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Aerial Analysis of the Strongest North Adriatic ALPEX Bora Case

Prostorna analiza najjačeg slučaja bure na sjevernom Jadranu u ALPEX periodu

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Abstract

This paper presents the results of an aerial analysis of the bora case on 6-7 March 1982 using aerological data from 10 stations in the region 40° - 49° N, 10° - 22° E. The objective analysis method has been constructed for the presentation of the isentropic surfaces and the two-dimensional isentropic divergence and the vertical component of vorticity. The objective analysis scheme considered seems to be capable of describing the main three-dimensional features of air flow during bora: the descent of a stable bora layer not only along the NE bora flow, but also perpendicular to this flow in the upstream region; the region of vertical divergence forming a "dead region" with strong turbulence downstream; the anticyclonic vorticity in the lee of the Alps and cyclonic circulation in the mid-Adriatic before the bora onset.

Key words: Adriatic bora, objective analysis, isentropes

Sažetak

Prikazani su rezulatati prostorne analize slučaja bure 5-7 ožujka 1982. na osnovi aeroloških podataka 10 postaja na području 40° - 49° N, 10° - 22° E. Konstruirana je objektivna metoda analize radi prezentacije visine izentropskih ploha, te dvodimenzionalne izentropske divergencije i vertikalne komponente vrtložnosti na njima. Danom metodom analize uspješno su dijagnosticirane osnovne trodimenzionalne karakteristike strujanja za vrijeme bure: spuštanje stabilnog sloja bure ne samo duž NE strujanja nego i okomito na njega u navjetrini; razdvajanje izentropskih strujnica ("mrtvo područje" s jakom turbulencijom) u zavjetrini Dinarida; anticiklonalna vrtložnost u zavjetrini Alpa i ciklonalna na srednjem Jadranu prije početka bure.

Ključne riječi: Bura na Jadranu, objektivna analiza, izentrope

1. Introduction

The dynamics of airflow over mountain ranges producing severe downslope wind continues to be a problem in meteorology. On mesoscale, the bora wind along the Croatian Coast is ideal for this type of scientific research since it provides the strongest effect and the highest frequency of such a phenomenon manifested by violent and often devastating surface wind and sea waves.

An extensive observational program on bora research was implemented during the field phase (March and April 1982) of the

ALPEX, the international research program for the study of the airflow over and around mountains in the Alpine region, in which aircraft measurements were an essential observation platform.

During the ALPEX Special Observation Period the strongest bora with maximum gusts greater than 30 m/s, was registered on the northern Adriatic on 5-7 March 1982. At the same time, two research flights were performed above the Croatian Coast near Senj. These cicrumstances have brought about many observational and theoretical studies of this bora case (Smith, 1982, 1984, 1987; Koračin, 1984; Jurčec, 1984; Pettré 1984, 1986; Vučetić 1984, 1985, 1987; Bajić 1988). The most detailed studies have presented analyses of the vertical atmospheric structure in the nearest upstream and downstream regions and analyses of surface and aircraft data. Great attention has been given to the possibe application of the hydraulic theory (Smith, 1985; Smith and Sun, 1987; Bajić, 1990) to such a strong Adriatic bora case. Existing studies show that two dimensional theories such as the hydraulic theory can not completely explain bora occurrence along the entire Adriatic coast. Therefore a study of a three-dimensional atmospheric structure is required.

This paper presents the results of an aerial analyses of the bora case on 5-7 March 1982 using aerological data from 10 stations. The analysis is based on an objective method for the presentation of isentropic surfaces as well as divergence and vorticity.

In spite of a large amount of high-resolution conventional and unconventional meteorological data, the aerial measurements in the ALPEX SOP, due to the bora violence and its spacial and temporal variability, are still incomplete. Thus, the present investigation is a further contribution to the knowledge of the bora peculiarities.

2. The method of aerial analysis

The basic bora characteristics are reflecting on the behavior of isentropic surfaces, which have a great importance in indicating low-level separation on the windward slope and wave breaking above mountain top level. Besides that, isentropic surfaces have the advantage of being material surfaces of adiabatic frictionless motions and isentropic air trajectories can be readily obtained. Thus, we have used an objective analysis method for the presentation of an isentropic surface analysis including divergence and vorticity.

For an objective three-dimensional presentation, regularly spaced data are required. For that purpose 10 aerological stations were used (Zagreb - ZG, Karlovac - KA, Pula - PU, Zadar - ZD, Vienna - WI, Budapest - BU, Belgrade - BG, Udine - UD, Rome - RO and Brindisi - BR). The area 40°

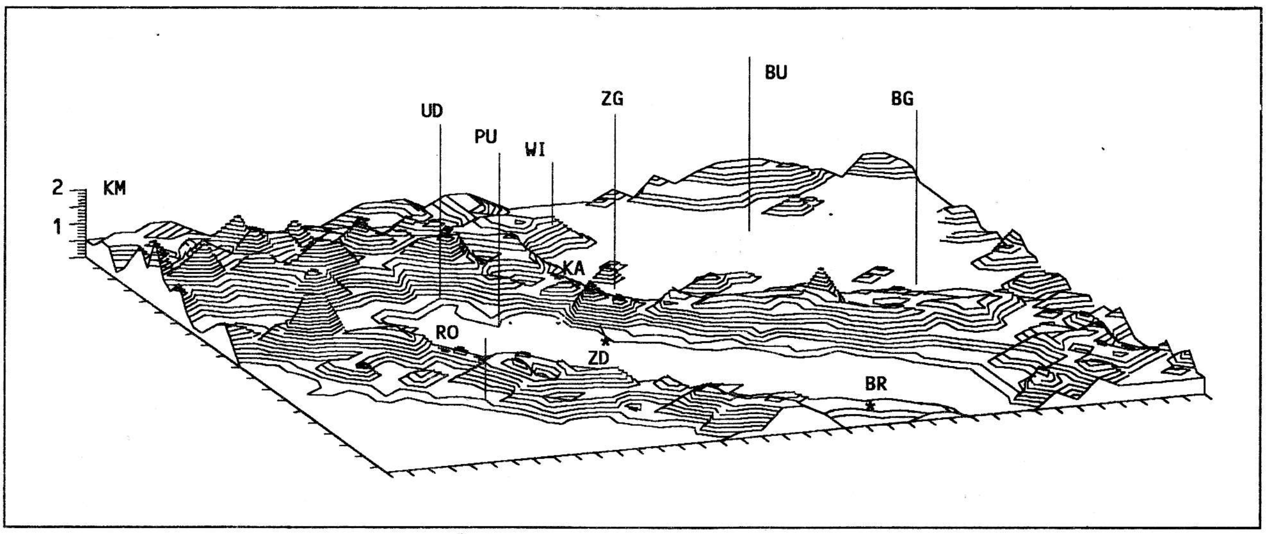

Fig. 1. The analysis domain with the position of the aerological stations.
Sl. 1. Područje analize s položajem aeroloških postaja.

- 49° N and 10° - 22° E presented on Fig. 1. was divided into a regularly spaced grid (25x25 km). The data from the 10 considered stations are irregularly spaced so the interpolation method must be used to obtain values in every grid point. The inverse distance interpolation method has been used. The data points which are used in the inverse distance option are weighted in such a way that the influence of one data point on another declines with their distance.

$$Z = \frac{\sum_{i=1}^{n} z_i/(d_i)^2}{\sum_{i=1}^{n} 1/(d_i)^2}$$

z_i are the neighbouring points around the Z element
d_i is the distance from z_i to Z
n is the number of z_i elements

For each interpolated grid value a neighbourhood search area is defined. The interpolation algorithm will select only a certain number of points from each neighbourhood. The number of points from each neighbourhood is determined by the search radius and the maximum number of points. Only data values within the specified search radius are used. The distance and the number of points used to estimate a grid element (n) are selected to be large enough to include all available aerological stations. From the obtained regularly spaced data a cubic spline is used to connect a set of points with a smooth curve.

Data have been preliminarily processed allowing manual quality control (to discard obvious corrections, when appropriate). No specific " initialization" procedure has been attempted to provide a dynamically consistent analysis.

3. The synoptic situation and spatial distribution of bora

The primary cause of the strong bora on 5-7 March 1982 was the most intense event of lee cyclogenesis during the SOP. A cyclone developed over the Gulf of Genoa on 4 March 1982, when a cold front, associated with a primary trough moving eastward over Europe, interacted with the Alps (Buzzi, 1984; Buzzi, Trevisan and Tosi, 1985). At the surface, the lee cyclone reached maximum intensity around 12 UTC on 5 March, and then gradually filled, moving very slowly to the southeast. Between the 4 and 5 March the upper level evolution showed the amplification of a trough over western Europe, which was slowly moving to the east. Lee cyclogenesis appeared at higher levels as a cut-off forming at 500 hPa. The upper cut--off low subsequently grew almost stationary over the Mediterranean, while a geopotential ridge, initially amplifying to the west of the trough, continued to move eastward over north-central Europe. The cyclonic movement outside the region of formation was slow, and a split-flow (blocking) pattern established itself over Europe on 7 March.

For the case of 5 March 1982 McGinley and Zupanski (1989, 1990) show that the cyclogenesis evolution was heavily influenced by upper-level processes. They concluded that the low level cyclogenesis was strongly related to the arrival of an upper-level wind speed and potential vorticity maximum which was advected into the development region from the northwest.

A mass flux divergence ahead of a potential vorticity maximum, which crossed the Alps, caused pressure to fall in the lee of the Alps while at the same time the influx of cold air in that area was retarded due to the blocking effect of the mountains (Tafferner, 1990). Those effects prevented warmer air from the Atlantic to reach the European continent which was occupied by an intense cold anticyclone in a shallow tropospheric layer.

Before the bora onset the sea-level pressure differences were small (Bajić, 1988). A cold air outbreak from the NE in the upstream region during the early hours of 5 March was connected with an increase in sea--level pressure in the upstream area. The cold air continued to penetrate into the upstream region until 8 March. The bora onset on the northern Adriatic occured in the morning of 5 March. Maximum gusts were measured in Omišalj at 10 p.m. on the same day (35.2 m/s) and in Senj at 1 p.m. on 6 March (31.8 m/s) (Fig. 5. in Bajić, 1988). Although in the majority of cases the strongest bora occurs in Senj, in this situation maximum bora gusts were stronger on some other locations. On the mid-Adriatic, bora was observed on 6 and 7 March with maximum gusts below 30 m/s. A protracted supply of cold air in the upstream bora region in the 1 km layer above ground caused a long lasting bora in Senj (102 hours). Such a long bora duration is a frequent case in Senj due to its specific location near the Vratnik Pass, which causes channeling effects.

The onset of bora was accompanied by a sudden drop in relative humidity, a decrease in temperature and an increase in pressure. As supply of cold air diminished the bora weakened.

The research flights on 6 and 7 March were performed mainly when the bora was already in a decaying stage at most places or by flying above the layer of the northeasterly bora flow. Therefore they could not give a real insight into the intense low level bora structure.

4. Vertical atmospheric structure

The bora genesis on 5 March 1982 was associated with a strong tropospheric cold air outbreak in the initial stage of the previously mentioned cut-off processes leading to a large scale blocking pattern on the northern side of the Alps. During the NW cold air flow the upstream blocking may have resulted in only a fraction of the air ascending and flowing across the Alps, whereas a large part of the flow was blocked and steered around the lower part of the barrier reaching the Croatian hinterland as a northwesterly flow (Fig. 2). At the same time a SE wind prevailed on the middle Adriatic as part of the cyclonic circulation.

On 6 March 1982 the cyclonic circulation had become much stronger due to the simultaneous pressure rise all around the western and northern sides of the cyclone. At the same time, the cyclone moved slowly to the southeast. Consequently the NE wind started to blow over all the considered stations except Vienna and Belgrade where a NW wind still prevailed (Fig. 3.).

The northeasterly wind occupied a 2.5-3 km deep layer. Above that a S-SE wind decoupled the upper and lower layers and prevented disturbances aloft. This feature was a normal outcome of upper-level trough position to the west with respect to the sea-level cyclone. The wind was then often light or reversed above the bora layer (as in our case). Inside the layer with NE wind (bora layer) the maximum speed was very pronounced in the upstream and downstream bora regions. The vertical wind shear below the low-level wind maximum reached 1 ms/100 m during the strongest bora.

Most cases of strong bora are associated with a significant inversion layer inside or above the bora layer (the layer with a positive cross mountain wind component) caused by warm air advection at higher levels and cold air outbreak at low tropospheric levels (Smith, 1987; Jurčec, 1984, 1988, 1989; Vučetić, 1984, 1985; Bajić, 1988). The thickness and altitude of this stable layer vary considerably from case to case and during each bora period. When stable air flows over a mountain, the flow pattern over the mountain and in the lee of the mountain is influenced by both the structure of the incoming flow and the shape of the obstacle. In the situation considered the vertical profiles of potential temperature (Fig. 3) show some stable layers. The height of the most intense inversion layer base was gradually rising with increasing NE wind speed. The lower boundary of the most pronounced stable layer was at 1-1.5 km bora at the bora beginning but shifted to 2-2.5 km during the period with the strongest bora wind (6 March). The height and strength of the inversion layers in the upstream area (Zagreb, Karlovac, Vienna) and the downstream bora region (Pula, Zadar, Rome) illustrate the fact that stable layers were more pronounced at higher altitudes in the upstream than in the downstream bora region. This is in agreement with the inversion layer descending toward the mountain barrier which was observed during the aircraft data analysis (Smith, 1987). The change

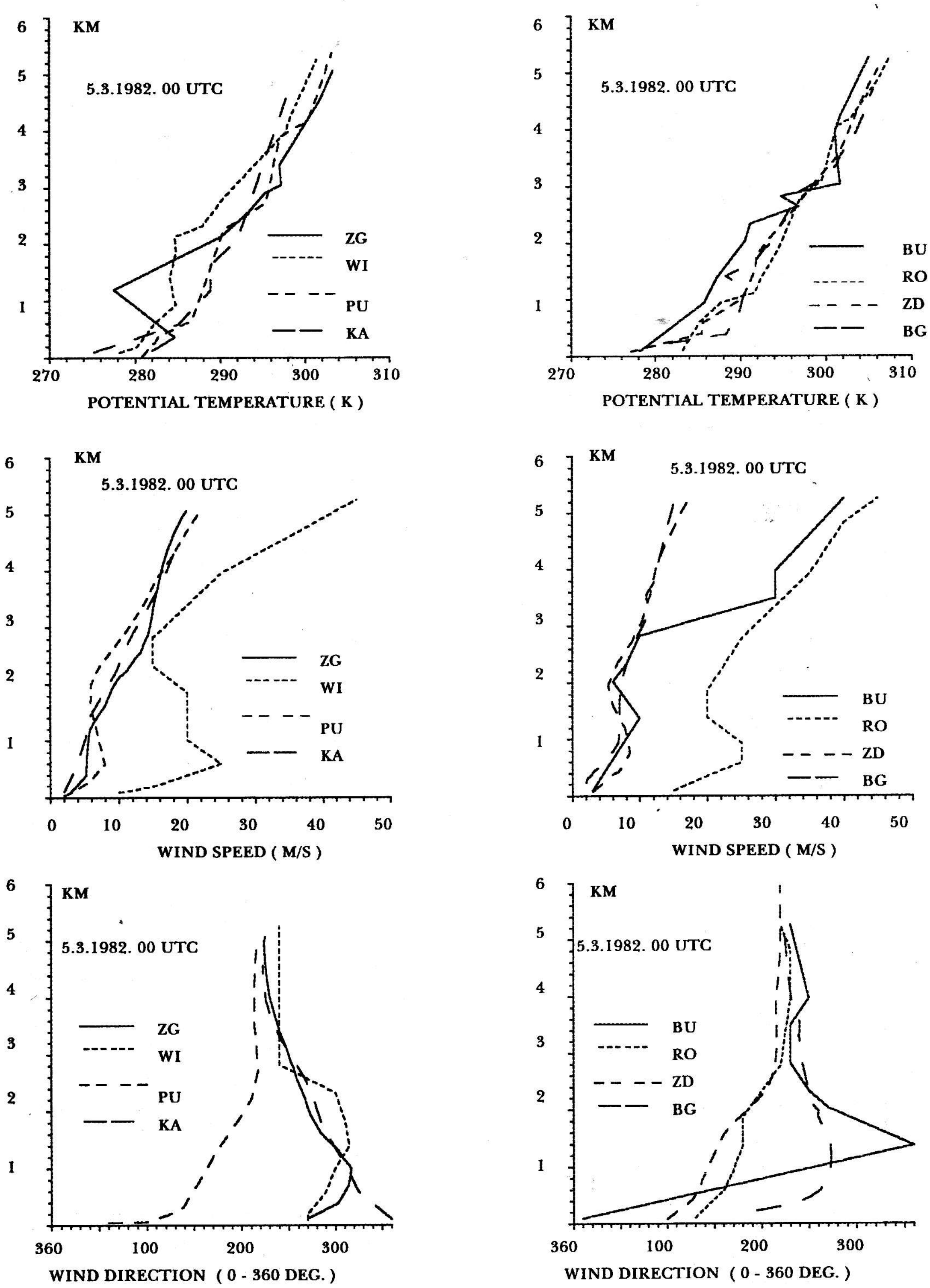

Fig. 2. The vertical profiles of potential temperature, wind speed and wind direction on 5 March 1982 at 00 UTC.

Sl. 2. Vertikalni profili potencijalne temperature, brzine i smjera vjetra 5. ožujka 1982. u 00 UTC.

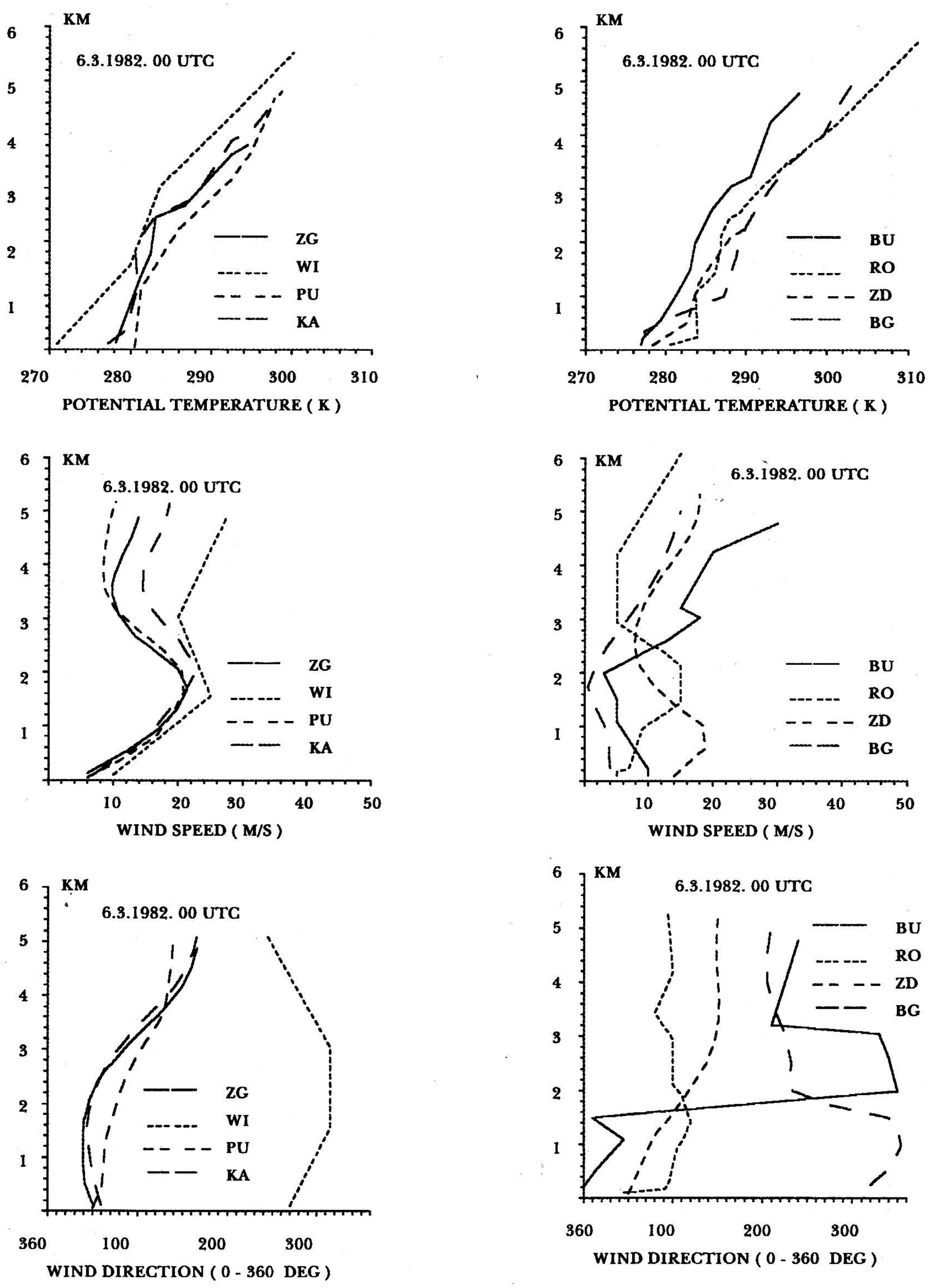

Fig. 3. The vertical profiles of potential temperature, wind speed and wind direction on 6 March 1982 at 00 UTC.

Sl.3. Vertikalni profili potencijalne temperature, brzine i smjera vjetra 6. ožujka 1982. u 00 UTC.

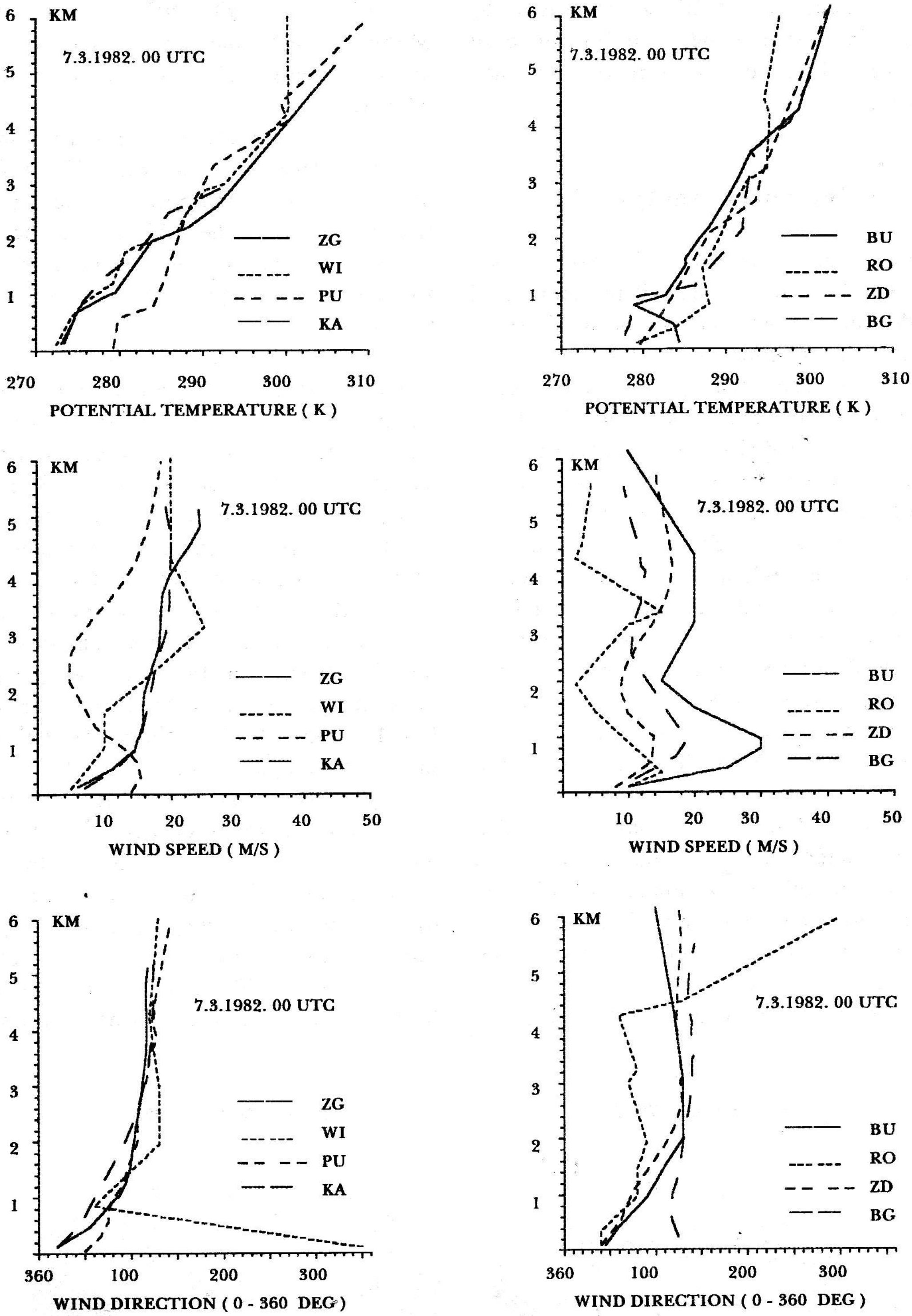

Fig. 4. The vertical profiles of potential temperature, wind speed and wind direction on 7 March 1982 at 00 UTC.

Sl.4. Vertikalni profili potencijalne temperature, brzine i smjera vjetra 7. ožujka 1982. u 00 UTC.

of vertical wind shear and the descending upstream stable layer on 7 March (see the difference between wind and potential temperatures on Fig 3. and Fig 4.) caused a rapid bora decay except at localities influenced by lower mountain passes under the influence of the three-dimensional channelling effects such as observed in Senj.

5. Results of the aerial analysis

The cyclogenesis on 4-5 March 1982 was selected by Buzzi, Trevisan and Tosi (1984, 1985) for the application of a high-resolution analysis scheme in isentropic coordinates based on the concept of variational analysis. The procedure described in their papers was developed for the description of meteorological phenomena on a scale of a few hundred kilometers (14° W - 27° E, 33° N - 57° N, mesh width 55 km), related to the presence of the Alps. The three-dimensional structure was analyzed in the phase in which the cyclone grows as a baroclinic disturbance. In describing the dynamic properties of this case study, they referred particularly to the two selected isentropic surfaces. The first is ϑ_1 = 290 K, which belongs to the low level front and is representative of the low-level flow in the lee cyclonic area. The second corresponds to ϑ_2 = 302 K which is representative of mid-tropospheric conditions. The authors showed that on 5 March, 00 UTC, the ϑ_1 surface indicated a lee cyclone and associated ridge north of the Alps. The cold advection which occurred to the west of the cyclone and also, in part, the nocturnal radiational cooling, caused a southward displacement of the intersection with the ground. At higher level, a considerable deepening of the trough occurred over the western Mediterranean, associated with the penetration of a wedge of cold air down to northern Africa.

The trajectories computed in the same paper between 4 March 12 UTC and 5 March, 00 UTC, indicate that cold air at 290 K flowed around the Alps, on both western and eastern sides. The trajectories on the ϑ_2 surface show a cyclonically curved flow over the Alps.

In order to see the behavior of the same isentropic surfaces in the upstream and downstream bora region in more detail we have used the analysis method presented in section 2. The 290 K and 302 K isentrope altitudes (Fig. 5) indicate a definite descent of the lower isentropic surface not only along the NE bora flow, but also perpendicular to this flow in the upstream region. This is in accordance with the behavior of the same isentropic surface on a greater scale presented in a paper by Buzzi, Trevisan, Tosi (1984, 1985). At this time, the descent of the upper isentropic surface (392 K) in the lee of the Dinaric Alps was less pronounced. A pronounced descent of 290 K and a less pronounced descent of 302 K could be clearly seen on the 286 K and 296 K isentropes (Fig. 6). Those two values could be separated on the vertical profile of potential temperature on 6 March 00 UTC. The reason why 6 March 1982, 00 UTC, was chosen was be-

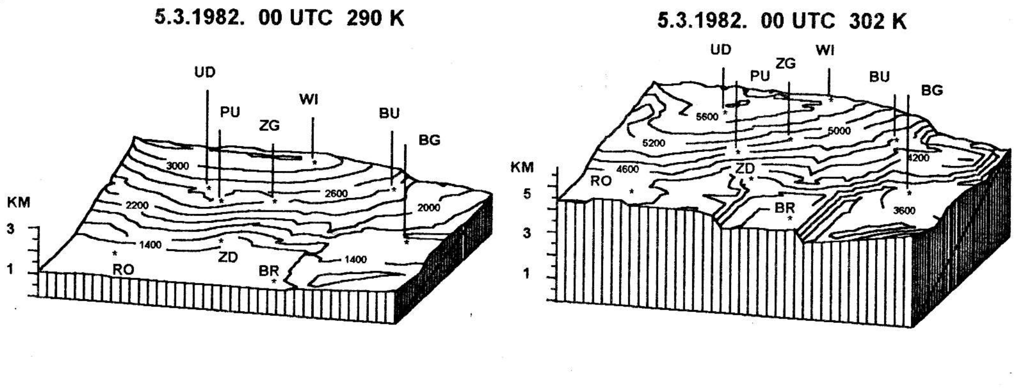

Fig. 5. Altitude of the 290 K and 302 K isentropic surfaces on 5 March 1982 at 00 UTC.
Sl.5. Visina izentropskih ploha 290 K i 302 K 5. ožujka 1982. u 00 UTC.

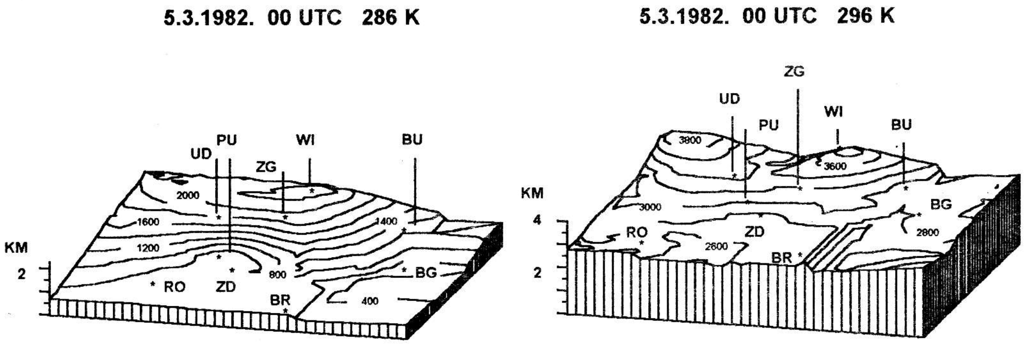

Fig. 6. Altitude of the 286 K and 296 K isentropic surfaces on 5 March 1982 at 00 UTC.
Sl.6. Visina izentropskih ploha 286 K i 296 K 5. ožujka 1982. u 00 UTC.

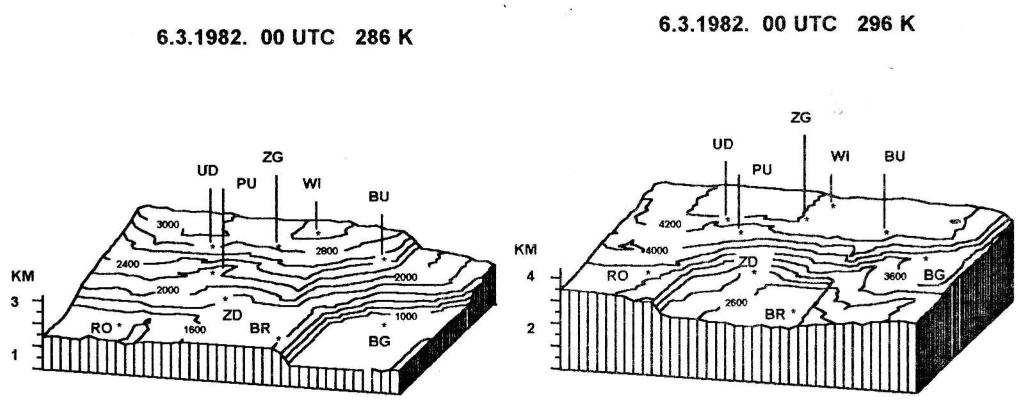

Fig. 7. Altitude of the 286 K and 296 K isentropic surfaces on 6 March 1982 at 00 UTC.
Sl.7. Visina izentropskih ploha 286 K i 296 K 6.ožujka 1982. u 00 UTC.

cause at that time the bora on the northern Adriatic strenghtened. The 286 K isentrope presented the lower base of a stable layer in the upstream and downstream region. Slightly below that point the wind speed reached its maximum value. The second isentrope coincided with the upper limit of the upstream bora layer.

The observation of a stable layer that descends from the upstream to the downstream bora region is consistent with the downdraft determined in the northeasterly flow and with the upstream acceleration obtained from aircraft measurements (Smith, 1987) in two ways. Firstly, the conservation of the mass flow rate between the rising terrain and the descending isentropes, would require flow acceleration. Secondly, the descending isentropes produce a horizontal density gradient which hydrostatically gives rise to a pressure gradient below. This pressure gradient is directly responsible for the flow acceleration.

With the bora strengthening (during the day of 6 March) the 286 K isentrope lawered whereas the altitude of the 296 K isentrope increased. This region of isentrope splitting seems to have filled the gap between the descending bora air and the less disturbed conditions aloft. This "dead region" downstream had slower winds and its leading boundary was, according to aircraft measurements, highly turbulent.

The local descent of isentropes implies both local baroclinicity, which generates horizontal components of vorticity, and differential vertical motion, which tilts the horizontal vorticity components into vertical (Dempsey, 1989).

The aerial analysis of the strongest ALPEX SOP bora case will be completed

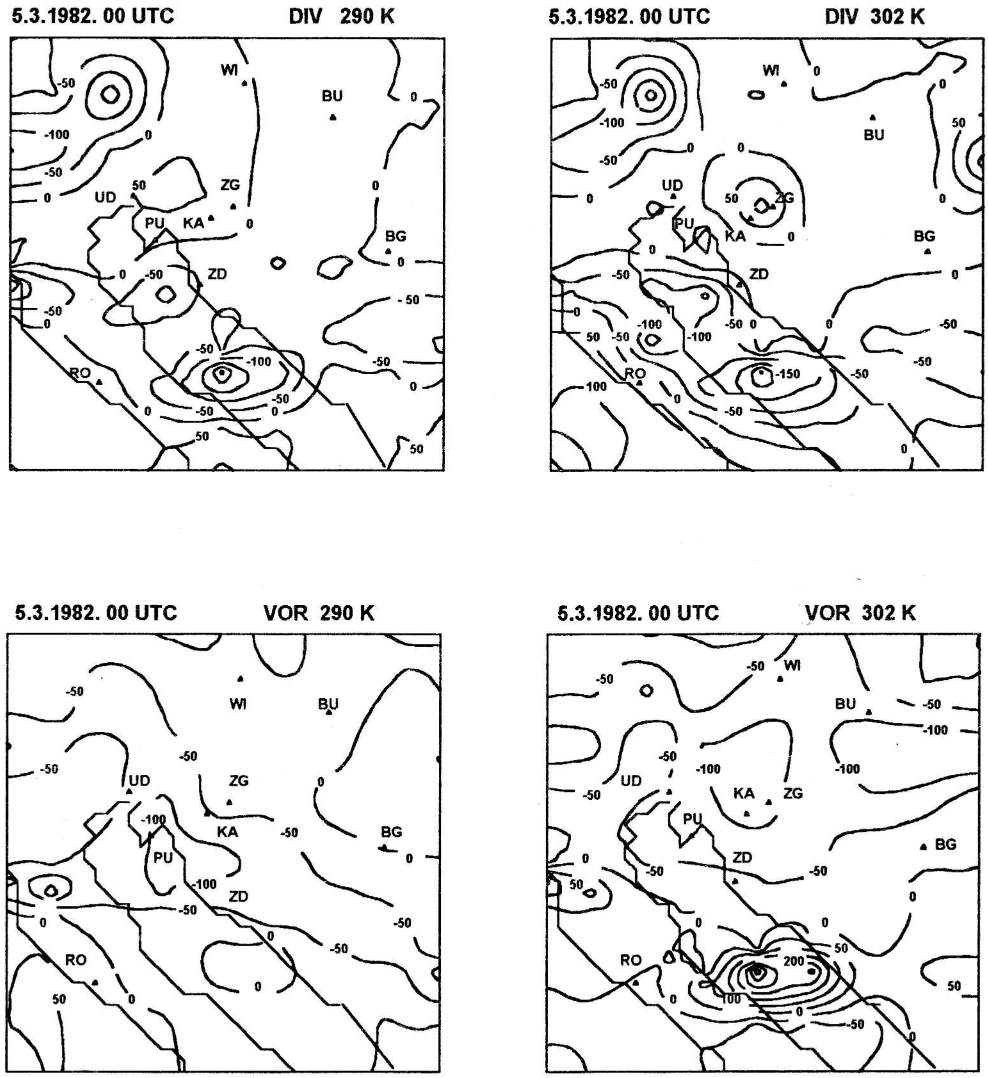

Fig. 8. Divergence and vorticity on the 290 K and 302 K isentropic surfaces on 5 March 1982 at 00 UTC.
Sl. 8. Divergencija i vrtložnost na 290 K i 302 K izentropskim plohama 5. ožujka 1982. u 00 UTC.

with the presentation of the two-dimensional horizontal divergence of the velocity field

$$DIV = \left(\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y}\right)_{\vartheta} \qquad (2a)$$

and the vertical component of the vorticity

$$VOR = \left(\frac{\delta v}{\delta x} + \frac{\delta u}{\delta y}\right)_{\vartheta} \qquad (2b)$$

on the considered isentropic surfaces. Horizontal velocity components are obtained on the regular mesh by the same method as in the case of the height of isentropic surfaces.

The existence of a SE flow in the lower troposphere over the northern and mid-Adriatic and a N-NW flow over the northeastern continental part suggest a flow convergence over the southern Adriatic on 5 March 1982 (Fig. 8. and 9.). This feature is in agreement with the observed belt of convergence which spreads over most of the western Mediterranean basin and the upward motion which dominate near cyclone centers in the developing stage (Radinović, 1985).

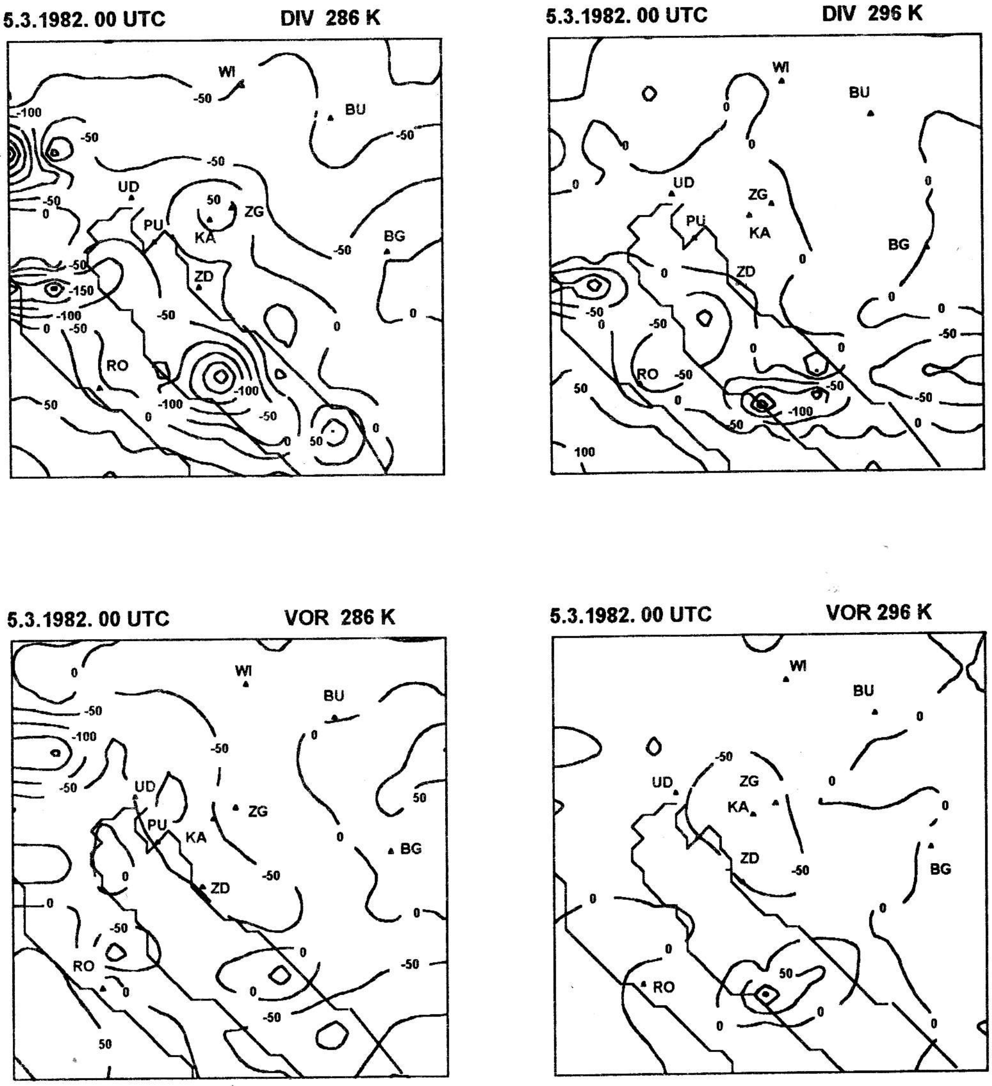

Fig. 9. Divergence and vorticity on the 286 K and 296 K isentropic surfaces on 5 March 1982 at 00 UTC.
Sl. 9. Divergencija i vrtložnost na 286 K i 296 K izentropskim plohama 5. ožujka 1982. u 00 UTC.

After a period of 24 hours there is a marked change in the divergence pattern (Fig. 10). The less pronounced convergence center is now located over northern Italy, while the southeasterly part of the analysis domain is covered by positive divergence values. In the middle troposphere a belt of positive divergence develops in the northern and northwestern parts of the considered area.

Some trajectory analyses of the flow over the Alps done until now lead to a picture of rather strong anticyclonic vorticity in the lee of the Alps (Pichler, Steinacker and Lanzinger, 1990). This feature could be also observed on Fig. 9. It is most pronounced on the 286 K isentrope as a consequence of blocking effects and flow splitting around the Alps. With the wind direction change to NE the area of anticyclonic vorticity spread over the entire northern part of the area considered and the center of cyclonic vorticity moves towards SE (Fig. 10 b). The northern edge of the Dinaric Alps represents a zone where vorticity changes its sign from anticyclonic to cyclonic. This is in accordance with the results of the aircraft data analysis. One flight leg of the aircraft on 6 March 1982 was nearly at the same altitude with

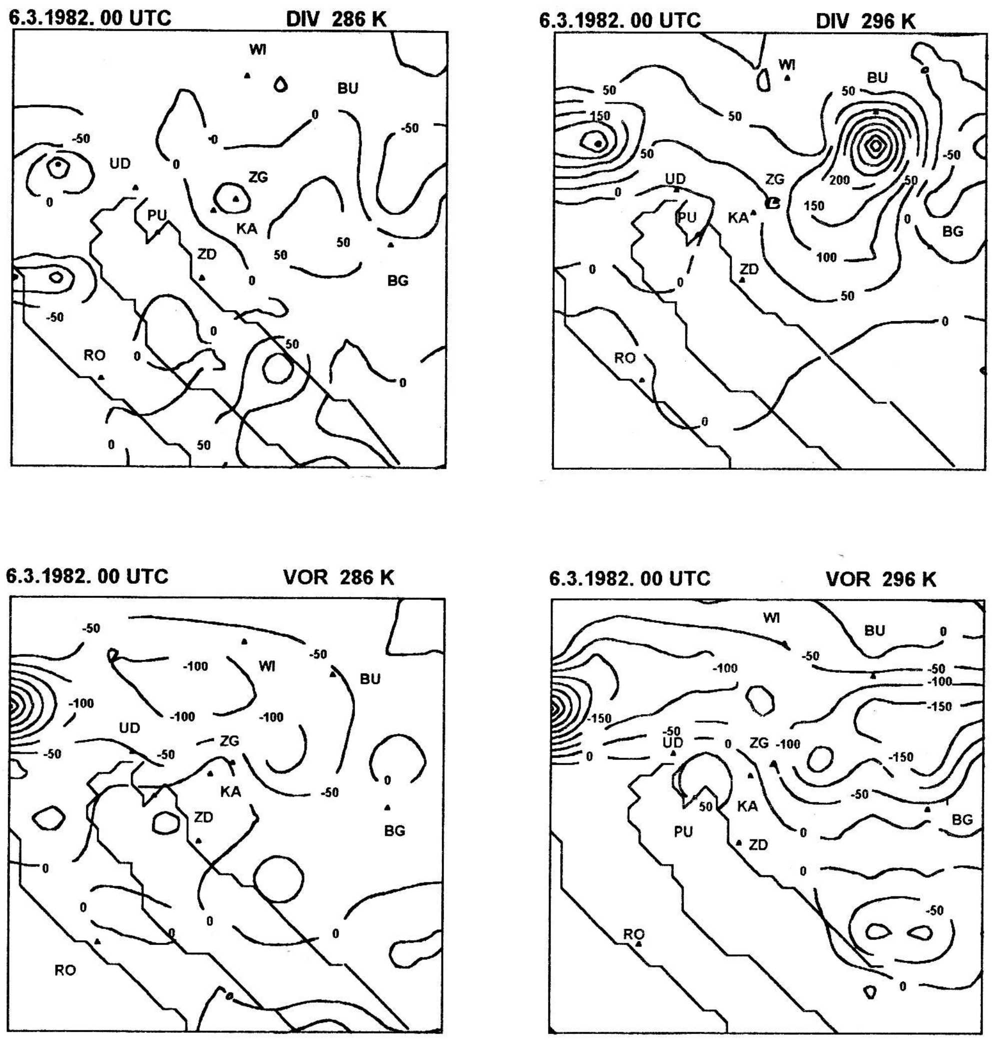

Fig. 10. Divergence and vorticity on the 286 K and 296 K isentropic surfaces on 6 March 1982 at 00 UTC.
Sl. 10. Divergencija i vrtložnost na 286 K i 296 K izentropskim plohama 6. ožujka 1982. u 00 UTC.

the 296 K isentrope over the mountain crest. The aircraft measurements just downstream of the crest showed, at this level, the existence of a zone in which the cross-mountain flow component changed sign from positive (NE) to negative (SW) while the vertical wind component changed sign from negative to positive. According to Pettre's suggestion (1985) this evolution presents the possibility of vortex generation with the horizontal axis parallel to the barrier.

6. Conclusion

In spite of its simplicity the presented method of objective analysis gives results which support several important characteristics of the air flow, supporting previously obtained theoretical results:

- a descending stable bora layer indicating the existence of upstream acceleration,
- an isentropic splitting region in which the air has little mean motion but considerable turbulence and is well mixed forming a "dead region",
- flow convergence and positive vorticity near

the cyclone center in the developing stage,
- strong anticyclonic vorticity in the lee of the Alps due to blocking effects.

These and other obtained results confirm the fact that the air flow in severe bora situations is a strictly three-dimensional phenomenon.

However, even with the increased number of upper air stations available for ALPEX, the network is still barely capable of resolving all the mesoscale, and especially local, bora characteristics, in order to fully understand all the processes associated with the interaction of the Dinaric Alps and the surrounding atmospheric flows.

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Kratak sadržaj

U ovom radu prikazana jednostavna objektivna metoda analize aeroloških podataka na izentropskim plohama i njeni rezulati predstavljaju doprinos poznavanju trodimenzionalne strukture atmosfere u slučaju najjače bure u ALPEX SOP 5-7 ožujka 1982 koja je s aspekta prizemnih podataka detaljno analizirana u prijašnjem radu A.Bajić, 1988.

Analiza je provedena na području 40° - 49° N i 10° - 22° E (Sl. 1) razdijeljenom na pravilno razmaknute točke (25x25 km). Podaci Zagreba, Karlovca, Pule, Zadra, Beča, Budimpešte, Beograda, Udina, Rima i Brindisia interpolirani su metodom inverzne udaljenosti kako bi se dobile vrijednosti u svakoj točki mreže. Pri tom je bilo potrebno definirati susjedno područje pretraživanja i najmanji broj točaka s podacima u tom području koji će se uzeti u obzir pri interpolaciji (jed. 1). Dobivene pravilno raspoređene vrijednosti povezane su izolinijama "cubic spline" metodom.

Ovom objektivnom metodom analizirane su visine karakterističnih izentropskih ploha, te dvo-dimenzionalna divergencija i vertikalna komponenta vrtložnosti na njima (jed. 2 i 3).

Usprkos svojoj jednostavnosti primijenjena metoda analize dala je rezultate koji su u suglasnosti s rezultatima autora koji su slične vremenske situacije analizirali drugim metodama. Pokazano je da visina izentropske plohe koja predstavlja donju bazu stabilnog sloja iznad NE strujanja (286 K) opada, ne samo u smjeru strujanja, već i okomito na njega (Sl. 5, 6, 7). Pad izentropa uzrokuje horizontalni gradijent gustoće koji hidrostatički daje porast gradijenta tlaka direktno odgovornog za akceleraciju strujanja koja je opažena tijekom avionskih mjerenja (Smith, 1987). Jačanje bure praćeno je padom izentrope 286 K i porastom visine izentrope 296 K (gornja granica navjetrinskog sloja bure). Područje između ovih ploha karakterizira slab vjetar i prema avionskim mjerenjima, jaka turbulencija, te prema Smithu (1985) označava "mrtvo područje".

Postojanje SE strujanja u donjoj troposferi nad Jadranom i N-NW strujanja nad sjeveroistočnim dijelom područja analize uzrokovalo je postojanje konvergencije i pozitivne vrtložnosti nad južnim Jadranom 5. ožujka 1982. (Sl. 8, 9) gdje se u to vrijeme nalazila ciklona mezorazmjera. Velike vrijednosti anticiklonalne vrtložnosti u zavjetrini Alpa na 286 K plohi posljedica su blokirajućeg efekta i strujanja oko prepreke. Prodiranjem hladnog zraka s NE i jačanjem bure područje anticiklonalne vrtložnost se širi na čitavu sjeverenu stranu promatranog područja, a centar ciklonalne vrtložnosti slabi i pomiče se ka SE.

Čak i uz povećani broj aeroloških postaja raspoloživih u ALPEX-u, mreža još uvijek ne može obuhvatiti sve mezoskalne, a naročito lokalne karakteristike strukture atmosfere u slučajevima bure. Da bi se u potpunosti iskoristili svi ALPEX podaci u svrhu boljeg razumijevanja i prognoze olujne bure na Jadranu, potrebno je koristiti metode analize koje su u mogućnosti razlučiti procese koji prate interakciju između Dinarida i atmosferskog strujanja, i koje bi asimilirale podatke različitog porijekla i prirode.