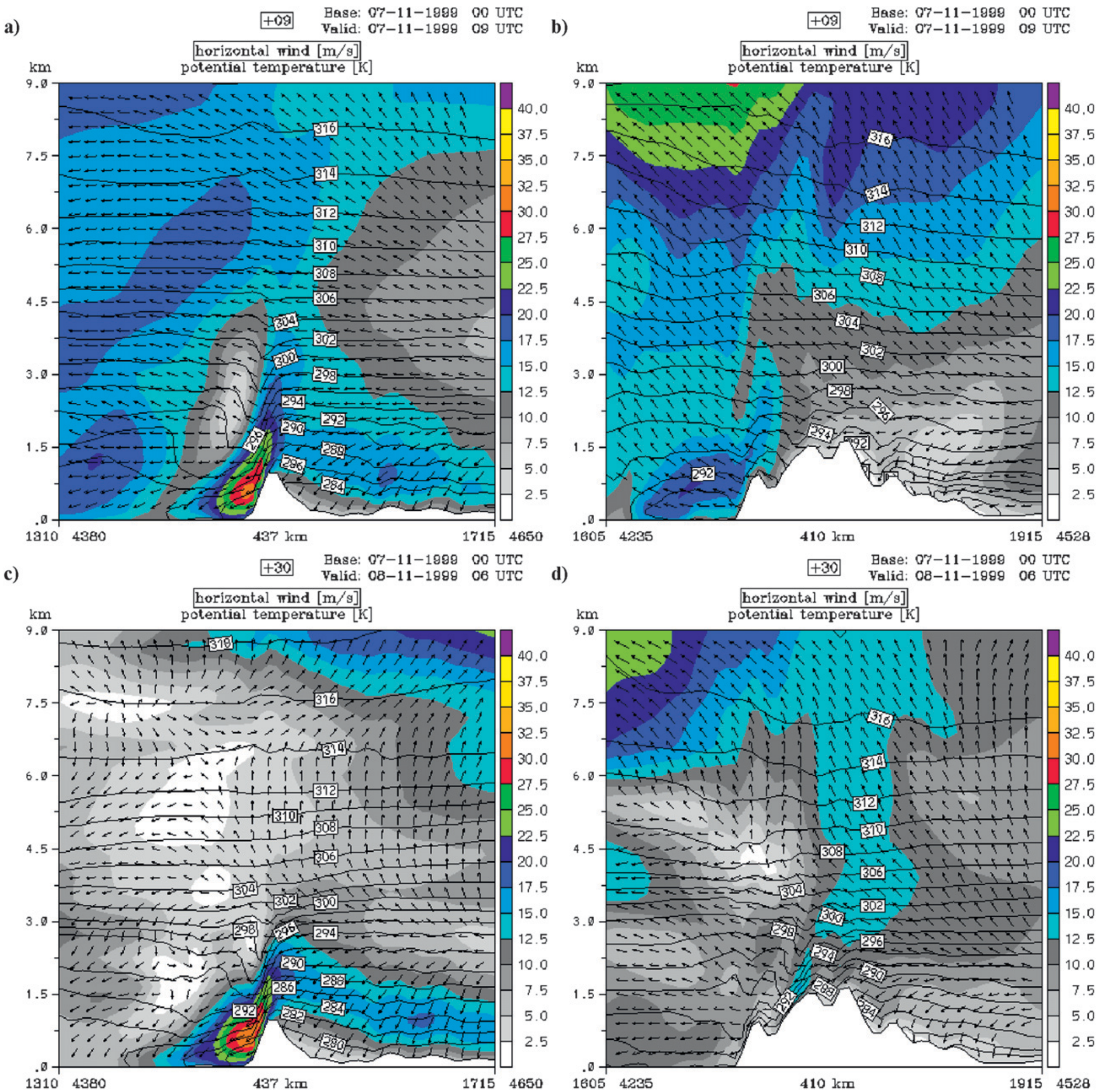

FIG. 11. ALADIN-HR model-simulated horizontal wind speed (m s^{-1}) and potential temperature (K) along the (left) northern Zagreb–Senj and (right) southern Vukovar–Makarska vertical cross sections in the (a),(b) initial and (c),(d) mature phases of the northern event.

parabolic shape with the maxima around 6 km MSL throughout 6 May, the profiles are quite uniform at both sites during the later stages of this event (Fig. 13). This would seem to indicate that the upstream flow of this bora was not prominently layered such as in the mature phase of the northern event. Nevertheless, as it will be shown further below, a mean-flow critical level did play a significant role in this event as well, defining the layer of the atmosphere involved in the bora dynamics.

3) CROSS-MOUNTAIN FLOW STRUCTURE

Vertical cross sections of the potential temperature and airflow in the initial and mature stages of this event are shown in Fig. 14. At 2100 UTC 6 May 2005, during the initial phase, the northerly low-level flow was present all along the upstream side of the Dinaric Alps. This flow was confined to altitudes below 3 km MSL in the north and 6 km MSL in the south (Figs. 14a and 14b), the respective altitudes of the environmental

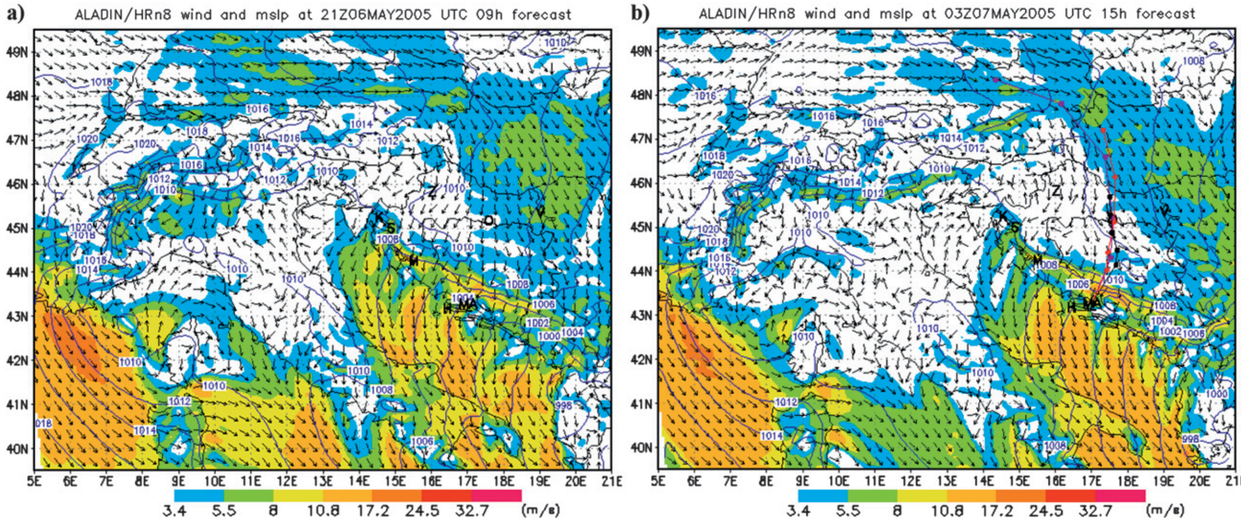

FIG. 12. ALADIN/HR model simulation of 10-m wind at (a) 2100 UTC 6 May and (b) 0300 UTC 7 May 2005. Backward trajectories with 3-h frequencies at 1000 (black), 950 (red), and 900 (purple) from Makarska starting at 0600 UTC 7 May 2005 for a 15-h period are shown in (b).

critical level at which the winds turned to the NNW mountain-parallel direction. In the near upstream region in the north, the northerly winds turned into the NE in the lowest 1.5 km, producing a shallow and weak cross-mountain flow at lower altitudes. While the environmental critical level was indicated at nearly the same height as in the northern event (cf. Fig. 11a), only weak wave activity was present over the lee slopes in this case, with no evidence of wave breaking and strong downslope winds. In the near upstream region in the south, a deeper northerly wind layer traversed the highest mountain peaks and descended toward the coast, while changing its direction to the NE over the windward side of the southern Dinaric Alps. This led to significant wave activity over the lee slopes, confined below the critical level. Therefore, it appears that wave generation

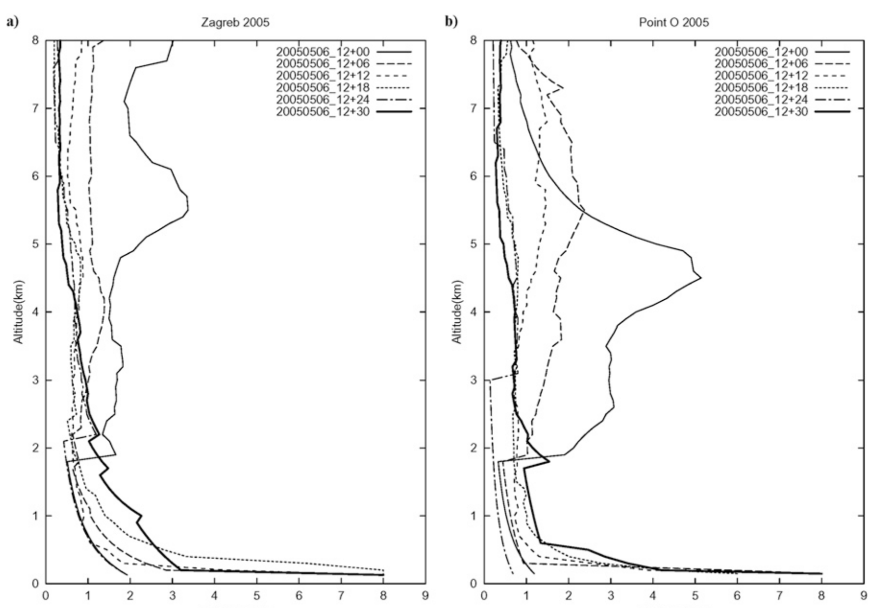

FIG. 13. Time evolution of the vertical profiles of the Scorer parameter above (a) Zagreb and (b) model gridpoint O derived from the ALADIN/HR model simulation of the southern event.

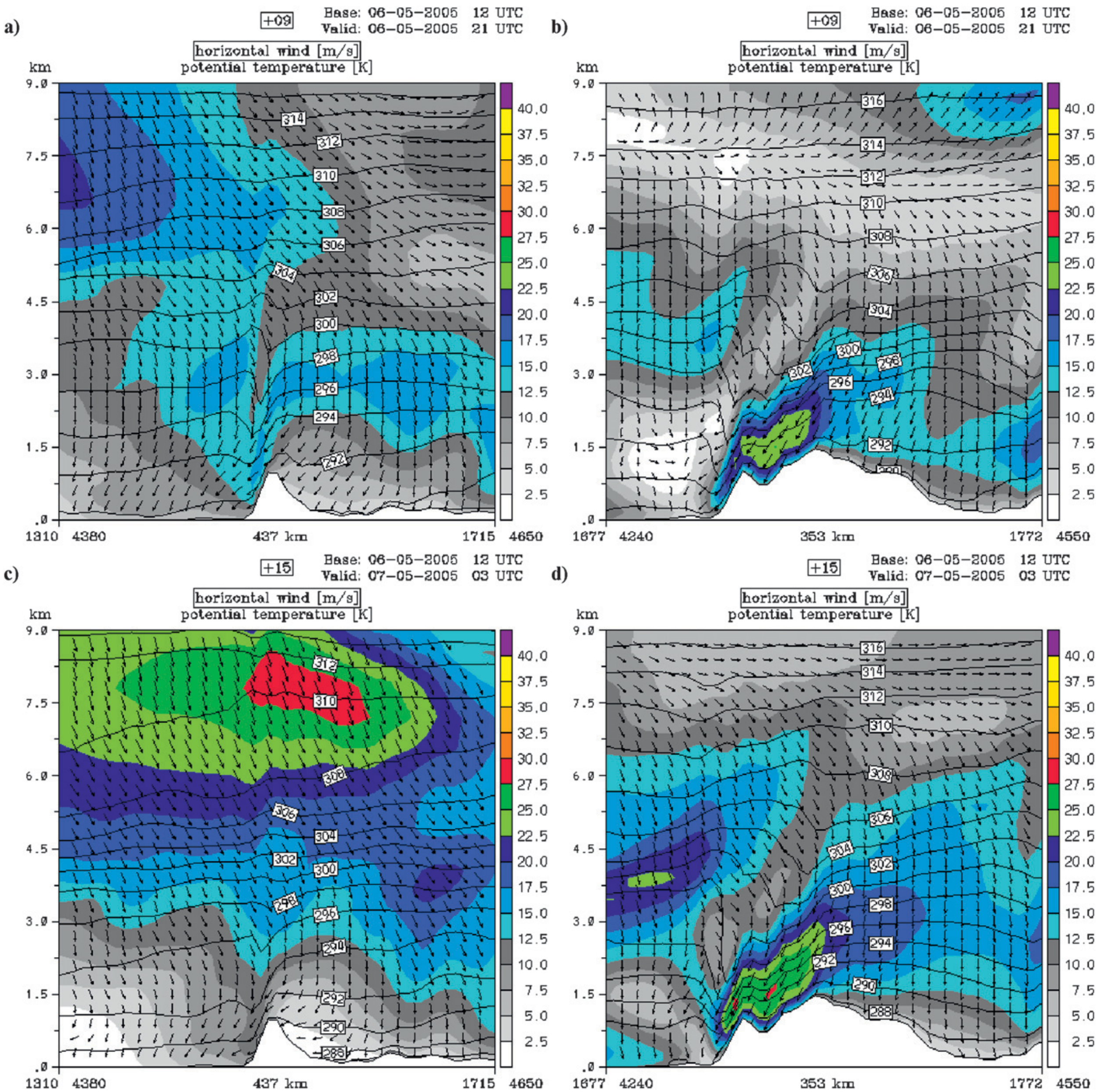

FIG. 14. ALADIN-HR model-simulated horizontal wind speed (m s^{-1}) and potential temperature (K) along the (left) northern Zagreb–Senj and (right) southern model grid point O–Makarska vertical cross sections in the (a),(b) initial and (c),(d) mature phases of the southern event.

and wave steepening are common ingredients of the initial phases of both the southern and northern Adriatic strong bora.

Six hours later, the northern cross section reveals an even weaker level of wave activity than in the initial phase. A NNW mountain-parallel upper-level jet stream was predicted right above the northern part of the coastal mountain range, associated with a less favorable background flow direction and reduced upstream layer height (Fig. 14c). Again, the appearance of the upper-level mountain-parallel jet appears to coincide with the weakening of the mountain waves and, consequently, of the leeside bora winds. Upstream of the southern Dinaric Alps, the critical level had descended to 5 km MSL (Fig. 14d), and the upstream low-level blocking is evident at the lowest levels in the form of NW winds. The jet over the Adriatic farther west is a reflection of the midtropospheric NW jet that had approached the region. The synoptically induced wind shear over the Adriatic, together with a wave-breaking-induced local critical level over the lee slopes, gave rise to a well-defined critical layer in the downstream environment as well. The presence of a well-defined critical layer, in both the upstream and downstream environments, is likely a key contributor to the bora severity in the southern Adriatic in this case. In this stage of the event, the numerical simulation results indicate that the bora flow has a hydraulic character, with a hydraulic jump located over the lower lee slopes. Slight differences in the exact location of the hydraulic jump and the downwind extent of the shooting flow could potentially lead to large differences in the predicted winds at the ground—another possible contributing factor to the underestimation of surface winds at the coastal site of Makarska in this case (cf. section 4b).

6. Summary and further remarks

In this study we examined two cyclonic bora events on the eastern Adriatic that produced severe winds in different parts of the Adriatic coast. The ‘‘northern’’ bora (7–8 November 1999) is the well-studied MAP IOP 15 event. The selected ‘‘southern’’ bora occurred on 6–7 May 2005 and inflicted significant infrastructural damage in the southern Adriatic. The two selected bora events were considered to be typical cases of cyclonic bora in the northern and southern Adriatic. The analysis presented here assessed the differences in the environmental conditions, spatial flow structure, and sequence of mesoscale and macroscale events leading to the appearance of severe bora winds in the northern and southern Adriatic.

At the synoptic scale, the two types of bora are clearly distinguished. The northern Adriatic bora (7–8 November 1999) was characterized by the existence of a primary and a secondary lee cyclone, located, respectively, over central Europe and in the Alpine lee. A rapid development of a cyclone over the central Mediterranean and southeastern Europe was a prominent feature of the southern Adriatic bora event.

On the mesoscale, further defining differences were found. During the northern event, strong mesoscale cross-mountain pressure gradients were established along the entire length of the eastern Adriatic, decreasing in strength from north to south. This bora, which displaced a strong jugo wind pattern over the Adriatic basin, produced severe winds in the northern Adriatic only. The main feature of the environmental conditions during the 2-day event was the presence of a persistent NE background low-level jet at 1–2 km MSL over western Croatia, which constitutes the upstream environment of the northern part of the coastal range. Weaker upstream flow and stronger low-level stability upstream of the higher and wider southern Dinaric Alps led to strong blocking there, resulting in only a weak bora in the southern Adriatic. While initially there were no sharp discontinuities in the upstream vertical atmospheric structure, both an inversion and an environmental critical level formed during the course of the event, capping a well-defined upstream bora layer (at ~3 km MSL) in its mature phase. This clearly illustrates a transition from the wave-dominated outbreak stage of the bora with incipient wave breaking over the lee slopes (Göhm et al. 2008) to a sustained wave breaking and bora flow pattern that more clearly displays the hydraulic character. The evidence for this transition was also found in the surface measurements, with highly variable wind speeds at the coastal sites as a hallmark of the outbreak stage, and persistent and sustained wind speeds in the mature stage. Therefore, any uncertainties in the prediction of the fine structure of the atmospheric layering and the related transitions have the potential to significantly affect predictions of the leeside bora winds.

During the southern bora event, which was not preceded by a jugo, mesoscale cross-mountain pressure gradients increased in strength from north to south, and were almost negligible in the north. The northern Adriatic was located in the near wake of the Alps with weak cross-mountain flow confined to a shallow ~1.5 km deep layer. The appearance of a mountain-parallel upper-level jet over the northern Dinaric Alps was associated with the further reduction of wave activity over the lee slopes due to an unfavorable background flow direction and reduced upstream layer height. In the south, the prevailing upstream low-level N and NW mountain-parallel winds over central and eastern Croatia within the lowest 5–6 km of the troposphere were sheared to the favorable NE direction over the upstream slope of the southern Dinaric Alps, apparently aided by the cyclone's presence south of the area. As the upstream bora layer in the southern case was primarily defined by an environmental critical level driven by the synoptic-scale winds, numerical prediction of the severe southern Adriatic bora is likely to be less affected by uncertainties in the prediction of upstream layering than its northern counterpart.

Due to the significant low-level directional wind shear upstream of the broad southern Dinaric Alps, the backward trajectory analysis from the coastal site at Makarska was utilized to determine the optimal points for the analysis of the upstream environment for the bora in the southern Adriatic. The identified locations for the two bora events are both in eastern Croatia and, at almost 100 km apart, both significantly deviate from the mountain-normal cross section through Makarska due to the flow curvature at the larger scale (cf. Fig. 1). Consequently, eastern Croatia is shown to be an optimal region for a possible future radio sounding site and/or a vertical profiling remote sensing instrument for the purposes of the operational data assimilation or a field experiment focused on the dynamics of southern Adriatic bora.

The presence of the mountain-parallel upper-level jets over the Dinaric Alps was found to impede severe bora development in both of the examined events. The similarity to the effects of the upper-level cross-mountain jet on the bora strength or its gustiness (Durran 2003; Belušić et al. 2007) is likely fortuitous as the underlying dynamical reasons appear to be very different. Whereas the cross-mountain jet impedes wave breaking through the diminishing effects of positive wind shear on the flow nonlinearity, the mountain-parallel jet likely controls the depth of the flow layer actively involved in the wave dynamics. Although the exact details of how mountain-parallel jets affect bora dynamics are not clear, answering these questions extends beyond the scope of the current study.

The presence or absence of a preceding jugo over the Adriatic is an important subsynoptic difference between the two cyclonic bora cases analyzed. This difference is likely an important element in the total bora response due to differences in the airmass properties over the Adriatic associated with a jugo, as in the sensitivity of the dynamically similar Foehn wind to thermal properties of the upstream and downstream air masses (Mayr and Armi 2008). Finally, while not examined in this study, moist processes have the potential to significantly alter flow over mountains and significantly impact severe bora development.

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