RASPRAVE 23, Zagreb 1988, str. 1-12

UDK: 551.555.4
Originalni znanstveni rad

THE STRONGEST BORA EVENT DURING ALPEX-SOP

Najintenzivniji slučaj bure u ALPEX-SOP

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Primljeno 23. kolovoza 1988, u konačnom obliku 15. studenog 1988.

Abstract: The most intense bora case on the northern Adriatic during the ALPEX-SOP (5-7 March 1982) was considered with emphasis on the surface and radiosounding data analyses. The bora onset was connected with a large increase of pressure gradient between the cold upstream air and a cyclone formed in the lee of the Alps. The vertical atmospheric structure shows the existence of stable layers inside and above the NE wind flow and SE wind aloft.

It is shown that the strong bora appearance could be successfully described by the generalized hydraulic theory, especially at the time period with the strongest bora.

The main problem still theoretically unsolved is the inclusion of the vertical wind shear in the upstream bora layer into theoretical consideration.

Key words: bora, generalized hydraulic theory, ALPEX-SOP

Sažetak: Analiziran je slučaj najjače bure u ALPEX-SOP (5-7. ožujak 1982) s posebnim naglaskom na detaljnu analizu prizemnih i radiosondažnih podataka. Pojava bure bila je praćena naglim porastom gradijenta tlaka između hladnog zraka u navjetrini Dinarida i ciklone formirane u zavjetrini Alpa. Vertikalnu strukturu atmosfere karakteriziraju stabilni slojevi unutar i iznad sloja NE strujanja te SE vjetar na visini.

Pokazano je da se generalizirana hidraulička teorija može uspješno primijeniti u slučaju jake bure (posebno u terminima u kojima je bura najjača). Osnovni problem koji bi bilo potrebno riješiti je uključivanje u teoretsko razmatranje stvarno opaženog znatnog vertikalnog smicanja vjetra u navjetrenom sloju bure.

Ključne riječi: bura, generalizirana hidraulička teorija, ALPEX-SOP

1. INTRODUCTION

During the ALPEX Special Observing Period bora was a very frequent event along the Adriatic Coast of Yugoslavia (Bajić, 1988). The strongest bora with maximum gusts greater than 30 ms^{-1} was registered on the northern Adriatic on 5-7 March 1982. At the same time two research flights were performed above the Yugoslav coast near Senj: 6 March (12-16 GMT) and 7 March (7-12 GMT). Because of this, many observational and theoretical studies of this bora case have been published till now (Smith 1982, 1984, 1987; Koračin, 1984; Jurčec 1984; Pettre 1984, 1986; Vučetić 1984, 1985, 1987). The most detailed studies concerned analyses of vertical atmospheric structure in the upstream and downstream bora regions and analyses of aircraft data. However, less attention was paid to surface data. The purpose of this work is to extend the existing analysis of the bora case on 5-7 March using all available surface and radiosounding data. The main attention is given to the possibility of the generalized hydraulic theory (Smith and Sun, 1987) application in such a strong Adriatic bora case.

2. THE SYNOPTIC SITUATION AND SPATIAL DISTRIBUTION OF BORA

The most intense event of lee cyclogenesis during the SOP wich caused the strongest bora on the northern Adriatic was 4-5 March. A cyclone developed over the Gulf of Genoa when a cold front associated with a primary trough moving eastward over Europe interacted with the Alps (Buzzi and Tosi, 1982). The cyclone movement out of the region of formation was very slow, with a pronounced cut-off low at 500 hPa (Fig. 1), which developed into blocking flow patterns over Europe on 7 March.

The pressure and wind fields over Yugoslavia on 6 March 12 GMT and 7 March 9 GMT are shown in Fig. 2. On 6 March at 12 GMT the pressure gradient over the

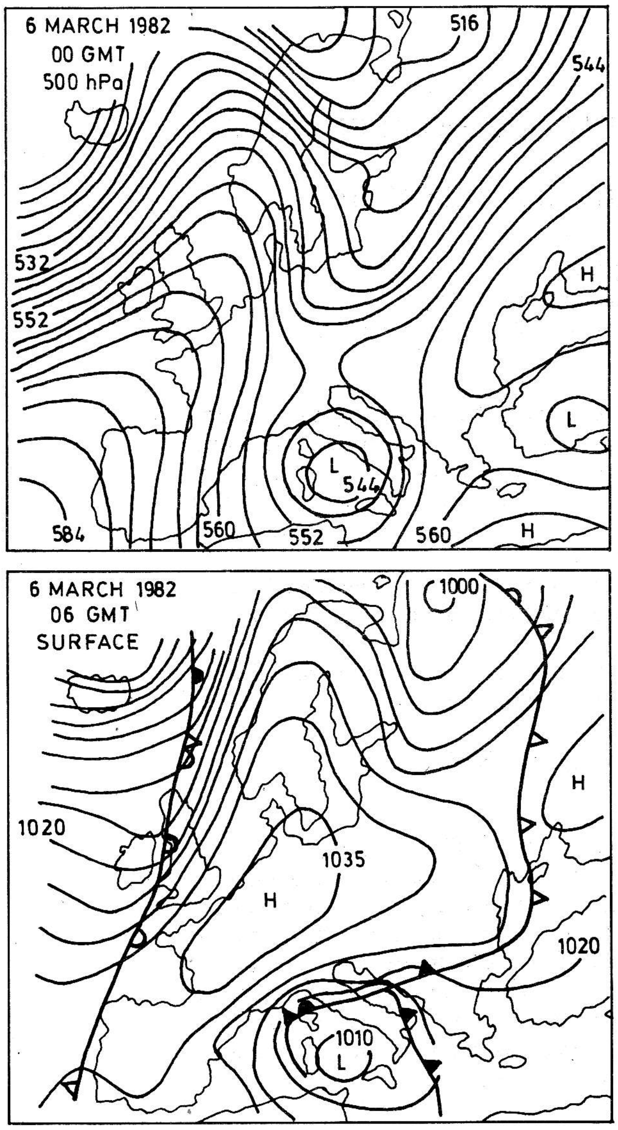


Fig. 1. **The synoptic situations: top-500 hPa on 6 March 00 GMT, bottom-surface on 6 March 06 GMT.**

Sl. 1. **Sinoptička situacija: gore-500 hPa za 6. ožujak 1982. u 00 GMT, dolje-prizemna za 6. ožujak 1982. u 06 GMT.**

Adriatic coast was stronger than on 7 March when the shallow layer supply of cold air from the N-NE still existed as a consequence of the mentioned blocking flow pattern. The strong N-NE winds could be noticed on 6 March over the greatest part of the Adriatic coast. The northeasterly wind over the inland areas is a part of the stream which flows around the eastern Alps.

A closer look at the pressure and wind fields over the northern Adriatic can be seen in Fig. 3. The data indicate the increase of wind speed as the flow approaches the mountain barrier. This upstream acceleration is in accordance with the observed flow behaviour at 2 km altitude given in the aircraft data analyses (Smith, 1987). The two ALPEX SOP flights with three-dimensional flight patterns (22 March and 15 April) find a remarkable regime change just southeast of Senj. On 6 March this

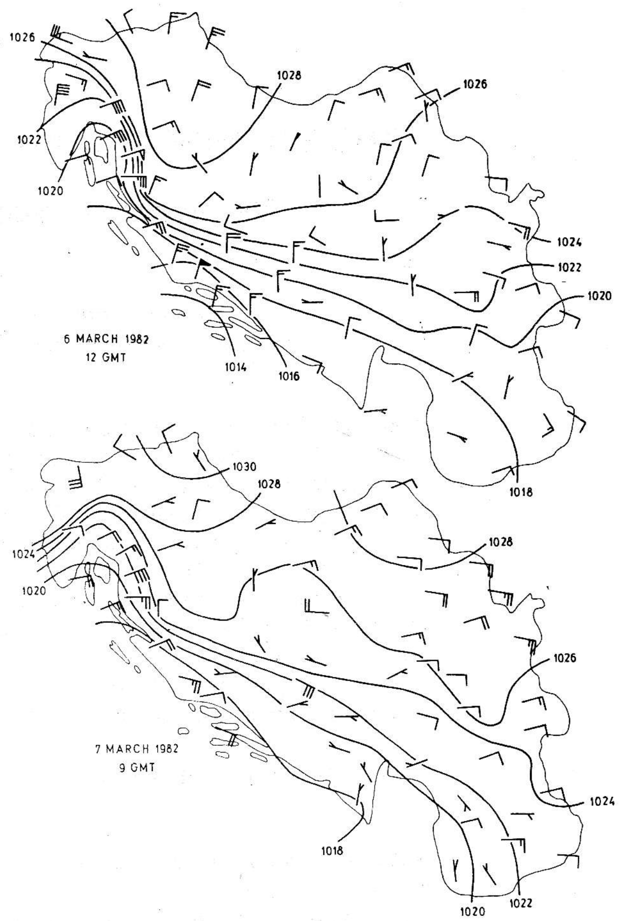


Fig. 2. **The sea-level pressure and wind fields over Yugoslavia on 6 March 12 GMT (top) and 7 March 09 GMT (bottom).**

Sl. 2. **Polja tlaka reduciranog na morsku razinu i vjetra nad Juguslavijom 6. ožujka 1982. u 12 GMT (gore) i 7. ožujka 1982. u 9 GMT (dolje).**

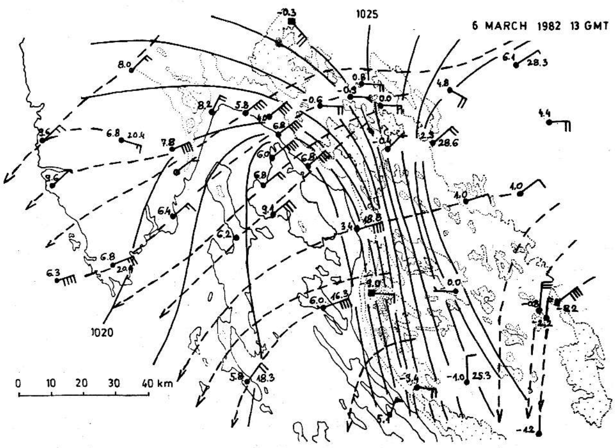


Fig. 3. **The mesoanalyses over the northern Adriatic on 6 March 1982 13 GMT. Solid lines indicate isobars every 1 hPa and dashed lines indicate streamlines.**

Sl. 3. **Mezoanaliza na području sjevernog Jadrana 6. ožujka u 13 GMT. Pune linije označavaju izobare, a isprekidane linije označavaju strujnice.**

flow characteristic was not noticable at the surface.

In accordance with such a situation are the daily courses of surface temperature and sea-level pressure at three stations: Zagreb-in the upstream bora region; Senj-on the northern Adriatic and Split-on the middle Adriatic (Fig. 4). Before bora onset the sea-level pressure differences between the upstream and downstream region were small. A cold air outbreak from the NE in the upstream region in the early hours on 5 March was connected with an increase of sea-level pressure in Zagreb. From the daily course of temperature it could be seen that cold air continued to penetrate the upstream region until 8 March. The increase of sea-level pressure in Zagreb and the considerably slower pressure increase in the downstream region caused the great pressure gradient between upstream and downstream areas.

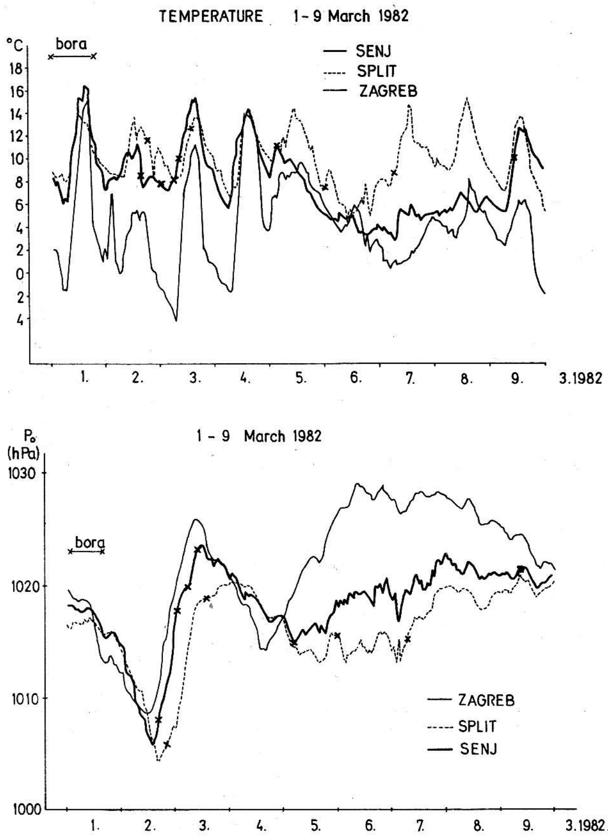


Fig. 4. The daily courses of surface temperature (top) and sea-level pressure (bottom) on 1-9 March 1982 for Zagreb, Senj and Split.

Sl. 4. Dnevni hodovi prizemne temperature gore i tlaka reduciranog na morsku razinu dolje 1-9. ožujka 1982. za Zagreb, Senj i Split.

In Fig. 5. the maximum gusts (hourly) of wind with NNE-ENE directions and mean hourly velocities above 5. 4 ms^{-1} (3 Beaufort) show the bora onset on the northern Adriatic on 5 March at a.m. Maximum gusts were measured in Omišalj at 10. p.m. on the same day (35. 2 ms^{-1}) and in Senj at 1 p.m. on 6 March (31. 8 ms^{-1}). Although in the majority of cases the strongest bora occurs in Senj, it is shown that in certain situations maximum bora gusts could be greater on some other locations.

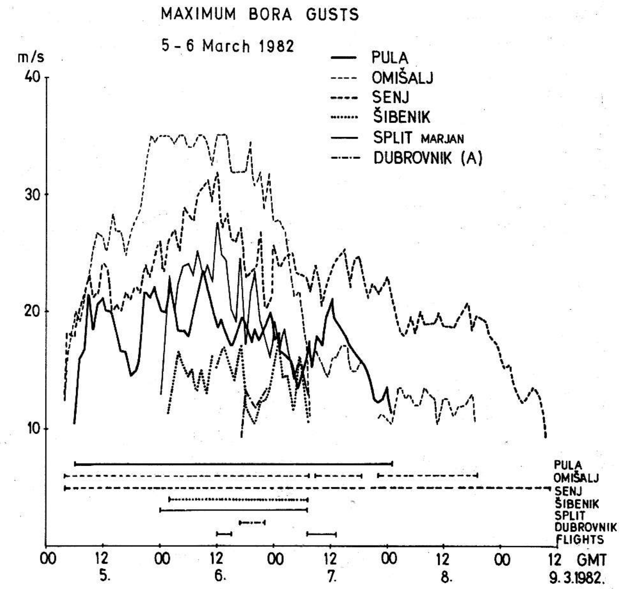


Fig. 5. The daily courses of maximum bora gusts 5-9 March 1982.

Sl. 5. Dnevni hodovi maksimalnih udara bure za 5-9. ožujak 1982.

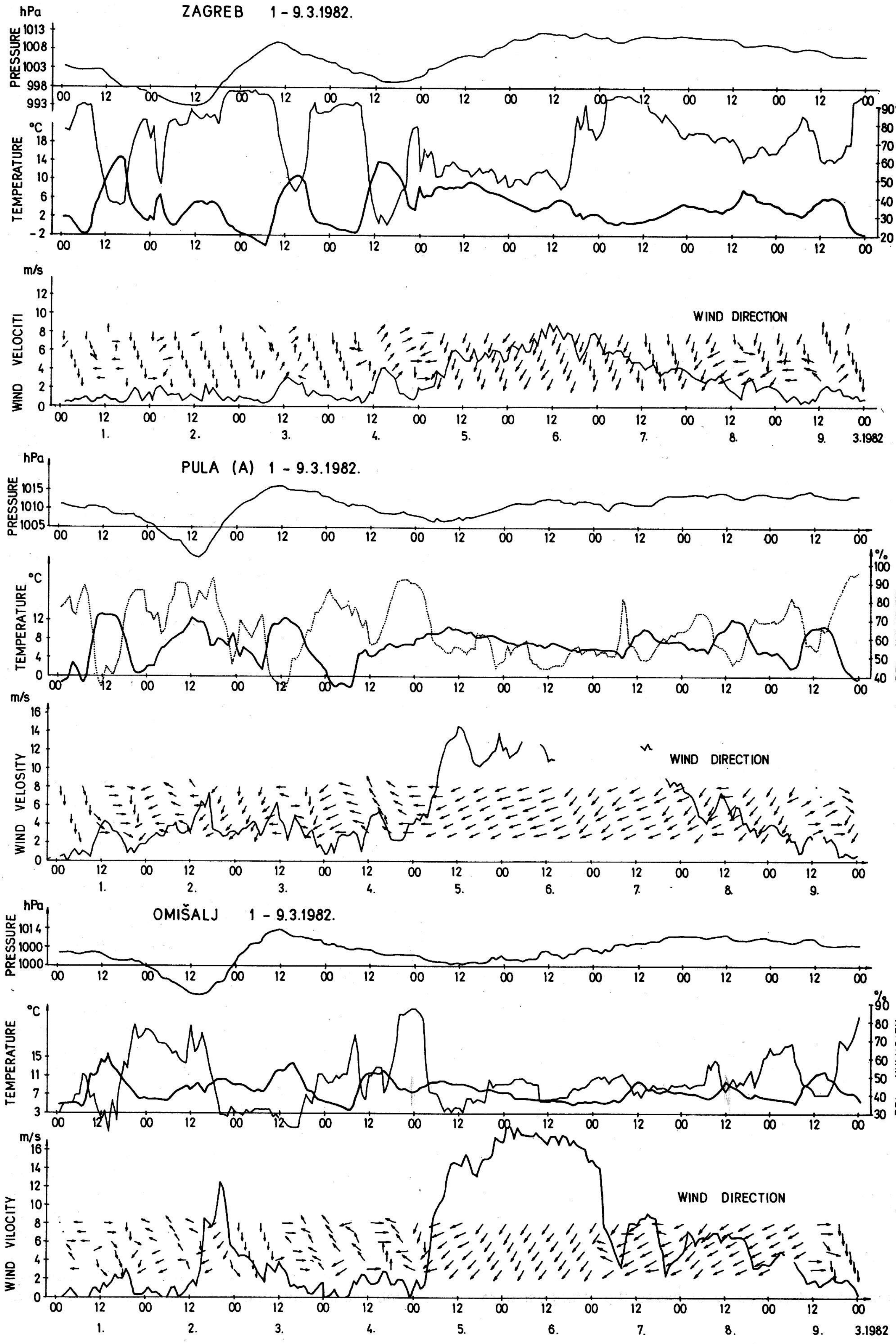
On the middle and southern Adriatic, bora was observed in Split and Šibenik and a weak bora also occurred in Dubrovnik, for only few hours. A protracted supply of cold air in the upstream bora region in the 1 km layer above ground caused a long lasting bora in Senj (102 hours). Such a long bora duration is a frequent case in Senj due to its specific location near Vratnik Pass causing channeling effects.

A more detailed view in the changes of main meteorological elements could be obtained from daily courses of station pressure, temperature, relative humidity and wind direction and velocity at 6 stations (one in the upstream region and 5 on the coast) (Fig. 6).The onset of bora at all considered stations was accompanied by a sudden drop of relative humidity, a decrease of temperature and an increase of pressure. As supply of cold air diminished the bora weakened.

The first ALPEX bora flight occured during mid-day on 6 March. At that time the bora reached its maximum and slowed down. A second bora flight on 7 March occured during the time when bora was weaker and it was the most pronounced in Senj, therefore this case could be representative for the Senj bora due to channeling.

3. VERTICAL ATMOSPHERIC STRUCTURE

For detailed analyses of vertical wind structure in the upstream region wind vectors over Zagreb are shown in Fig. 7. The cold front passage on 2 March between 12 and 18 GMT was characterized by wind strenghthening and its direction changing from WSW to NE throughout the lower troposphere. After the frontal passage the lee cyclone formed in the Gulf of Genoa and the flow over Zagreb became SW oriented. As the postfrontal cold air


ZAGREB 1 - 9.3.1982.
PRESSURE
hPa
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PRESSURE
TEMPERATURE
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WIND VELOSITY
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3.1982

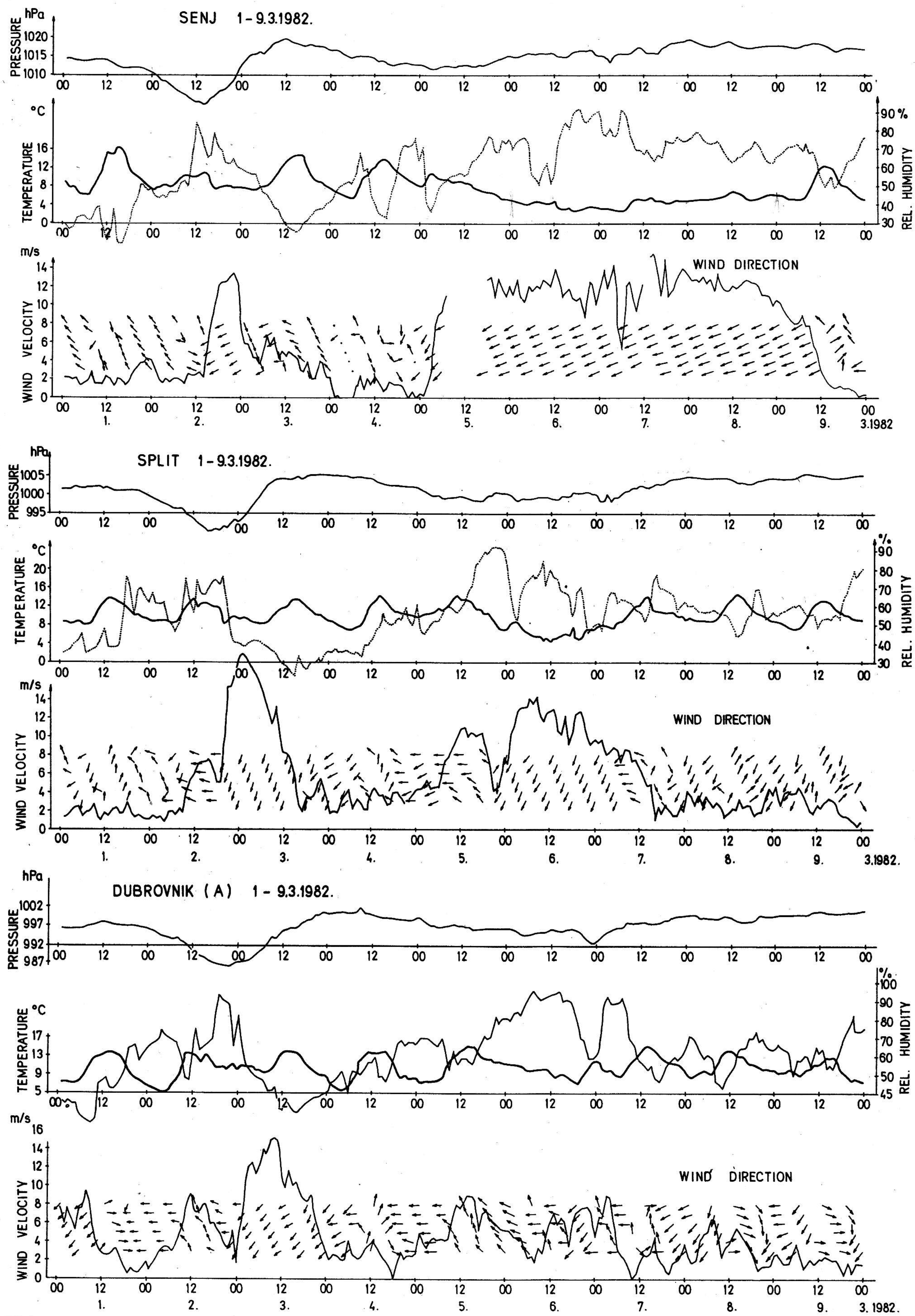


Fig. 6. The daily courses of mean meteorological elements 1-9 March 1982.

Sl. 6. Dnevni hodovi osnovnih meteoroloških elemenata 1-9. ožujka 1982.

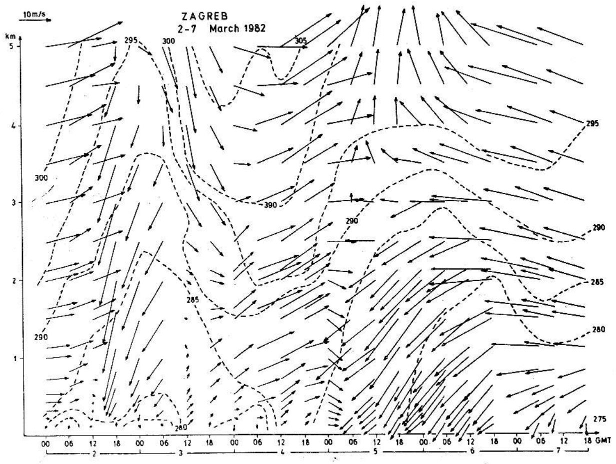


Fig. 7. Time-height cross section of wind and potential temperature (isentropes every 5 K).

Sl. 7. Vremenski vertikalni presjek vjetra i potencijalne temperature (izentrope svakih 5 K) nad Zagrebom.

moved around the eastern Alps it encountered the Dinaric Alps. This cold air coming to Zagreb from the NE occupied the 2.5-3 km deep layer. Above that a S-SE wind prevailed.

The vertical profiles of u_B (NE wind component) and v_B (normal to the u_B) wind component over Zagreb, Karlovac, Pula and Zadar are presented in Fig. 8. and

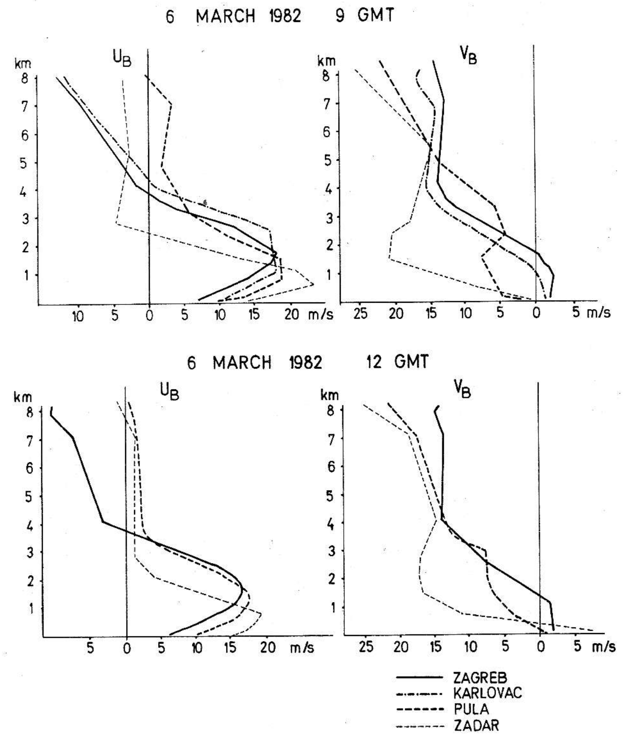


Fig. 8. Vertical profiles of u_B wind components on 6 March 09 GMT (top) and 6 March 12 GMT (bottom).

Sl. 8. Vertikalni profili u_B i v_B komponente vjetra 6. ožujka u 09 GMT (gore) i 6. ožujka 1982. u 12 GMT (dolje).

Fig. 9. The low level u_B maximum is almost equally pronounced on all considered profiles. The bora layer (u_B > o) was deeper in the upstream than in the downstream bora regions. Smith (1987) defined the bora layer as a layer with wind directin between 15° and 105°. With the acception of this definition the bora layer extended from 3 km (6 March) to 1.5 km (7 March) in the upstream region (Table 1). The wind had a maximum speed at 1.7-2 km in the period with the strongest bora and at 800-900 m when the bora was ending.

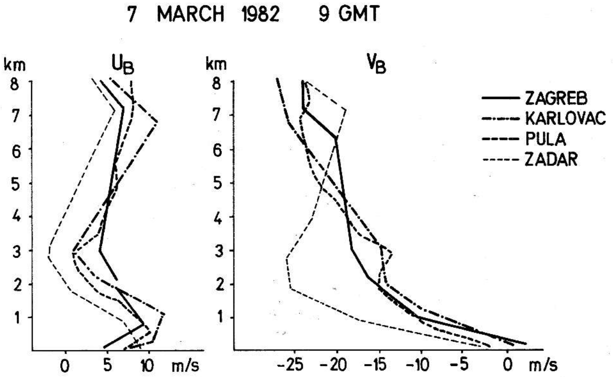


Fig. 9. Vertical profiles of u_B and v_B wind components on 7 March 09 GMT.

Sl. 9. Vertikalni profili u_B i v_B komponente vjetra 7. ožujka 1982. u 09 GMT.

Table 1. The wind characteristics in the bora layer over Zagreb.

Tabela 1. Karakteristike vjetra u sloju bure nad Zagrebom.

Time	Z	U	U_{max}	z_{max}
6 M 12 GMT	3200 m	14.0 ms^{-1}	16.6 ms^{-1}	1700 m
6 M 15 GMT	3000 m	13.1 ms^{-1}	15.3 ms^{-1}	1900 m
7 M 09 GMT	1500 m	12.5 ms^{-1}	13.7 ms^{-1}	1000 m
7 M 12 GMT	1550 m	9.2 ms^{-1}	9.6 ms^{-1}	800 m

Z - level where the wind direction differs from 15° - 105°
U - mean wind speed in the considered layer
U_{max} -maximum wind speed in the considered layer
z_{max} - the U_{max} height

It is known that all cases of strong bora occur with a significant inversion inside or above the cold bora air (Smith, 1987; Jurčec; 1984, Vučetić, 1984, 1985). The thickness and mean altitude of this stable layer vary considerably from case to case and during the bora period. In the considered situation the vertical profiles of potential (θ) and equivalent potential (θ_e) temperature (Fig. 10.) show a few stable layers. The lower boundary of the most pronounced stable layer varied from 1-1.5 km at the bora beginning and ending to the 2-2.5 km at the period with the strongest bora wind (Fig. 11). The heights of inversion layers above Zagreb and Pula illustrate the fact that the stable layers were more expressed and at higher altitudes in upstream than in the downstream region. This agrees with the descending inversion layer toward the mountain barrier observed during aircraft data analyses (Smith, 1987).

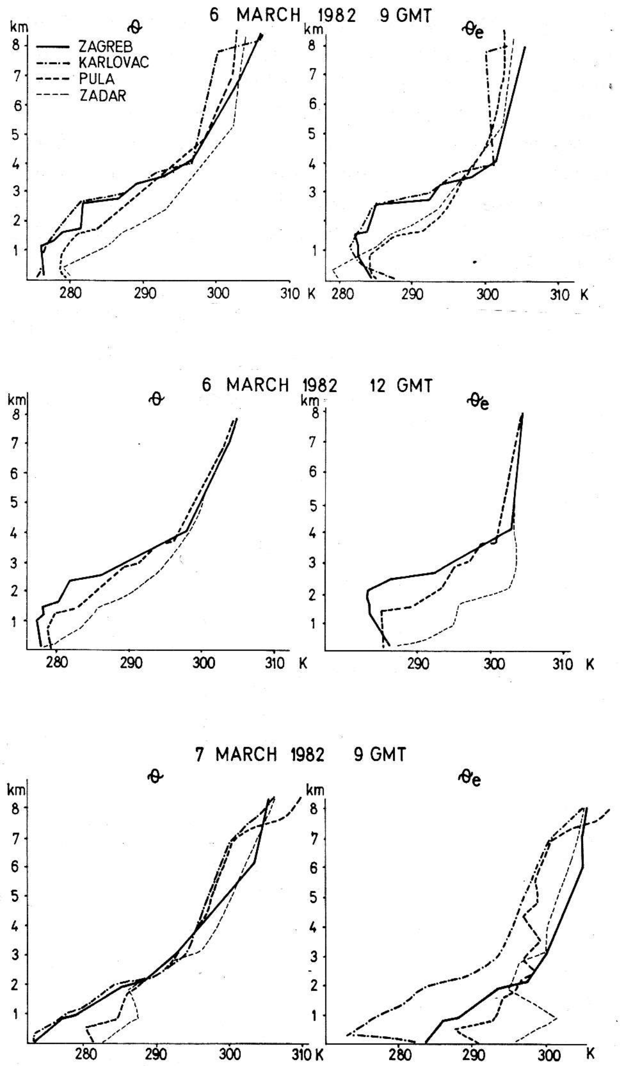
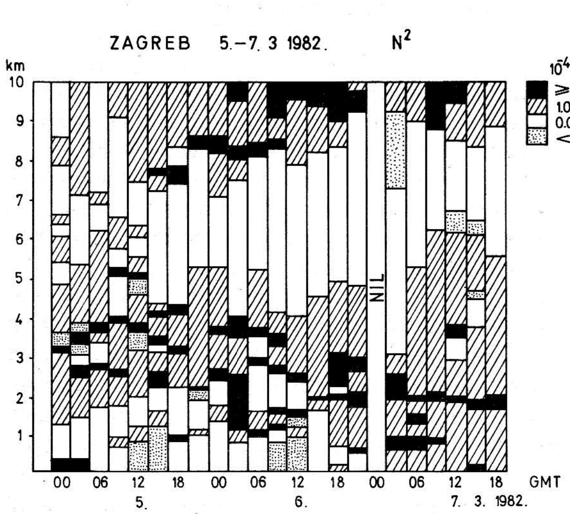
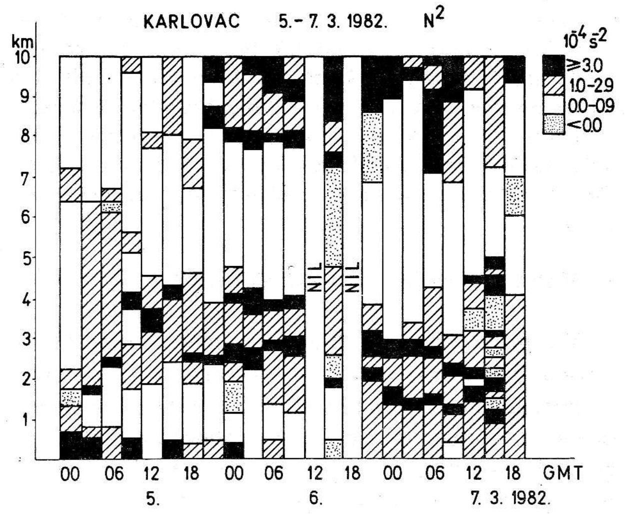
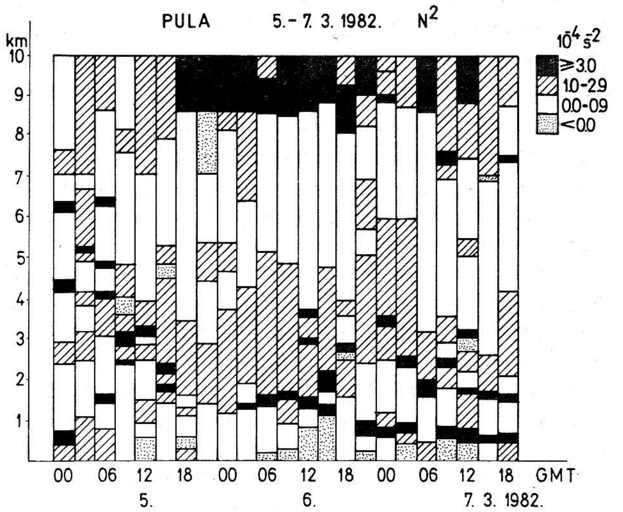


Fig. 10. Vertical profiles of potential (θ) and equivalent potential (θ_e) temperature on 6 March 09 GMT 12 GMT and on 7 March 09 GMT.

Sl. 10. Vertikalni profili potencijalne (θ) i ekvivalentne potencijalne temperature (θ_e) 6. ožujka u 09 GMT i 7. ožujka u 09 GMT.







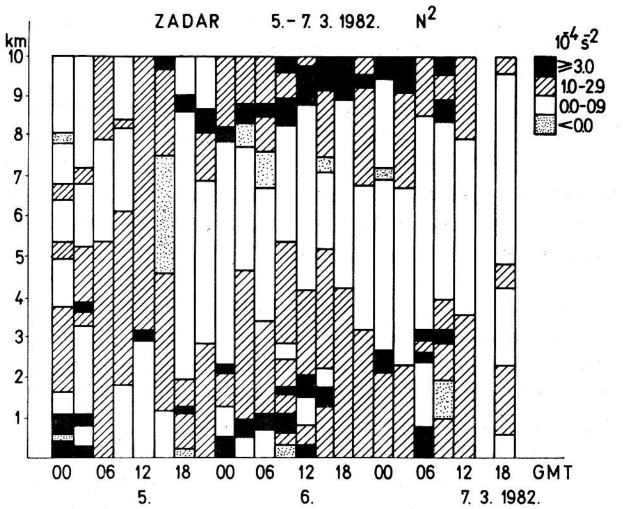


Fig. 11. Time-height cross section of the Brunt-Väisälä frequency (N^2) 5-7 March 1982.

Sl. 11. Vertikalni vremenski presjek Brunt-Väisälä frekvencije (N^2) u razdoblju 5-7. ožujak 1982.

Research flights on 6 March were performed at altitudes of about 2400-4500 m, mainly above the northeasterly bora flow. Because of this the aircraft data do not allow a detailed study of the intense low level bora structure. In the downstream region the temperature inversion and the layer of NE wind were lower on 7 March than on 6 March and the aircraft was not inside the bora layer.

4. APPLICATION OF HYDRAULIC THEORY

At present there are three main mechanisms of the severe downslope wind generation that have been proposed. One mechanism is based on the linear theory of internal gravity waves in a continuously stratified, semiinfinitive fluid (Klemp and Lilly, 1975). A second mechanism is based on results obtained from numerical integrations of the equations which govern the dynamics of the flow (Clark and Peltier, 1977, 1979, 1983, 1984). The third mechanism is based on hydraulic theory (Long, 1954) in which the airflow over a mountain is modeled by fluid flowing over an obstacle. According to hydraulic theory, strong winds will occur along the lee slope when the fluid undergoes a transition from subcritical flow upstream to supercritical flow over the mountain. Smith (1985) constructed a new theory of severe downslope winds which made use of Long's equation in the strongly disturbed low-level flow. His analytic model link downslope windstorms to breaking waves in a continuously stratified atmosphere by solving Long's equation subject to the assumption that the overturning region is well mixed so that the density in that region is constant. The vertical profile in density is the most obvious difference between Long's and Smith's models. The improvement of the theory was done by Smith and Sun (1987). The non-linear steady state solutions for stratified two layer flow over a ridge proposed by Smith and Sun encompass any distribution of stability. In parameter space these solutions lie between the interfacial case of Long and the constant stratification case of Smith (1985).

The results of the theory application to five APLEX bora cases (Smith, 1987; Smith and Sun, 1987) indicate an internal hydraulic mechanism for the bora, with the mountains partially controlling the flow upstream and a turbulent layer helping to decouple the descending layer from the less disturbed flow aloft. The estimation of flow parameters was done by using the aircraft data and radiosounding data from Zagreb only in terms with aircraft measurements. In this paper the application of internal hydraulic theory will be extended to all terms with NE wind in the upstream bora region (from 5 March 03 GMT to 7 March 18 GMT).

In the generalized two-layer model Smith and Sun considered the incompressible stratified flow which approaches a ridge with uniform speed. The stability profile consists of two layers of constant stability. They presumed that the fluid selects a certain critical streamline in the upper layer to serve as the top of the disturbed flow. The height of this disturbed flow (upstream bora layer height H_o) is difficult to define by using the sounding data far upstream from the mountain top. In the considered case we have defined H_o height in two ways: 1) as a level where NE "bora component" ($45^o \pm 90^o$) is vanishing H_{01} and 2) as a level where the wind direction differs from 15^o - 105^o H_{02} (same as in Smith, 1987). In Fig. 12 we indicated H_{01} and H_{02} in three terms: 5 March 06 GMT (the bora onset on the northern Adriatic), 6 March 15 GMT (first bora flight) and 7 March 12 GMT (second bora flight). The same was done for a mean vertical atmospheric structure over Zagreb and Karlovac (Fig. 13).

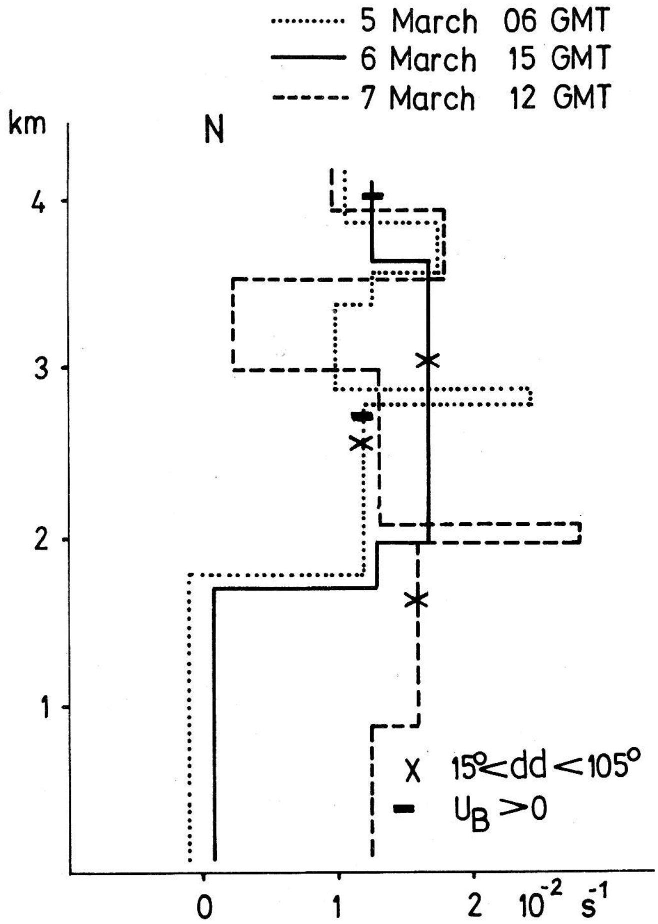
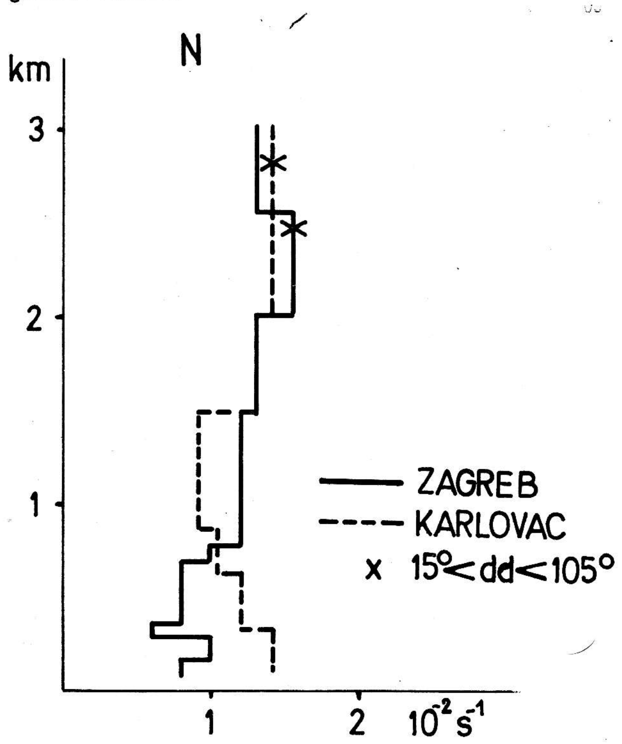


Fig. 12. Vertical profiles of the Brunt-Väisälä frequency over Zagreb.
Sl. 12. Vertikalni profili Brunt-Väisälä frekvencije nad Zagrebom.

The mean values of potential temperature, wind speed and direction on standard geometrical levels were obtained by using all available sounding data for the time period between 5 March 03 GMT and 7 March 18 GMT. The assumption that the flow is in steady state during the entire bora period allow us to use Smith's theory in the appropriate way. The description of atmospheric structure given in the previous section shows that the steady state approximation is not unresonable. At the beginning of the NE flow the difference between H_{01} and H_{02} is negligible. Later on this difference becomes greater. Because of the SE wind above the bora layer on 7 March the NE wind component exists throughout the troposphere but the wind direction exceeds 105^o at 1550 m. According to this H_{02} is more appropriate for the critical level height in the considered situation with SE wind above lower bora layer. The H_{01} and H_{02} heights are given in Table 2.



Sl. 13. Srednji vertikalni profili Brunt-Väisälä frekvencije nad Zagrebom i Karlovcem za razdoblje 5-7. ožujak 1982.

Fig. 13. The mean vertical profiles of the Brunt-Väisälä frequency over Zagreb and Karlovac for 5-7 March 1982.

Because of the short distance between Zagreb and Karlovac the difference in mean atmospheric structure is not large.

The next step in theory application is the determination of stability stratification. As we can see in

Table 2. H_{01} and H_{02} heights over Zagreb.
Tabela 2. Visine H_{01} i H_{02} nad Zagrebom.

Time	H_{01}	H_{02}
5 M 06 GMT	2650 m	2500 m
6 M 15 GMT	3950 m	3000 m
7 M 12 GMT	11650 m	1550 m
5 - 7 M (mean)	3700 m	2500 m
Karlovac		
5 - 7 M (mean)	3800 m	2800 m

Fig. 12 the stability profiles over Zagreb in the three considered terms consist of two layers of constant stability. The generalized hydraulic theory requires the neutral lower layer. According to given stability profiles the assumption that $N_1=0$ is realistic. The upper (d) and lower layer (H_a) thicknesses together with the upper layer stability N_2 (given in terms of the Brunt-Väisälä frequency), mean wind speed in the whole bora layer U and Scorer parameter $l_2=N_2/U$ are given in Table 3.

The mean wind speed in the upstream bora layer U represents a weighted average throughout the layer. The assumption that the upstream flow has constant speed is questionable here because of the relatively pronounced wind speed maximum in the bora layer (Fig. 8). The failure to take into account the existing wind shear could lead to difficultes in the theory application and its successfulness.

The θ_c values given in Table 3. are measured potential temperatures on the top of the critical layer.

According to hydraulic theory, a certain relationship must exist between upstream wind, depth, stratification, and mountain height, whenever the airflow accelerates over the ridge crest. For two layer atmosphere this is given by

$$\frac{h}{H_{eff}} = 1 + 1/2\, F_o^2 - 3/2\, F_o^{2/3}$$

where h is a mountain height

$$H_{eff} = H_a + \gamma d, \quad F_o^2 = \frac{U^2}{N_2^2\, d\, H_{eff}}$$

Table 3. The vertical atmospheric structure parameters over Zagreb

Tabela 3. Parametri vertikalne strukture atmosfere nad Zagrebom.

Time	H_a (m)	d (m)	$r=\frac{d}{H_a}$	N_2 (s^{-1})	θ_c (K)	U (ms^{-1})	l_2 (m^{-1})
5 March 06 GMT	1700	800	0.47	0.012	288	7	1.7×10^{-3}
6 March 15 GMT	1700	1300	0.76	0.017	289	13	1.3×10^{-3}
7 March 12 GMT	850	700	0.82	0.016	282	9	1.8×10^{-3}

Table 4. The measured and the theoretical values of F_o, d and h.

Tabela 4. Izmjerene i teoretske vrijednosti F_o, d i h.

Time	h (m)	$\hat{h}$	$\hat{d}$	$\hat{H}_a$	F_o	F_ox	d_p (m)	h_p (m)
5 March 06 GMT	800	1.36	1.36	2.89	0.45	0.29	1640	410
6 March 15 GMT	800	1.04	1.69	2.21	0.43	0.33	2150	420
7 March 12 GMT	800	1.44	1.26	1.53	0.63	0.10	2110	100

$\hat{h} = h \times l_2$ $\hat{d} = d \times l_2$ $\hat{H}_a = H_a \times l_2$

For $\gamma = 0.5$ (same as in Smith and Sun, 1987) and other parameters given in Table 2. we can caculate H_{eff}, F_o^x predicted by hydraulic theory for known h and H_{eff} (Table 4). The generalized hydraulic theory is intended for r=1. In all of the three considered cases the r values are not far from 1 making the theory application possible.

The theoretically predicted height of the split streamline (d_p) and the values of h which would be associated with the observed d (h_p) are also given in Table 4.

The obtained values show reasonably good agreement with theory, considering the complicated wind and stability vertical structure in the real atmosphere. The theoretically obtained F_o^x is smaller than F_o in all considered terms. The smallest difference is noticed on 6 March (term with the strongest bora) which is a good indicator of the possible jump on the lee according to the critical flow at the mountain top and supercritical somewhere on the lee side. The Froude number F_o obtained for 7 March indicate an unsteady state with the supercritical flow instantaneously at the mountain top, although remaining subcritical upstream and downstream. This is in accordance with bora weakening on 7 March.

The tendency of the theory to overestimate the depth of the accelerating layer could be seen in all terms. The same was remarked by Smith and Sun (1987). The difference between measured and theoretically predicted values of d was the greatest at the bora ending time.

All of the presented results show that the application of internal hydraulic theory is not justified at the time of bora weakening.

The mean stability profile over Zagreb and Karlovac does not show a two layer structure. These upstream profiles could be fit by eye with a constant stability layer. For such a case the hydraulic theory equations are given by Smith (1985). For the theory application the upstream flow is assumed to have a constant speed U and constant stability N_o which are shown in Table 5. The critical level height H_o and potential temperature at that level θ_c (streamline which splits over the mountain) are also given in Table 5.

According to theory the next relationship between H_o and h (mountain height) must exist (see Vučetić in this Volume).

The mentioned hydraulic parameters together with $F_o = U/N_oH_o$ are given in Table 6.

As we can see the predicted H_o^x is heigher than measured by about 1800 m. According to this the F_o^x is smaller than F_o but not too much considering all the approximations we have done (constant U and N).

Following Smith (1985) we can calculate the vertical displacement of the lower dividing streamline above the crest δ_c. Using H_o^x for Zagreb we obtained $\delta_c = -1100$ m and for Karlovac $\delta_c = -1170$ m. With the approximation that the final terrain height in the lee is the same as upstream we can calculate the vertical displacement of the lower dividing streamline δ_{c1}, and the vertical wind profile on the lee side of the mountain (Table 7).

H_1^x is the height at which the wind speed is the same as upstream. The obtained H_1^x values do not differ considerably from mean Pula wind profile which is at z = 2000 m wind speed of 14.5 ms^{-1}. Considering the maximum wind gusts (hourly) in Senj and Omišalj the obtained u values for z=o m are somewhat overestimated but nevertheless they do not seem unreasonable.

Having H_o^x and H_1^x we can get the pressure drag on the mountain per unit length as a measure of strength of the transitional flow. Following Smith's expression for the drag and using $\rho = 1$ kg m^{-3}, N = 0.012 s^{-1} and $H_o^x - H_1^x$ = 2700 m (according to Zagreb's mean vertical atmospheric structure):

$$D = 472 \times 10^3 \text{ kg s}^{-2}$$

Table 5. The parameters of mean atmospheric structure over Zagreb and Karlovac for 5-7 March 1982.

Tabela 5. Parametri srednje strukture atmosfere nad Zagrebom i Karlovcem za 5 - 7. ožujak 1982.

5-7 March (mean)	U	N_o	H_o	θ_c	$l=N_o/U$
	ms^{-1}	(s^{-1})	(m)	(K)	(m^{-1})
Zagreb	12.5	0.012	2500	287	0.0010
Karlovac	14.0	0.013	2800	289	0.0009

Table 6. The hydraulic parameters for mean atmospheric structure over Zagreb and Karlovac for 5-7 March 1982.

Tabela 6. Hidraulički parametri srednje strukture atmosfere nad Zagrebom i Karlovcem za 5 - 7. ožujak 1982.

5-7 March (mean)	h	$\hat{h}$	$\hat{H}_o$	F_o	H_o^x	F_o^x
	(m)				(m)	
Zagreb	800	0.80	2.50	0.40	4285	0.24
Karlovac	800	0.72	2.52	0.40	4549	0.24

Table 7. The theoretically obtained vertical wind profile for the mean atmosphere over Zagreb and Karlovac in the period 5-7 March 1982.

Tabela 7. Teoretski dobiven vertikalni profil vjetra za srednju strukturu atmosfere nad Zagrebom i Karlovcem u periodu 5 - 7. ožujak 1982.

		wind speed u				
	δ_{c1} (m)	z=0m	z=100 m	z=500 m	z=H_1^x	H_1^x (m)
Zagreb	-2720	46.5	46.3	42.3	12.5	1570
Karlovac	-2810	49.4	49.3	45.9	14.0	1745

For the 800 m high mountain this is equivalent to an average pressure difference across the mountain of 5. 9 hPa. The calculated pressure difference is very simillar to the mean pressure difference between Zagreb and Pula for the time period of 5-7 March which is 6.7 hPa.

This means that the contribution to the total pressure difference produced by splitting and descending of the lower part of the bora layer is here very large.

All presented results show that the internal hydraulic theory can rather succesfully describe the strong bora apperance in the situation with strong postfrontal bora on the entire Adriatic Coast. Only the time when bora was weakening the hydraulic theory application is not justified.

5. CONCLUSION

The most intense lee cyclogenesis during the APLEX-SOP (4-5 March 1982) caused the strongest bora on the Adriatic Coast. Bora was observed along the northern and middle Adriatic with maximum gusts in Omišalj (35.2 ms^{-1}) and Senj (31. 8 ms^{-1}). The longest bora duration observed in Senj is a common feature for most bora cases due to Senj's specific location near Vratnik Pass. Onset of bora was accompanied by a sudden drop of relative humidity, a decrease in temperature and increase in pressure. Vertical atmospheric structure in the upstream bora region shows the existance of stable layers inside and above the NE wind flow. The SE wind aloft decouples the upper and lower regions and prevents disturbances aloft. The observation of stable layer descent from upstream to the downstream region is consistent with upstream acceleration measured during the aircraft measurements. Research flights which occurred on 6 and 7 March were performed mainly above the northeasterly bora flow and therefore they could not give real insight into the intense low level bora structure.

The results of the generalized hydraulic theory application in three time periods (at the bora beginning, at the time with the strongest bora and at bora ending) show that this theory can rather successfully describe the severe wind appearance in the situation with strong postfrontal bora on the Adriatic coast, except at the time when bora was weakening. The assumption that the flow is in the steady state during the entire bora period allowed us to use the generalized hydraulic theory on the main atmospheric structure in the upstream bora region. The mean vertical profiles show the constant stability layer with the critical dividing streamline on 2.5 km over Zagreb and 2.8 km over Karlovac. The theory overestimated the height of disturbed bora flow. In spite of this, the theoretically obtained vertical wind profiles on the lee side of the mountain barrier did not differ considerably from the mean Pula wind profile and maximum wind gusts measured in Senj and Omišalj.

We can conclude that the theoretically predicted hydraulic parameters show reasonably good agreement with observed values considering the complicated wind and stability vertical structure in the real atmosphere.

The main problem we encountered was the determination of mean wind speed in the bora layer. The constant upstream wind speed assumption is questionable here because of the observed pronounced wind shear in the upstream bora layer. The failure to take into account the existing low level wind maximum was probably the main reason for the obtained differences between observed and theoretical bora parameters.

Acknowledgements: This paper is based on research supported by the U.S.-Yugoslav Joint Fund for Scientific and Technological Cooperation in cooperation with the NSF under Grant JF 735.

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KRATAK SADRŽAJ

Najjača bura u ALPEX-SOP opažena je na sjevernom Jadranu u razdoblju od 5. do 7. ožujka 1982. Njenoj pojavi prethodila je intenzivna postfrontalna ciklogeneza u Genovskom zaljevu. Sjeveroistočni vjetar zabilježen je u ovoj situaciji duž čitave jadranske obale, a njegovo najdulje trajanje u Senju posljedica je specifične lokacije Senja podno Vratnika.

Analiza osnovnih meteoroloških parametara pri tlu pokazala je da pojava promatrane bure prati nagli pad relativne vlage, pad temperature i porast tlaka zraka. Istovremeno vertikalnu strukturu smjera i brzine vjetra, kako u navjetrini, tako i u zavjetrini, karakterizira pojava maksimalnih brzina unutar sloja NE strujanja te promjena smjera na SE iznad 2-3 km. Spuštanje sloja u kojem je smjer vjetra unutar granice od 15° do 105°, kao i spuštanje temperaturne inverzije unutar sloja bure u zavjetrini u odnosu na navjetrinu u skladu s hidrostatičkom aproksimacijm, ukazuje na pojavu akcelaracije strujanja već u navjetrini Dinarida, što je opaženo, kako u analizi prizemnih tako i u analizi avionskih podataka.

U postojećim teoretskim razmatranjima (Smith, 1985; Smith i Sun, 1987) hidraulički mehanizam naglašen je kao osnovni mehanizam koji opisuje dinamičke karakteristike bure kao olujnog vjetra. Primjena generalizirane hidrauličke teorije u određenim vremenskim periodima puhanja bure (5. ožujka u 6 GMT, 6. ožujka u 15 GMT i 7. ožujka u 12 GMT) pokazala je da ova teorija uspješno opisuje pojavu bure, osim u periodu njenog slabljenja. Pretpostavka da je strujanje stacionarno za čitavo vrijeme trajanja bure omogućila nam je da generaliziranu hidrauličku teoriju primijenimo i na srednje stanje atmosfere. Prosječne vrijednosti potencijalne temperature, smjera i brzine vjetra dobivene na standardnim geometrijskim visinama ukazale su na postojanje sloja konstantne statičke stabilnosti ograničenog tzv. kritičnom strujnicom (razdvaja turbulentno strujanje u sloju bure od onog iznad njega) na 2.5 km nad Zagrebom i 2.8 km nad Karlovcem. Iako su teoretski dobivene vrijednosti visine kritičkog nivoa precijenjene, teoretski izračunate prizemne brzine vjetra u zavjetrini (46.5 m/s) ne razlikuju se znatno od zabilježenih maksimalnih udara bure (35.2 m/s^{-1}).

Rezultati primjene generalizirane hidrauličke teorije ohrabruju, budući da je vertikalna struktura vjetra i temperature u stvarnoj atmosferi znatno složenija od one koju zahtijeva teorija. Teorija koja bi uključivala realniju vertikalnu strukturu atmosfere u navjetrini (osobito znatno smicanje vjetra) vjerojatno bi dala vrijednosti osnovnih hidrauličkih parametara manje različite od onih opaženih.