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A case study of a severe Adriatic bora on 28 December 1992

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ABSTRACT

Most bora research, until now, considered the appearance of the severe bora only on the northern Adriatic. However, the important topic of this paper is the internationally less known southern Adriatic bora. Preliminary results, including ours, begin to change the traditional view of bora as a local small-scale phenomenon by suggesting that bora-related airflow has a multi-scale nature. Here, we present a rare synoptic situation which was characterised by the strong NE flow through the entire depth of the troposphere, which could be responsible for the appearance of the unusually severe wind over the continental part of Croatia and the bora on the southern Adriatic at 27/29 December 1992. The results of isentropic diagnostics show that the southern Adriatic bora mechanism could not be explained by 2-D hydraulic theory with simpler upstream conditions as was mainly the case on the northern Adriatic. The *downstream* effects, due to the isallobaric component of the ageostrophic motion, play an essential rôle in the southern Adriatic bora genesis. This does not diminish the importance of upstream effects on the bora flow. From the theoretical approach, it is considered that upstream conditions for the southern Adriatic bora should be based on 3-D theories and numerical simulation which could explain the flow splitting, divergence and steep lowering of isentropic surfaces.

1. Introduction

Strong, gusty downslope winds are observed in many mountainous regions of the world. One of the most famous *local winds* is the bora, a severe north-easterly downslope wind along the eastern Adriatic coast.

Although the previous research shows that bora can occur under a wide range of conditions (Bajić, 1988; Ivančan-Picek and Vučetić, 1990; Jurčec, 1988; Tutiš, 1988), one condition is necessary: there must be a supply of low-level cold air. Therefore, we define an upstream bora layer as a low-level cold air flow usually capped with an inversion, or as the NE "bora flow" above which wind may or may not change its direction. The upstream bora layer characteristics may greatly differ from case to case as a consequence of the deformable frontal system and the baroclinic structure of the lower troposphere over the region. Wind reversal or inversion formation is usually observed at the bora onset and its developing stage, whereas the decaying period is mostly marked by a lowering of temperature inversion (Glasnović and Jurčec, 1990).

The recent major strides in our knowledge of the bora phenomenon have been made possible by the data set collected during the field experiment in ALPEX SOP with broadened surface and upper air measurements, and particularly by first aerial observations of this phenomenon (Smith, 1987). The theoretical results obtained by Smith (1985) have succeeded in *changing the traditional view of the bora* as a "fall wind" by suggesting that cold bora might have a hydraulic character. The

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results of the ALPEX bora analyses mostly coincide with the assumptions of the hydraulic theory (Smith,1987; Bajić,1991). The major benefit of the ALPEX bora studies, in addition to aircraft measurements, is an upper air data set with 4 radiosounding stations working at short-time intervals of 3 h. The major deficiency of these studies is a lack of typical severe bora cases usually defined by the mean hourly wind speed larger than 17 m/s with gusts exceeding 30 m/s, which commonly occur during severe winter conditions. This fact already leads to a partial answer to the question of how representative are the ALPEX bora cases for truly severe Adriatic bora storms.

Many case studies of the bora events, particularly during the Alpine experiment (ALPEX, March-April 1982) indicate the phenomenon of low-level jet stream (LLJ). The LLJ associated with the Adriatic bora flow undergoes a marked diurnal variation in strength: it is stronger at night and weaker during the day (the same variation follows the surface bora wind). The phenomenon of LLJ is observed in many other mountain regions around the world. Examples are the wind maxima above the Great Plains of the USA (Bonner, 1968) and also the LLJ which precedes the cold fronts. This later phenomenon follows the propagation of the front and shows no diurnal modulation.

Most bora research until now considers the appearance of the severe bora only on the northern Adriatic. Yet, the remaining problem in the study of the bora wind is its appearance in the southern Adriatic (Dalmatia), where the bora layer is not so well defined on the windward side and the data coverage is not satisfactory. Thorough comparisons of observational analyses of the more well-known northern Adriatic bora and the less known southern Adriatic bora cases reveal *the multiscale nature of bora wind* (Jurčec,1989). The bora speed and direction are greatly influenced by topographic shape, so mountain and coastal circulation are clearly responsible for a daily variation of wind speed and direction during a bora period. However, in spite of these local effects, the bora onset, its longevity and severity are closely *related to larger mesoscale features*, in particular those resulting from the interaction processes of synoptic scale flow with the Alpine massif. In particular, the cyclonic activity in the Mediterranean and over the Balkans influences the bora structure and behaviour more in the southern Adriatic (Dalmatia) than in the northern Adriatic. According to surface manifestations, the essential difference between the northern and the southern Adriatic bora is not in the intensity of maximum wind speed, but in the frequency and persistence. It must be emphasised, that a strong bora rarely appears along the entire Adriatic coast simultaneously; in most cases it starts at the northern Adriatic coast and then gradually (if synoptic development permits) spreads southwards, while the NE wind at the northern Adriatic usually weakens.

The unusually severe bora case at the end of 1992, presented in this paper, is associated with a very rare synoptic situation. It was characterised by exceptionally strong stably stratified NE flow throughout the troposphere over south-east Europe. Since the air mass involved was relatively dry, in the isentropic analysis procedure, only the adiabatic motions are assumed. For the horizontal analysis, we applied the modified Barnes-Maddox interpolation algorithm (Gomis and Alonso, 1990) with the correction scheme included (Buzzi et al., 1991). Analyses are obtained on the selected isentropic levels on the basis of the radiosound data over the area of interest (0–28°E, 35–60°N). An a posteriori survey of analyses and forecasts produced by ECMWF reveals that this event has been not very well forecasted, particularly in the low troposphere where the wind speeds were underestimated.

The paper is organized as follows. In Section 2, a short description of southern Adriatic bora research is presented. Section 3 contains a brief synoptic overview, and a description of thermodynamic characteristics on 27/29 December 1992 is given. Severe wind observations are described with respect to some climatological facts. Section 4 contains the results of investigation of the degree of geostrophy of this bora and the cause of agoestrophy. Section 5 deals with a summary of the observational evidence and concluding remarks.

2. Synoptic climatology of southern Adriatic bora

Jurčec and Visković (1994) selected 15 severe storms in Split (Dalmatia) during the period January 1980 to January 1983. Several facts proved to be important for the severe southern Adriatic bora:

- all bora cases occur in winter months (December to March);
- severe bora periods in most cases do not last longer than 8 h;
- gusts of the wind speed above 30 m/s, with an absolute maximum of 45 m/s are comparable with the northern Adriatic bora;
- the mean surface pressure distribution and 500 hPa geopotential height show a mesoscale cyclone in the southern Adriatic sea.

The statistical analysis (Bajić, 1989; Vučetić, 1991) in the 30-year period of observation (1958–1987) show that a severe bora with maximum gusts > 40 m/s may appear along the entire Adriatic coast, but its duration and frequency decrease from the north to south.

Some observations of windward conditions during southern Adriatic bora indicate the flow splitting and low-tropospheric divergence in the Pannonian plain (15–21°E, 44–48°N) (Vučetić, 1993). Preliminary research shows a much thicker upstream bora layer compared to the northern Adriatic cases, and also similarity in many aspects to the Boulder windstorms. Such an example is the bora case of 28 December 1992.

3. Synoptic overview and thermodynamic characteristics of the atmosphere on 27–29 December 1992

The synoptic situation on 27–29 December 1992 was characterised by 2 large-scale low-level pressure centres: on 00 UTC 28 December, one was a strong anticyclone with the centre of 1045 hPa over the north-western part of Europe and the other a Mediterranean cyclone with the centre over the south Italy (1010 hPa) (Fig. 1). The upper-level trough axis was tilted from the north-east to the south of Europe, and accompanied the upper-tropospheric jet stream propagated towards the Adriatic Sea and the Mediterranean area. Simultaneously, there was an increase of the surface pressure gradients due to the low-level cyclogenesis. The mesoanalyses of the pressure field show a very high correlation between the enhanced gradients and the bora strength. The largest surface pressure difference between Zagreb (continental part of Croatia) and Split (at the Adriatic coast) was 18.5 hPa (9 hPa/100 km) and occurred during the strongest wind period on 28 December 1992. Simultaneously, the maximum gust (41.4 m/s) was observed in the Split area. The existence of large-amplitude pressure perturbations across the Dinaric Alps has significant implications regarding mountain drag in the atmosphere. Tutiš and Ivančan-Picek (1991) have shown, that the pressure drag maximums during ALPEX SOP for the Dinaric Alps are always related to bora periods, and that the drag becomes comparable to surface friction.

However, in distinction from common bora cases, these exceptional weather conditions were characterised by gale winds in the northern inland part of Croatia, too (Fig. 2). The maximum wind

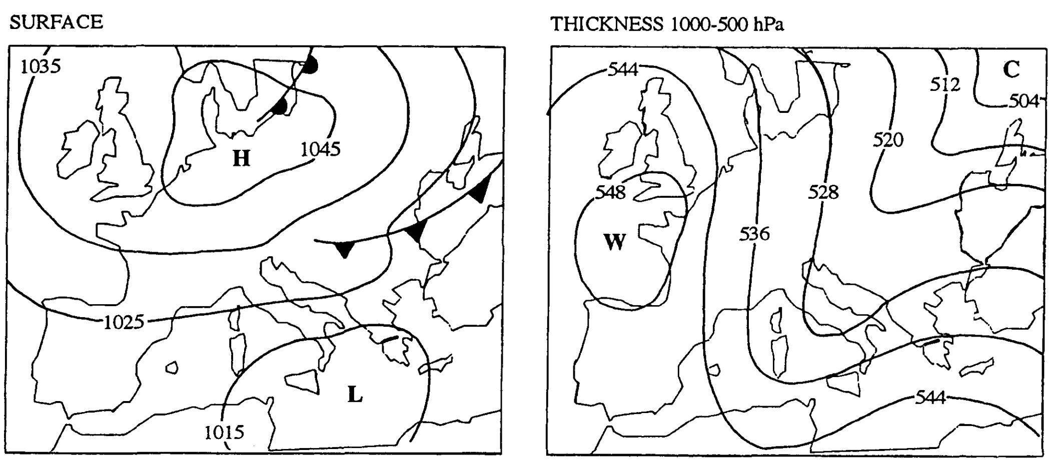

Fig. 1. Synoptic charts on 00 UTC 28 December 1992 for surface (left) and thickness 1000–500 hPa (right).

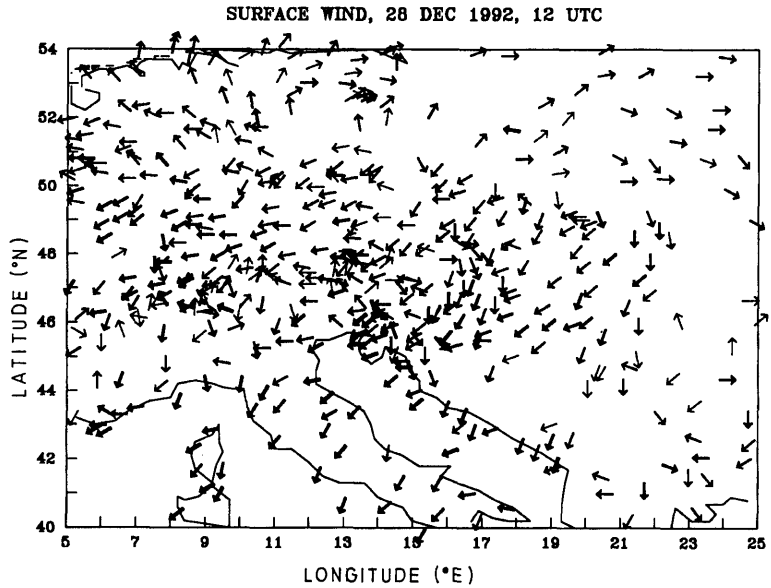

Fig. 2. Observed surface wind (SYNOP stations): the thickness of arrows is proportional to the wind speed (thicker arrows belong to the wind speed higher than 15 m/s), 12 UTC 28 December 1992.

gust registered in the Zagreb area was 18 m/s. According to the climatological analyses, the wind speeds higher than 18 m/s are very rare and, in principle, they occur only for a few minutes in a limited area during thunderstorms or passages of cold fronts in the warmer part of the year. In the last 20 years, there have been only 3 brief cases with the maximum wind gust greater than 18 m/s. However, the wind conditions on 28 December were of a completely different nature: very strong winds were blowing over a large area for many hours.

Fig. 3 presents the time cross-section of the NE wind component and the potential temperature of the air over Zagreb during the period from 27 to 29 December 1992. The analysis of atmospheric structure shows the strong NE flow throughout the whole troposphere to the east of the Alps and also a strong stable stratification of the entire troposphere. The LLJ over the western part of Croatia was associated with the cold air outbreak (in the afternoon on 27 December) in the rear of the surface front. There is also a temperature inversion layer at the heights from 2 to 5 km, a common feature of the bora flow (Jurčec, 1989).

However, simultaneously with the strengthening of the surface bora flow, there is also a strengthening of the wind in the upper troposphere, a situation quite opposite to the present knowledge of the northern Adriatic bora genesis. During the 28 December, the upper tropospheric wind intensified and the tropospheric maximum wind (wind speed exceeding 30 m/s) was 8 km deep, with a jet streak maximum of 72.2 m/s at a height of 9.5 km over the western part of Croatia. The consequent surface gale winds during a 3-day period, from 27 to 29 December 1992, caused a lot of damage and a complete traffic break in many parts of Croatia.

4. Diagnosis of ageostrophic winds

A detailed investigation of the degree of geostrophy completed conventional synoptic studies of the considered bora case. The cause of ageostrophy assesses quantitatively the relationship between the cyclogenesis and the intensification of the LLJ. To get more insight into governing dynamical processes and to consider the severe bora from several points of view, it is also convenient to have

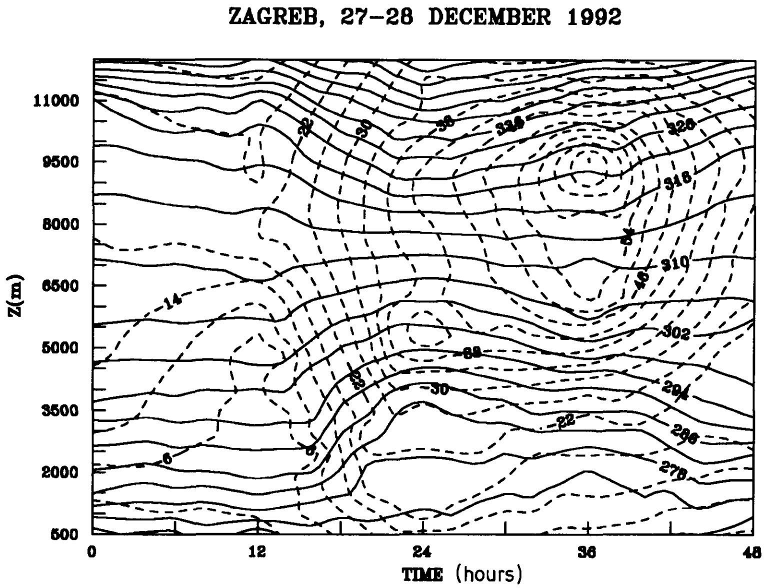

Fig. 3. Vertical time cross-sections of the wind component (azimuth 70°) and potential temperature (solid) of the air over Zagreb during the period from 27 to 29 December, 1992, 00 UTC.

a look at other derived quantities on selected levels (e.g., vorticity, divergence).

Here we present the results within an isentropic framework on 290 K and 316 K levels (Fig. 4). The 290 K level height corresponds to the top of an inversion layer visible on the cross section (Fig.3), while the 316 K level conforms to the maximum of a jet stream. The strong gradients in the geopotential height of the 290 K and 316 K isentropic surfaces, were restored during the maximum bora gusts over northeastern Europe, particularly over Dinaric Alps and the Adriatic sea. This is connected with a supply of cold air from the north-east throughout the troposphere. A strong lowering of isentropic surfaces is evident. From the wind field, we clearly see that the cold air supplying bora flow originates in the NE (Figs. 5a, 6a).

According to Uccellini and Johnson (1979), the relationship between horizontal acceleration and ageostrophic flow combined with the assumption of adiabatic flow can be written as:

$$U_{ag} = f^{-1}\left[\underbrace{k \times \frac{\partial U_g}{\partial t_\theta}}_{A} + \underbrace{U \cdot \nabla_\theta (k \times U_g)}_{B}\right], \qquad (1)$$

where U, U_g, U_{ag} are the horizontal, geostrophic and ageostrophic flow, respectively. Here we consider the isallobaric contribution to the ageostrophic wind (term A), which can be substantial in the presence of a rapidly deepening cyclone. Term A represents the local contribution to the horizontal acceleration and the ageostrophic wind, while term B accounts for advective-inertial processes. In the lower troposphere, where advective velocities are small and inertia wind components are strongly damped by friction, the isallobaric wind modified by friction becomes a more important factor for the low-level parcel accelerations and resultant ageostrophic flow (Young, 1973). The physical interpretation of the local acceleration and the isallobaric gradient indicates that the horizontal pressure force varies with time and, in general, that a lack of balance exists between the pressure and Coriolis forces. This means that the isallobaric wind must be directed across isobars toward lower pressure.

Fig. 5, 6 show the total, geostrophic, ageostrophic and isallobaric wind on the 290 and 316 K surfaces at 12 UTC 28 December. The low-level maximum wind was observed at that time.

The isallobaric wind vectors on the 290 K

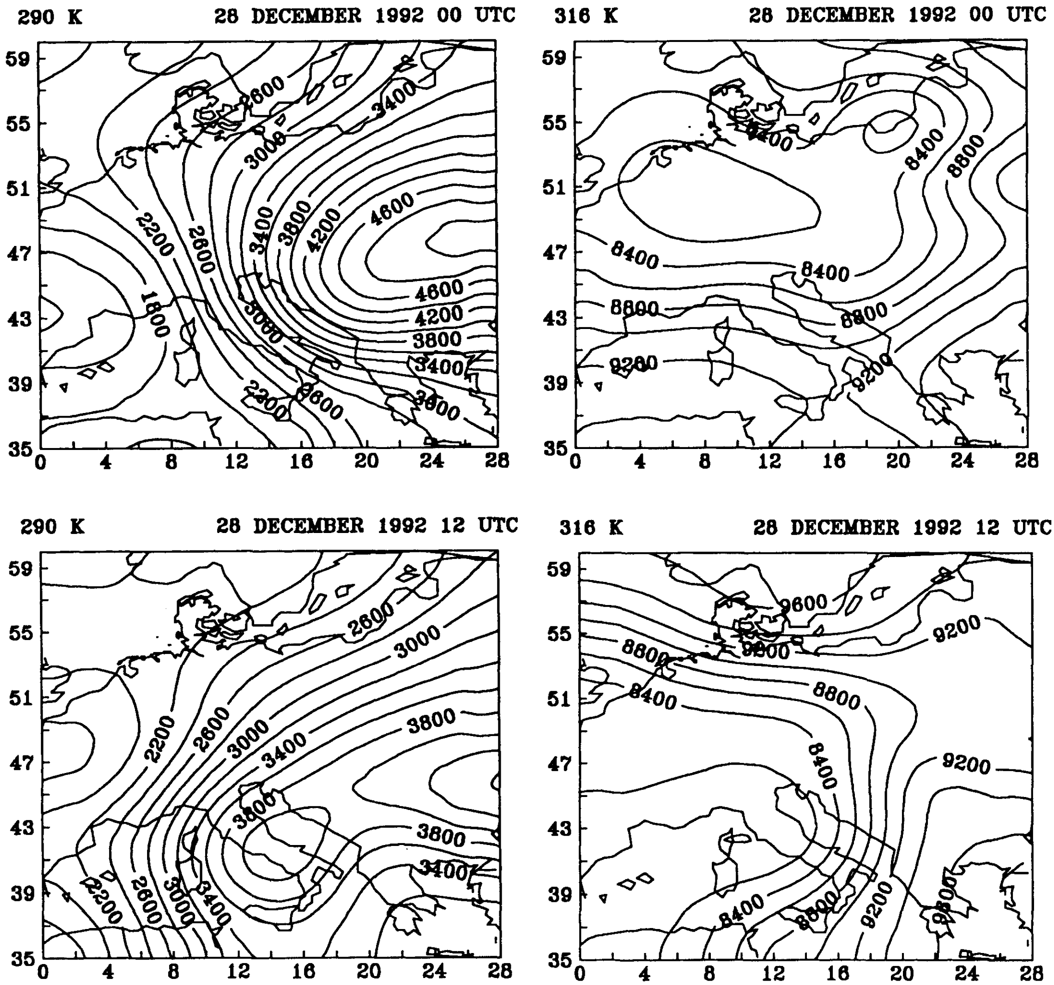

Fig. 4. Geopotential height on the 290 K and 316 K levels, 00 and 12 UTC 28 December 1992.

surface (Fig.5d) converged toward the cyclonic wave over the southern Adriatic and southern Italy. This north-easterly *isallobaric part of ageostrophic wind* is of particular interest, since it coincides with the position of the LLJ over the continental part of Croatia and severe bora in Dalmatia. It could continuously contribute to parcel accelerations. Therefore, the isallobaric wind plays an important rôle in the evolution of the LLJ and bora in Dalmatia. In contrast, the speed and direction of the LLJ on the northern Adriatic sea shows a weak ageostrophy.

Simultaneously with the strengthening of the surface bora flow and LLJ, there was also a strengthening of the NE wind in the upper troposphere (Fig. 6). An upper-level jet was located over the LLJ without any significant angle between them, in contrast to the case presented by Uccellini and Johnson (1979). The intensification of the upper level jet was also linked to isallobaric winds that pointed toward lower pressure across the upper jet as the wave cyclone amplified. In other words, the intensification of low and upper tropospheric winds is a part of the geostrophic adjustment process related to the deepening of a cyclone. The speed and direction

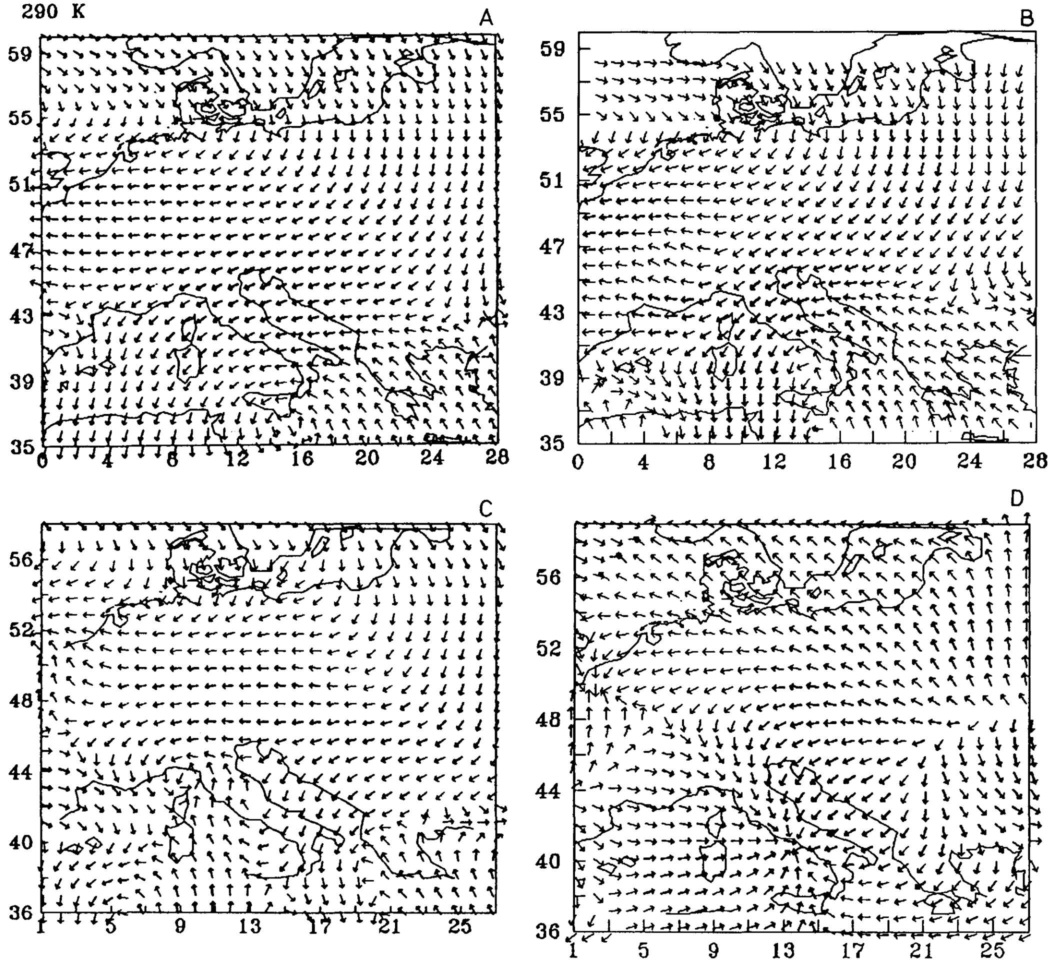

Fig. 5. Total (a), geostrophic (b), ageostrophic (c) and isallobaric wind (d) on the 290 K surface at 12 UTC 28 December 1992. Thickness of the arrows indicates relative wind speed intensity.

of upper level jet were close to its geostrophic value. The diagnosis of the ageostrophic winds show that in the upper level, the supergeostrophic wind received a contribution from the inertial-advection term *B*, which is dominated by the curvature effect (Chen et al.,1994).

The total, geostrophic and ageostrophic wind components and the isallobaric ageostrophic components on the 290 and 316 K surfaces for the 2 points on the northern and southern Adriatic are presented in Table 1. The geostrophic and isallobaric winds were determined in a method similar to that used by Uccellini and Johnson (1979). The ageostrophic wind is calculated from the difference between the total and geostrophic winds.

The ageostrophic motions were significant only along the middle and the southern Adriatic coast. However, the Alps, the western part of Croatia and the bora region along the northern Adriatic coast, indicate the geostrophic origin of the severe bora, or just a weak ageostrophy.

The ageostrophic wind field is dominated by the net mass adjustment and is thus related to the isallohypsic wind (Bluestein, 1993). The isallohypsic wind is substantial in the presence of a rapidly deepening cyclone, as in our case. This

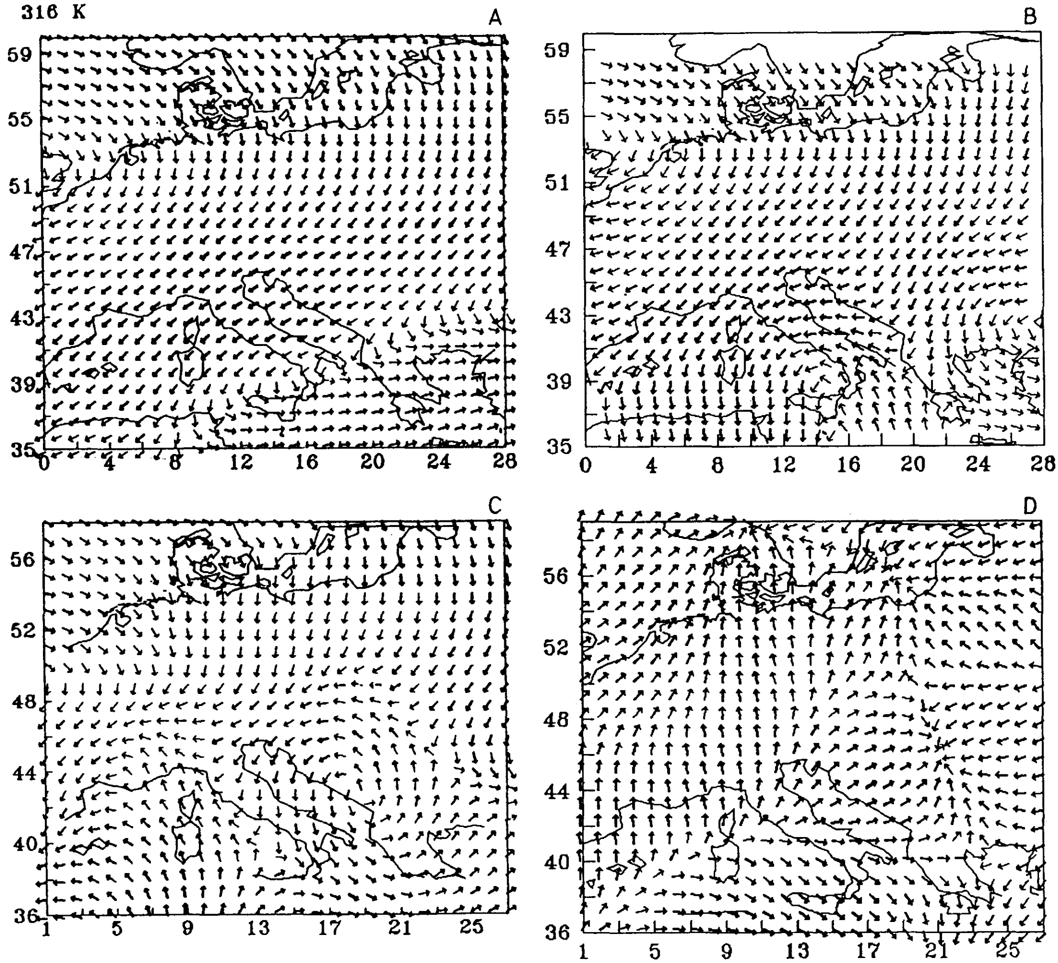

Fig. 6. Total (a), geostrophic (b), ageostrophic (c) and isallobaric wind (d) on the 316 K surface at 12 UTC 28 December 1992. Thickness of the arrows indicates relative wind speed intensity.

Table 1. *Total (u,v), geostrophic (u_g, v_g), ageostrophic (u_{ag}, v_{ag}) and isallobaric (u_{agi}, v_{agi}) wind components on the 290 and 316 K surfaces for the 2 points on the northern (15°E,45°N) and southern Adriatic (18°E,42°N), 28 December 1992, 12 UTC*

Position	K	Total wind	u	v	u_g	v_g	u_{ag}	v_{ag}	u_{agi}	v_{agi}
northern	290	24.1	−22.4	−8.8	−16.8	−4.9	−5.6	−3.9	−4.6	−3.9
Adriatic	316	42.8	−37.6	−20.5	−26.6	−6.2	−11.0	−14.3	6.1	5.4
southern	290	14.9	−14.9	−1.3	−7.5	10.0	−7.4	−11.3	−6.7	−4.3
Adriatic	316	16.8	−14.4	−8.7	−18.8	1.0	4.4	−9.7	9.0	2.7

component of the wind is proportional to the time rate of change of the acceleration induced by the pressure-gradient force. If the potential temperature is the vertical coordinate, the isallobaric component of the ageostrophic wind U_{agi} is related to the horizontal gradient of the local tendency of the Montgomery streamfunction M:

$$U_{agi} = -f^{-2}\nabla_\theta \left[\frac{\partial M}{\partial t}\right]. \quad (2)$$

If the atmosphere follows that scenario, it is reasonable to expect the increase of the Montgomery potential values over the area of interest during the period of severe wind. As we can see in Fig. 7, the field of the Montgomery potential on the 290 K level in 3 consecutive instants indeed experienced marked changes over the region of interest.

The divergence itself is due to part of the ageostrophic component of the wind. An analysis of horizontal divergence and relative vorticity at both levels on 12 UTC 28 December (Fig. 8) shows a prevalence of cyclonic vorticity over the southern Adriatic and the Balkan peninsula with an upslope movement and divergent flow components. Simultaneously, the moisture and temperature advections are maximised by large wind speeds in the core of both jets (resulting in drifting snow in the south Adriatic area). However, the anticyclonic vorticity occupies the whole troposphere over the Alpine region, presenting the well-known horizontal splitting of streamlines around the eastern Alps. Simultaneously, the cold air which penetrates the Adriatic area experienced a strong divergence over the Pannonian Plain, causing lowering of isentropic surfacs toward the Adriatic. The increasing slope contributes to an enhanced isallobaric wind component directly toward the cyclonic side of the jet, along the sloping isentropic surface.

5. Conclusion

The results of the case study support the concept that the development of conditions favorable for

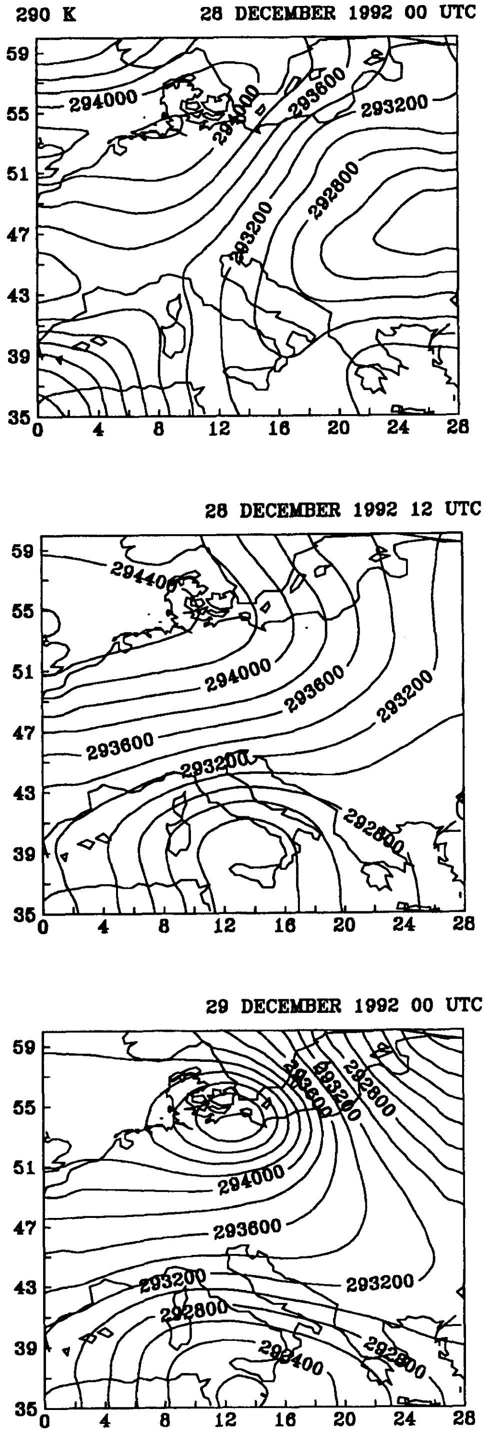

Fig. 7. Montgomery potential on 290 K at the 3 instants: 00 and 12 UTC 28 December 1992, and 00 UTC 29 December.

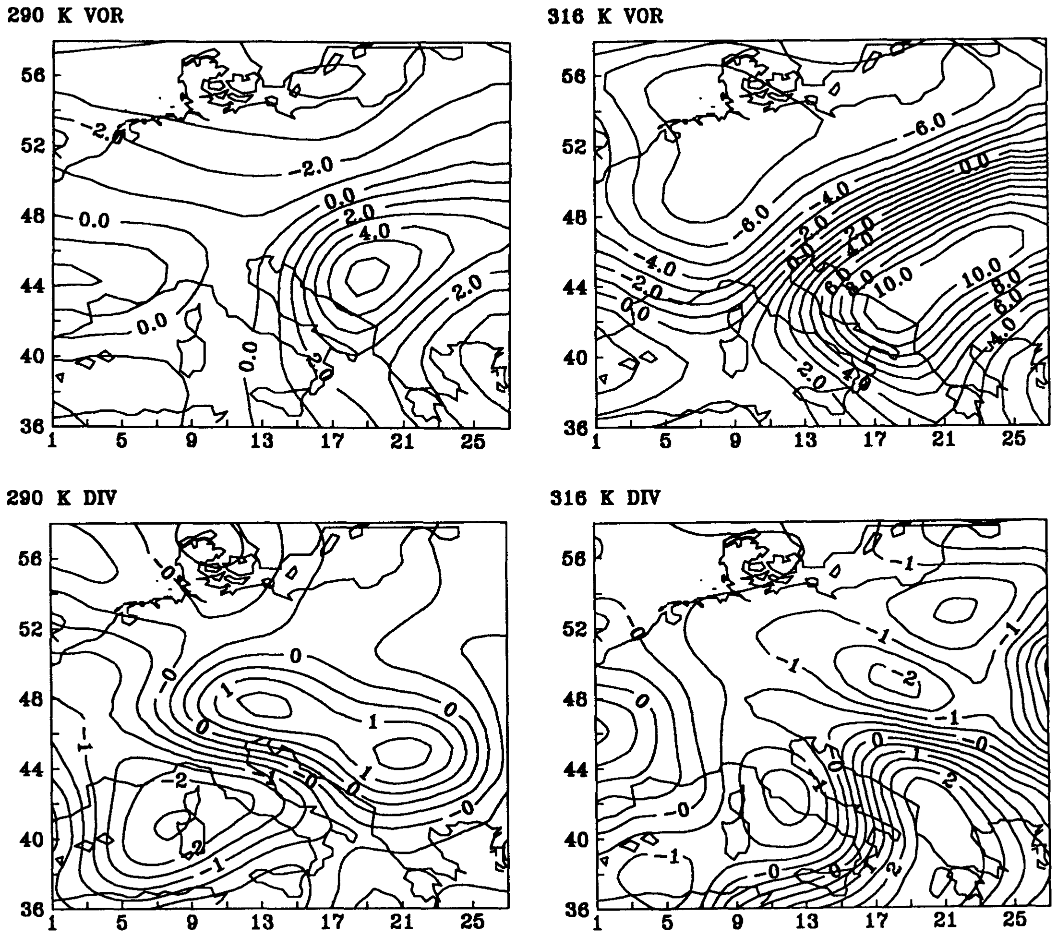

Fig. 8. Vorticity and divergence fields (*10^{-5} s^{-1}) on the 290 K and 316 K levels, 12 UTC 28 December 1992.

severe storms can be forced by momentum adjustments which accompany the propagation of an upper tropospheric jet streak.

The results presented here modify the traditional view of bora as a local small-scale phenomenon and reveal the multiscale nature of bora-related airflow. The *downstream* effects, due to the isallobaric component of the ageostrophic motion, play an essential rôle in the southern Adriatic bora genesis. This does not diminish the importance of upstream effects on the bora flow. From the theoretical approach, it is considered that upstream conditions for the southern Adriatic bora should be based on 3-D theories and numerical simulation, which must explain the flow splitting, divergence and steep lowering of isentropic surfaces.

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