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APPLICATION OF THE HYDRAULIC THEORY IN CASES OF BORA WITH STRONG UPSTREAM FLOW

Primjena hidraulične teorije na bure sa snažnom strujom zraka u navjetrini

VANDA GRUBIŠIĆ
Geofizički zavod PMF-a, Zagreb
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Abstract: Two cases of strong bora on the southern and the northern Adriatic coast, 2 – 3 December 1983. and 10 – 11 February 1984, related to the strong upstream wind conditions, are presented. The bora was caused by a strong cold air inflow from the northeast resulting from a large scale synoptic situation characterized by an anticyclone over western Europe and a cyclone over the Adriatic.
The application of Smith's (1985) hydraulic theory shows that these bora cases are characterized by strong wind in the deep upstream bora layer and low effective mountain height.
The hydraulic theory proved appropriate in considering the observed effects in spite of poor steady-state approximation. Much greater descrepancies from the theory are observed in the bora case of February 1984.
Key words: bora, hydraulic theory, wind, upstream region.

Sažetak: U radu su prikazane situacije s jakom burom na sjevernom, srednjem i južnom Jadranu, 2 – 3. prosinca 1983. i 10 – 11. veljače 1984, od kojih je posebno poslijednja poznata po izuzetno velikoj brzini vjetra u navjetrini. Bure su uzrokovane jakim prodorom hladnog zraka sa sjeveroistoka u okviru vrlo sličnog razvoja sinoptičkih situacija s anticiklonom nad zapadnom Evropom i ciklonom nad Jadranom.

Primjena Smithove (1985) hidrauličke teorije pokazuje da su ovo situacije s velikom brzinom vjetra u dubokom sloju bure u navjetrini, što rezultira malom efektivnom visinom planine.

Hidraulička teorija dobro opisuje opažene efekte unatoč nestacionarnosti situacija. Veća odstupanja od teorije su u slučaju bure iz veljače 1984.
Ključne riječi: bura, hidraulička teorija, vjetar, navjetrina.

1. INTRODUCTION

Theoretical work on the dynamics of the bora phenomenon has recently been intensified due to the first in situ aircraft observations on the North Adriatic coast. Observations were carried out during the special observation period of Alpine experiment (ALPEX-SOP) in March and April 1982.

Smith (1985) and Smith and Sun (1987) presented the hydraulic theory as an explanation of the severe downslope wind structure and proposed its application to bora and Boulder windstorms. The first observational studies of the soundings data showed that the hydraulic theory may be applied to the ALPEX bora cases (Pettre, 1984). Further and more firm evidence is given in the study of aerial observations of ALPEX bora cases (Smith, 1987, Smith and Sun, 1987).

On the other hand detailed analysis of soundings and the surface stations data resulted in a series of studies (Jurčec, 1984, 1987; Vučetić, 1984, 1985) which pointed to the common bora features as well as to the special characteristics determined by the macro- and meso-scale conditions. Recent studies of Bajić (1988), Vučetić (1988) and Tutiš (1988) have shown that the application of the hydraulic theory is successful in the case of »postfrontal« bora. Jurčec (1988) stressed the problem of the »frontal« type of bora and in a case study 11 – 12 March 1982 (Jurčec and Visković, 1989) showed that it can also be explained by the hydraulic theory.

The purpose of this paper was to examine the applicability of hydraulic mechanism in bora cases with strong upstream flow. Two bora cases are presented: 2 – 3 December 1983 and 10 February 1984, known as the »Olympic Game Storm«.

2. SYNOPTIC SITUATION AND VERTICAL TROPOSPHERIC STRUCTURE IN BORA CASES

The description of the synoptic situation as well as the analysis of the distribution of relative vorticity, horizontal divergence and vertical velocity in the lower troposphere for these two bora cases have already been published (Letinić-Sabljak and Razumović, 1985: Poje, 1984: Razumović et al.,1984). Therefore, only the main features of these situations will be presented here.

2.1. Bora case 01-03.12.1983.

2.1.a) Synoptic situation

The synoptic situation in this period was characterized by the presence of two large baric centers: strong anticyclone with a center of 1040 hPa in Central Europe and a cyclone with a center of 1000 hPa in the southern Adriatic. In the middle troposphere a trough, layed along the line connecting surface centers, was deepening and cold air was drifted from Central Europe to the Mediterranean. As the anticyclone moved eastwards, a strong pressure gradient formed on the east Adriatic coast and bora began on the 1st December on the southern Adriatic coast. During the next day anticyclone continued progressing toward the east, the pressure in its center raised and the pressure gradient across the coast became even stronger. This resulted in stronger bora which appeared also in the middle and northern parts of Adriatic coast. While the bora was ceasing on the southern coast during the 3rd, it strengthened on the northern coast due to the cold air inflow in its upstream region, connected to the further raise of pressure gradient across the northern coast alone.

The strongest wind gusts during the 2nd were up to 40 ms^{-1} along the entire coast. The next day the wind gusts were about 20 ms^{-1} on the southern coast and somewhat higher than 40 ms^{-1} on the northern coast. The exception in this maxima distribution is Tito's Bridge location (laying between the island of Krk and the coast) where during the first day wind gusts reached 50 ms^{-1} and in the 3rd December maximum of 54.5 ms^{-1} was registred.

2.1.b) Verical tropospheric structure over Zagreb

The analysis of the vertical tropospheric structure during this period is based on 00 GMT Zagreb soundings. The vertical profiles of wind, temperature, potential temperature and stability for the 2nd and 3rd December are shown in figure 1.

On the 1st December (not shown) weak NE flow was confined to the shallow layer. On the next day northeasterlies extended up to 10 km intensifying with height and possessing the low-level jet structure with the maximum of 23.3 ms^{-1} at 1400 m. On the 3rd December wind direction gradually changed with height. It began as the north-easterly at the ground but already at 2 km shifted to the easterlies which extended throughout the rest of the troposphere.

Two stabile layers on the 2nd and as many as four stabile layers on the 3rd December can be seen in vertical profiles of potential temperature and stability which is expressed in terms of Brunt-Väisälä frequency

$$N^2 = \frac{g}{\theta}\frac{\partial \theta}{\partial z}$$

Existence of more than one stabile layer in the upstream region is an already established bora characteristic (Jurčec, 1987; Vučetić, 1985).

2.2.Bora case 10.02.1984. – Olympic Game Storm

2.2.a.) Synoptic situation

The synoptic situation, as in the previous case, is determined by the presence of the deep cyclone with a center of 980 hPa in the southern part of the Adriatic Sea, and strong anticyclone with a center of 1040 hPa above Biskaya Bay whose ridge was intensifying above Central Europe. The cold upper air advection in pronounced

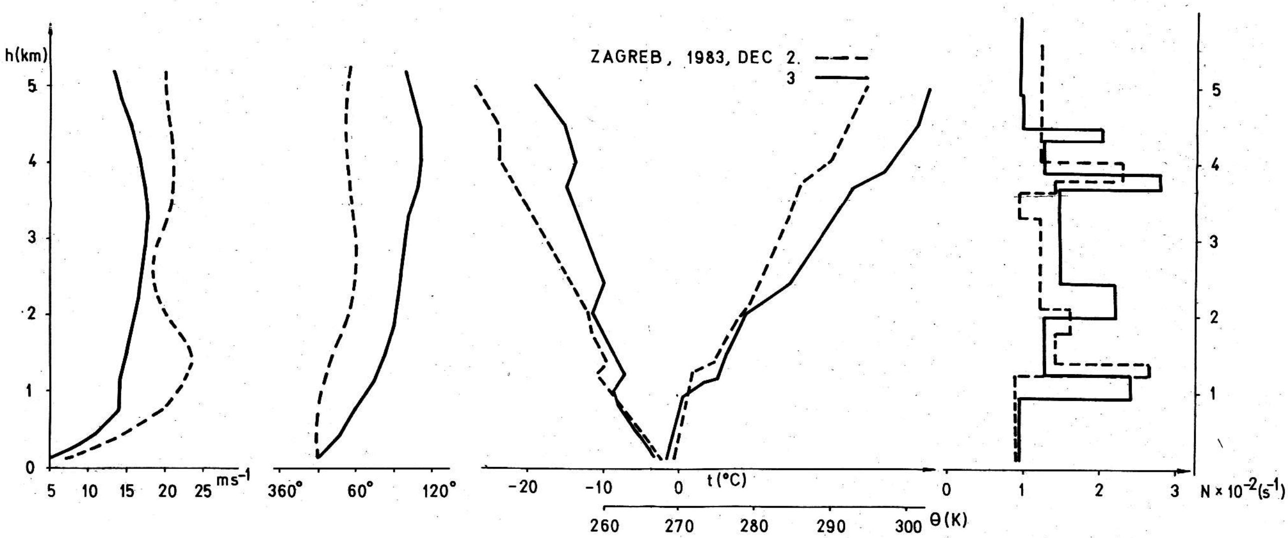

Fig. 1. Vertical profiles of wind speed (ms^{-1}) and direction, temperature (t in °C), potential temperature (θ in K) and static stability (N in 10^{-2} s^{-1}), Zagreb-Maksimir, 2-3 December, 1983.

Sl. 1. Vertikalni profili brzine (ms^{-1}) i smjera vjetra, temperature (t u °C), potencijalne temperature (θ u K) i stabilnosti (N u 10^{-2} s^{-1}). Zagreb-Maksimir, 2-3, prosinca 1983.

meridional flow over the European continent stimulated the cyclogenetic process in the southern Adriatic which spanned the whole troposphere.

As the anticyclone moved eastwards, the cyclone stayed almost stationary and the zone of large horizontal pressure gradients moved to the Alpine region. In the lower troposphere east of the Alps a strong cold advection toward northern Yugoslavia took place. All previously mentioned factors led to exceptional weather conditions with gale winds in northern Croatia, dense snowfall in the central and eastern parts of Yugoslavia and strong bora on the coast which started already on the 9th February but the maximum was reached at the beginning of the 10th. During the 10th the bora was the most intense on the southern coast where the strongest wind gusts up to 40 ms^{-1} were recorded for several hours. On the middle and the northern coast maxima gusts were up to 30 ms^{-1}, except Tito's Bridge location again, where the maximum gust of 39.5 ms^{-1} was recorded for only one hour. The next day the cyclone moved to the east and bora persisted during the next few days with lower and very variable wind speed.

2.2.b) Vertical tropospheric structure over Zagreb

The vertical profiles of the same parametars as in the former case, for 9-11 February for Zagreb at 00 GMT are shown in fig. 2.a),b).

The wind direction on the 10th February was approximately NNE in the lowest 4500 m. Further up it gradually turned to the ESE direction. In the layer of northeasterlies the wind speed had jet structure with a maximum of 43 ms^{-1} at 2000 m. As high wind speed at such a low level is rarely observed over Zagreb (Poje, 1984). The wind speed was again increased in the ESE layer, so that these two layers could clearly be distinguished. Potential temperature and stability profiles indicate a 2 km deep layer of neutrally stratified atmosphere capped with shallow inversion and stabile layers aloft.

On the next day northeasterlies extended through the whole troposphere but were significantly weaker, while the potential temperature profile was not significantly changed, except for slight lowering of the stabile layers.

3. APPLICATION OF HYDRAULIC THEORY

3.1. Basic relations

Hydraulic theory is a steady-state, nonlinear hydrostatic theory which describes the flow of fluid over an obstacle. One of the possible solutions to the former problem is a flow which is accelerated in both the upstream and downstream region of an obstacle leading to the occurence of severe wind in the lee side. The first analysis of observations of ALPEX bora cases (Pettre, 1984; Smith, 1987) showed that hydraulic theory may be relevant to bora.

For the case of continualy accelerating flow over an obstacle according to hydraulic theory a particular relationship between upstream wind, depth and stratification of fluid and the height of an obstacle can be derived. There exist two mathematical models of hydraulic flow by which the former relationship can be derived analitically.

One is Long's (Long, 1954, hereafter L54) two-layer model with a neutral shallow layer capped by a thin density interface and a deep layer aloft. The upper mentioned relation in this model is:

$$(1/2)F_o^2 - (3/2)F_o^{(2/3)} + 1 = h^{\div}H^{-1}, \tag{1}$$

where $h^{\div}$ is the critical mountain height, H_o is the depth of the upstream flow which equals to the depth of the neutral layer. F_o is the Froude number given by $F_o=U_o(g'H_o)^{1/2}$ as a ratio of upstream constant wind velocity U_o to the speed of internal gravity waves. g' is a reduced gravity defined by $g'=g(\theta'-\theta)/\bar{\theta}$, where θ, θ' and $\bar{\theta}$ are potential temperatures at the base, on the top and mean value in inversion, correspondingly. g is the acceleration of gravity.

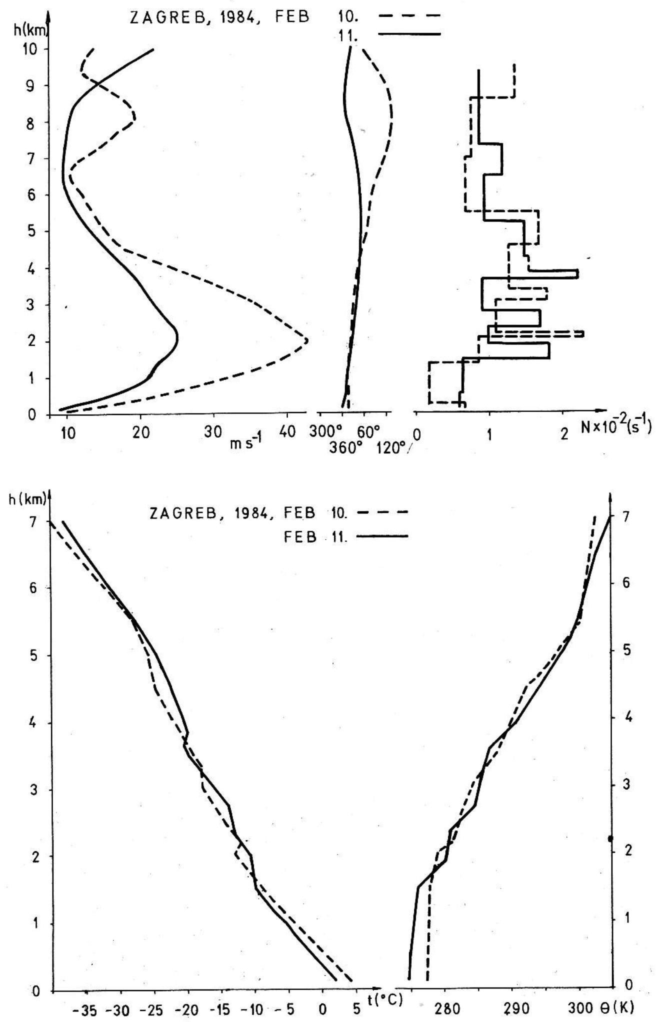

Fig. 2. a) Vertical profiles of wind speed (ms^{-1}) and direction and static stability (N in 10^{-2} s^{-1}), Zagreb-Maksimir, 10-11 February, 1984.

Fig. 2. b) Vertical profiles of temperature (t in °C)and potential temperature (θ in K), Zagreb-Maksimir, 10-11 February, 1984.

Sl. 2. a) Vertikalni profili brzine (ms^{-1}) i smjera vjetra, i stabilnosti (N u 10^{-2} s^{-1}). Zagreb-Maksimir, 10-11. veljače 1984.

Sl. 2. b) Vertikalni profili temperature (t u °C), potencijalne temperature (θ u K). Zagreb-Maksimir, 10-11, veljače 1984.

The other model was derived by Smith (1985), (hereafter S85). It describes a decouplig of the low level accelareted laminar flow from the undisturbed flow aloft by a slowly moving and highly turbulent region. This decoupling begins already upstream of the mountain crest in the layer of constant stratification and continues farther downstream.

The demanded relationship in this model is:

$$\hat{H}_o = \hat{h}^* - \delta^* + \arccos(\hat{h}^*/\delta^*), \tag{2}$$

$$\delta^* = -2^{-12} [\hat{h}^{*2} + \hat{h}^* (\hat{h}^{*2} + 4 —^{1/2}]^{1/2}, \tag{3}$$

where $\hat{H}_o = lH_o$, $\hat{h} = lh$, $\hat{\delta}^* = l\delta^*$ are nondimensional quantities.

$l = N_o/U_o$ where N_o is constant static stability in the upstream layer. U_o, h and H_o have the same meaning as before. δ^* describes the lowering of the, so called, critical streamline above the mountain crest. The critical streamline represents the upper boundary of the descending flow which is being accelerated.

For the symetrical mountain shape the velocity U_1 at the horizontal distance x_1 in the downstream region where the terrain is horizontal and its height is the same as before the mountain is:

$$U_1 (x_1,z) = U^o (1 - \hat{\delta}_{c1} \cos lz) \tag{4}$$

$\hat{\delta}_{c1}$ represents the height by which the critical streamline is lowered at the horizontal distance x_1. In case when the terrain height downstream from an obstacle is different from the upstream height, the wind speed, according to the S85 model, will be greater or lower than U_1 given in (4), depending on the sign of the height difference. In case of lower downstream terrain height the higher velocity is predicted and vice versa.

The pressure difference across the mountain is caused hydrostatically by the lowering of the critical streamline which in turn be observed as a high mountain drag. The mountain drag can be calculated from:

$$D = \varrho N^2 (H_o - H_1)^3/6 \tag{5}$$

ϱ is air density and H_1 is the depth of accelerated flow at the downstream point x_1.

It is further shown that both of these models can be derived as special cases of the generalized hydraulic model (Smith and Sun, 1987), hereafter SS87. The structure of this model greatly resembles the S85 model, except that it deals with two layers of different stability in the upstream region with the critical streamline laying in the upper layer. If the lower layer is neutral and upper layer stable, the L54 model can be derived in the limiting case of the stable layer being thin compared to the total depth of the system, and the S85 model in the case of the thin neutral layer. In general, when the ratio of upper to lower layer thickness lies anywhere in interval $(0,\infty)$ numerical methods must be used.

From the analysis of the vertical tropospheric structure over Zagreb in the former section, where it is assumed that Zagreb conditions are representative for the upstream region, it results that in the bora case of 2-3 December the S85 model can be applied while in the case of the 10 February both SS87 and S85 models under proper approximations become suitable.

The hydraulic parametars of the SS87 model using appropriate input parametars are obtained from the solution graphically presented in SS87.

3.2. Determination of the upstream bora parametars

To calculate hydraulic parametars for a particular bora case for known mountain height using relations (2) and (3), velocity and air stability have to be determined from the data of vertical structure in the upstream region. These are calculated as weighted averages in the corresponding vertical layers.

The actual bora height H_o is determined from the upstream data using the empirically founded criterions which are based on common upstream wind and stability profile characteristics of bora situations. According to Yoshino (1976) the bora layer is defined as the layer where the wind direction lies in the interval [0,90]. Smith (1987) defines it as a height where the wind direction becomes equal to 105°[60+45] and according to Jurčec (1988) it is the height where the NE component of wind u_B becomes equal to zero. In recent papers the later two criterions are more frequently used. In the a priori determination of the upstream bora depth H_o, the vertical profile of stability can also be used, because the top of the bora layer often tends fo coincide with the location of well defined inversion.

However in case when the NE wind extends through the whole troposphere the upstream bora height cant be determined with significant accuracy or cannot be determined at all on the base of data of only one upstream sounding.

For the bora cases presented here a u_B component of wind as defined by Jurčec (1988) was positive throughout the whole troposphere so that the criterion $U_B=0$ couldn't be satisfied. Instead, H_o is determined as the height, where the wind direction becomes equal to 105° according to Smith (1987) or as a base of well defined inversion.

3.3. Results and discussion

3.3.a) Case 1, 2-3 December 1983

The wind direction profile of December 2 didn't possess required turning but from the wind velocity profile it could be concluded that H_o was higher than 2 km as the low level jet is expected to be found in the bora layer. According to stability profile it was located at 3700 m. On the next day the H_o couldn't be determined. The hydraulic parametars for case 1 are given in table 1.

The relations (2) and (3) are plotted in figure 3, which was taken from Smith (1987). The points for the ALPEX bora case of March 6 (marked as M6) and Boulder windstorm 11 January 1972 (B) were also taken over. The point for December 2nd (D2) is also included. The agreement with theory is resonably good in regard of complexity of the actual stability structure and partial violation of constant wind assumption.

In assesment of the comparability of the hydraulic and the real bora structure, aside of a priori determined bora height, the bora speed and the observed pressure difference Zagreb-Senj were used.

Table 1. Hydraulic parametars for 2-3 Decembar 1983. All heights, except δ^*, are rounded off to the nearest 50 metars. For explanation of symbols, see text.

Tabela 1. Hidraulički parametri za 2-3. prosinac 1983. Sve visine, osim δ^x, su zaokružene na najbližih 100 metara. Objašnjenja svih simbola se nalaze u tekstu.

							PREDICTED VALUES FOR			h = 800 m		
day	GMT	H_o m	N $10^{-2}s^{-1}$	U ms^{-1}	l $10^{-4}m^{-1}$	$\hat{h}$	F_o U/NH_o	H_o^* m	δ^* m	δ_{c1} m	H_1 m	U_1 ms^{-1}
2	00	3700	1.28	20	6.40	0.51	0.42	5600	−1270	−3100	2500	60
3	00	—	1.29	15	8.60	0.69	—	4700	−1140	−2850	1850	52

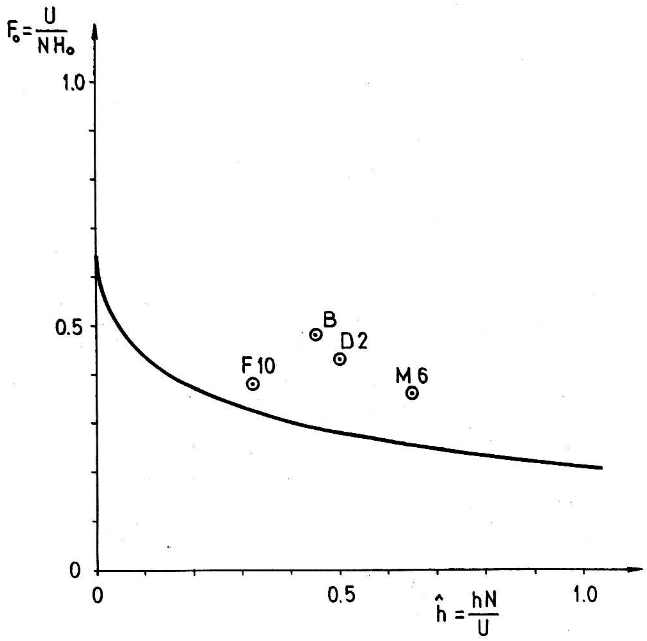

Fig. 3. A comparison of upstream conditions with the prediction of the S85 model [equations (2) and (3)]. Points M6 and B are overtaken from Smith (1987). D2 and F10 represent December 2 1983 and February 10 1984, respectively. Data are taken from Tables 1. and 4.

Sl. 3. Usporedba stanja u navjetrini s prognozom S85 modela [jednadžbe (2) i (3)]. Točke M6 i B su preuzete iz Smith (1987). D2, D3, F10 i F11 označavaju redom 2. i 3. prosinac 1983. te 10. i 11. veljače 1984. Podaci su uzeti iz tablice 1. i tablice 4.

In the last column of table 1 the wind speed U_1 is given. The calculated values are only comparable with the values measured at Krk location and the overestimation for December 2 can be noticed.

The mountain drag calculated from relation (5) and corresponding horizontal pressure differences are given in table 2. The agreement with the observed value for the 2nd December is satisfactory but it can be seen that the rise of the Zagreb-Senj pressure difference from the 2nd to the 3rd of December, which was caused by the renewed cold air inflow on the 3rd with the simultaneous lowering of the upstream wind speed, could not be reproduced by the hydraulic theory.

3.3.b) Case 2, 10-11 February 1984

On February 10 the top of the bora layer is determined as the height where the wind direction becomes equal to 105 as described in section 3.2. This gives H_o=6600 m which is unusually high for upstream bora conditions. On the other hand it is already known from Jurčec and Visković (1989) that in the situations with strong bora on the southern Adriatic coast the higher bora layer can be expected. On the next day H_o couldn't be a priori determined.

By the existence of three well-defined layers of different stability, as can be seen in figure 2.a), and treating the upper two stable layers as the one layer of mean stability, the prerequisite for the use of the SS87 model is fullfilled. The corresponding hydraulic parametars are shown in table 3.

It should be noted that the bora case 2 falls in the group of large r cases. The overestimation of predicted d^* equals 11% which is considerably smaller compared to 25% overestimate, especially in large r cases, obtained by Smith and Sun (1987) for Boulder windstorm and ALPEX bora cases.

Approximating the entire bora layer to be the layer of constant stability, the S85 model could be applied. The hydraulic parametars for case 2 are given in table 4, and corresponding point for February 10 is included in figure 3.

It can be seen that the discrepancy between empirically determined and the predicted value of H_o for the 10th February is now greater what is in accordance with the introduction of stability profile approximation. For February 11 both hydraulic models predict much lower upstream bora height and lee side wind speed than for the previous day. Although the agreement of H_o and H^* for February 10 is quite well the other two predicted quantities, wind speed U_1 and mountain drag with resulting horizontal pressure difference, are twice the observed ones. Nevertheless, the observed falling of bora wind speed from one day to another is correctly simulated by the calculated values.

The discrepancy between the observed and calculated wind speed and pressure drag is caused by the low sta-

Table 2. Mountain drag D, corresponding horizontal pressure difference for the mountain height h=800 m and maximal observed pressure difference Zagreb-Senj $\Delta p_{ZG\text{-}SENJ}$ for 2-3 December 1983.

Tabela 2. Planinski otpor i pripadna horizontalna razlika tlaka za planinu visine h=800 m, te maksimalna opažena razlika tlaka Zagreb-Senj za 2-3 prosinac 1983.

day	GMT	D 10^5 kg s^{-2}	ΔP hPa	$\Delta P_{ZG-SENJ}$ hPa
2	00	8.3	10.4	12.8
3	00	6.4	8.0	14.0

Table 3. Hydraulic parametars of the SS87 model for h=800 m, for 10-11 February, 1984. H_a is the depth of the lower neutral layer, d is the depth of the upper layer with stability N_2 and U is the constant wind speed in both layers.

Tabela 3. Hidraulički parametri SS87 modela uz h=800 m za 10. veljače 1984. H_a je debljina donjeg neutralnog, a d debljina gornjeg stabilnog sloja. N_2 je stabilnost u gornjem sloju, a U je konstantna brzina u oba sloja.

day	GMT	h m	H_a m	d m	N_2 $10^{-2}s^{-1}$	U ms^{-1}	l $10^{-4}m^{-1}$	r d/H	PREDICTED VALUES d* m
10	00	800	2000	4600	1.12	25	4.8	2.3	5100
11	00	800	1500	—	1.17	15	7.8	—	3400

Table 4. Hydraulic parametars for 10-11 February 1984. See table 1. for explanation.

Tabela 4. Hidraulički parametri za 10-11. veljače 1984. Sve ostalo isto kao i kod tabele 1.

day	GMT	H_o m	N $10^{-2}s^{-1}$	U ms^{-1}	l $10^{-4}m^{-1}$	$\hat{h}$	F_o U/NH_o	PREDICTED VALUES FOR h = 800 m: H_o^* m	δ^* m	δ_{c1} m	H_1 m	U_1 ms^{-1}
10	00	6600	0.99	25	3.96	0.32	0.38	7700	−1540	−3700	4000	62
11	00	—	1.09	15	7.27	0.58	—	5200	−1200	−3000	2200	48

bility and high wind speed (small l) which in turn according to the S85 model gives high upstream bora depth and deep lowering of the critical streamline. The observed horizontal pressure difference on February 10 of 5.6 hPa would be accomplished, with the same upstream stability and wind speed, by the lowering of the critical streamline for 3000 m which, according to the S85 model could happen for upstream bora depth H_o=7000 m and mountain height of 560 m. However even now the wind speed U_1, which equals 55 ms^{-1} is too high compared to the observed ones.

4. Conclusion

The analysis of two selected bora cases with strong upstream flow revealed several common features. Both boras were triggered by strong low level cold air inflow from the north or northeast. The bora onset was rapid while the upstream velocity had the low-level jet structure which was more pronounced as the cold air inflow was more intense. Bora was more severe on the southern than on the northern coast and it persisted for a next few days after the quasistationary situation was established.

The hydraulic parametars for both bora cases were calculated on days with the strongest bora on the coast. In spite of apparent unsteadiness and simplifications made on the actual vertical profiles of wind and static stability the application of hydraulic theory of Smith (1985) and Smith and Sun (1987) proved appropriate in account of observed effects. However, neglect of unsteadiness caused much greater discrepancies in the bora case of February 1984.

Both bora cases can be characterized by a deep upstream bora layer with strong incoming wind speed resulting in low effective mountain height – $\hat{h}$.

It should be emphasized that the presented hydraulic parametars apply to bora on the northern coast owing to the choice of Zagreb's conditions as a representative of the upstream region and estimate of average mountain height to be 800 m. This was apparently not critical when the hydraulic theory was applied on bora in December 1983, which showed transient behaviour from the southern to northern Adriatic bora. However it could be critical in the February case when the main bora was on the southern coast, the intense cold air inflow spanned a much larger area but gale winds appeared only in northern Croatia.

The discrepancy between the observed and theoretically predicted values of downstream wind speed and mountain drag in the February 1984 case requires further study.

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KRATAK SADRŽAJ

U ovome radu analizirana je mogućnost primjene hidrauličke teorije Smitha (1985) na bure koje su karakteristične po jakom vjetru u sloju bure u navjetrini. Prikazane su dvije situacije: 2-3. prosinca 1983. i 10-11. veljače 1984, poznata pod imenom »Olympic Game Storm«.

Analiza sinoptičkih situacija kao i vertikalne strukture troposfere nad Zagrebom ukazala je na nekoliko zajedničkih karakteristika. Bure su naglo započele prodrom hladnog zraka sa sjevera ili sjeveroistoka u donjoj troposferi. Profil brzine vjetra u navjetrini ima oblik niske mlazne struje koji je to jače izražen što je prodor intenzivniji. Bure su bile jače na južnom nego na sjevernom Jadranu i trajale su nekoliko dana nakon uspostavljanja kvazistacionarnog stanja.

Analiza profila stabilnosti pokazuje da su za buru u prosincu 1983. sa stabilnim slojem u navjetrini ispunjeni preduvjeti za primjenu hidrauličkog modela Smitha (1985). Vertikalna struktura s dva sloja različite stabilnosti (donji neutralni i gornji stabilni sloj) omogućava primjenu i generaliziranog modela (Smith and Sun. 1987) za buru u veljači 1984.

Za oba slučaja karakteristična je velika brzina u dubokom sloju bure u navjetrini, što uzrokuje malu efektivnu visinu planine.

Unatoč nestacionarnosti situacija hidraulička teorija u okviru svojih aproksimacija dobro opisuje opažene efekte. Međutim slaganje teoretskih i opaženih vrijednosti lošije je u slučaju bure u veljači 1984.