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THE ADRIATIC FRONTAL BORA TYPE

Frontalni tip bure na Jadranu

VESNA JURČEC
Hydrometeorological Institute of Croatia, Zagreb
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Abstract: The bora of 9 April 1982 on the northern Adriatic associated with the most pronounced cold air outbreak during the ALPEX SOP is presented and classified as the "frontal bora type" in terms of environmental **large scale** characteristics. The main **local** characteristics of this type are a sudden increase of bora speed and a brief duration.

In spite of the changes of the mesoscale flow characteristics in the shallow bora layer, as well as a stronger flow above the wind reversal level, the application of Smith's (1985) steady state hydraulic theory proved useful to describe the basic features of this phenomenon. The calculated hydraulic parameters are compared to those of the strong bora case of 11 March 1982 on the middle and southern Adriatic characterized by a deep bora layer, stronger incoming flow and lower effective mountain heights.

Although real atmospheric structure pinpoints to the numerous factors which could be incorporeted in the bora model, it is shown that the application of hydraulics is successful in many respects, and particularly as a guide toward classification of bora types and the essential differences in bora onset, intensity, duration and weather characteristics at different localities along the Adriatic coast.

Key words: bora, Adriatic wind, bora layer, hydraulic theory

Sažetak: Prikazan je slučaj bure od 9. travnja 1982. na sjevernom Jadranu povezan s najizraženijim prodorom hladnog zraka za vrijeme Alpskog eksperimenta (ALPEX-a). Ovaj slučaj bure je klasificiran kao "frontalni tip" u odnosu na karakteristike makro-razmjera. Glavne lokalne karakteristike ovoga tipa su nagli početak bure i njezino kratko trajanje.

Unatoč promjenama termodinamičkih karakteristika unutar sloja bure u mezorazmjerima, kao i jačem vjetru iznad sloja bure, primjena Smithove (1985) stacionarne hidrauličke teorije pokazala se korisnom pri opisu osnovnih značajki ovog fenomena. Izračunati hidraulički parametri su uspoređeni s parametrima za slučaj jake bure na srednjem i južnom Jadranu, 11. ožujka 1982. karakterizirane dubokim slojem bure, jačim navjetrinskim vjetrom i nižim efektivnim visinama planina.

Premda struktura stvarne atmosfere ukazuje na mnoge faktore koji bi trebali biti uključeni u model bure, pokazano je da je primjena hidraulike uspješna s različitih aspekata a posebno kao pomoć pri klasifikaciji tipova bure i znatnim razlikama u početku bure, njezinom intenzitetu, trajanju i karakterističnim lokalnim prilikama duž obale Jadrana.

Ključne riječi: bura, vjetar na Jadranu, sloj bure, hidraulička teorija.

1. INTRODUCTION

The main objective of the recent Adriatic bora study by the Hydrometeorological Institute of Croatia was a detailed analysis of bora cases during the special observation period of Alpine experiment (SOP ALPEX) in March and April 1982. The emphasis was on local conditions described by daily courses of wind, air temperature, humidity and pressure at the surface stations, and the upper air soundings which were available during the ALPEX SOP at three stations (Zagreb, Pula and Zadar) at sixhourly intervals, and for the intensive observation periods at three-hourly intervals at four stations (including Karlovac).

The preliminary studies (Jurčec, 1984; Vučetić, 1984, 1985) emphasized some local features and special characteristics under particular meso - and macro-scale conditions. Although the Adriatic bora is known by its severity and longevity, these are not the primary characteristics of all bora types and at all localities. In particular, the well known bora in Senj is not representative for the bora along the entire Adriatic coast due to the lower mountain height and very pronounced channeling effects at this locality.

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 Alps.

The objective of this paper is to call the attention of researchers to the "frontal" bora type characterized locally by a **sudden** bora speed increase. From this viewpoint it is an essential forecasting problem concerning the interpretation of local severe weather phenomenon in terms of large scale features.

The present study is necessarily incomplete since more cases of **severe bora storms** should be studied and their dynamic structure explored before we can claim to understand the frontal bora mechanism. Nevertheless the theory is beginning to develop and encouraging agreement is found.

A profound influence and a great step forward in our knowledge of bora dynamics was provided by Smith's results both from observational studies of ALPEX bora cases (Smith, 1987, hereafter **S87**) and theoretical approach to downslope wind structure based on hydraulic theory (Smith, 1985, **S85**, and Smith and Sun, 1987, **SS87**). Smith's analysis of five ALPEX bora cases shows good agreement with a mathematical description of common features indicated by severe wind's flow field.

The analysis of two postfrontal bora cases by Bajić and Vučetić in this Volume provide further proof for a successful application of Smith's theory in **postfrontal** bora condition where the concept of the mountain as a control point could explain the maintenance of severe wind state.

The striking result of our analysis is that in spite of a moving front and condition not strictly valid for a steady state hydraulic flow, bora layer depth and the other hydraulic parameters are very reasonable and stress the basic characteristics of the observed bora structure. This helps in better understanding of physical processes associated with bora phenomenon following the frontal passage and the cold air outbreak. The supply of cold air gradually changes the upstream bora condition and set the stage for a stronger postfrontal bora after a few days.

2. CASE STUDY 9 APRIL 1982 AND COMPARISON WITH POSTFRONTAL CHARACTERISTICS

2.1. Synoptic situation

Although we are mainly interested here in the case of 9 April when the front had passed across the entire area of Yugoslavia in a N-S direction, in some respects we will follow this case as long as bora was observed in order to emphasize the differences between the frontal and postfrontal bora features.

The surface front with a very cold air outbreak behind it was not only the most pronounced frontal system in the SOP but it was the strongest in April for at least 10 years 1973-1982 (Bajić, 1984).This case is also known for apparent flow splitting over the Alps and the most pronounced oreigenic blocking as shown by surface trajectories of Chen and Smith (1987).

The upper level flow on 9 April was characterized by a deep trough with an axis from the Baltic to the northern Adriatic (Fig. 1) moving slowly eastward with the surface front reaching the Adriatic Sea after 10 GMT.

More precise position of the front is seen in Fig. 2a with mesoscale analysis over Yugoslavia at 09 GMT indicating a rapid pressure rise behind the front. Fig. 2b shows a mesoscale map of the northern Adriatic at 13 GMT using the climatological stations, which illustrates a large variation in wind speed and direction along the coast and islands with a maximum bora in Senj.

2.2. Surface mesoscale characteristics

The intensity of the low-level frontal system could be seen from a large drop of temperature and humidity in the continental part of Croatia and the northern Adriatic. Fig. 3 illustrates a daily course of surface equivalent potential temperature in Zagreb-Maksimir and Senj. During several hours of front moving between Zagreb and Senj the θ_e - gradient was very large. For a comparison Fig. 3b presents the same course for the period 13-15 April indicating a smaller drop in temperature on 13 April and an almost constant value of θ_e during this period.

Mean hourly wind speed and maxima gusts in Senj for the same periods are shown in Fig. 4a. The essential feature on this graph is the sudden increase of the bora speed and gust characterizing the frontal passage. The bora was interrupted on 11 April and the second period, beginning on the next day, was marked by the less pronounced bora onset and almost constant mean wind speed.

In Fig. 4b gusts in Senj for the period 9 - 11 April are compared with those in Krk, Pula and Zadar which emphasize the largest bora speed and its longest duration in Senj under the same upstream condition.

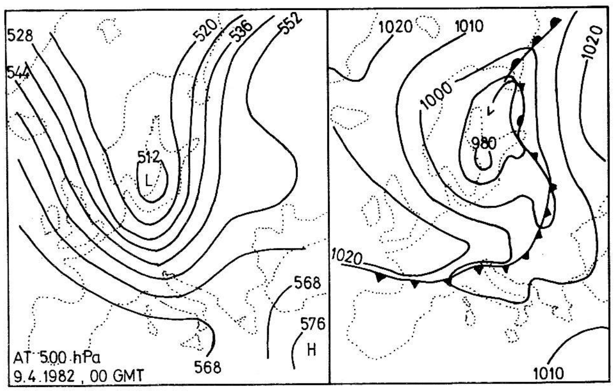


Fig. 1. 500 hPa and surface charts on 9 April 1982, OO GMT

Sl. 1. 500 hPa i prizemna sinoptička karta 9. 4. 1982, OO GMT

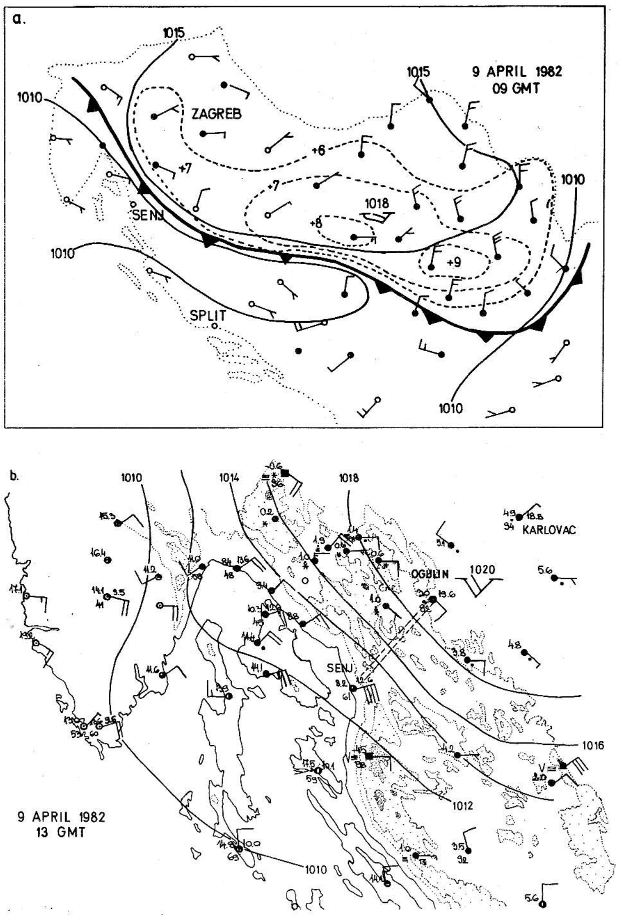


Fig. 2. Mesoscale surface charts on 9 April 1982: a) over western Yugoslavia with synoptic stations, front, isobars and isallobars, 09 GMT, and b) the northern Adriatic mesoanalysis on the basis of climatological stations, 13 GMT

Sl. 2. Prizemna mezoanaliza 9. 4. 1982: a) nad zapadnim područjem Jugoslavije sa sinoptičkim stanicama, frontama izobarama i izalobarama, OO GMT, i b) mezoanaliza na sjevernom Jadranu na osnovu klimatoloških stanica, 14 sati.

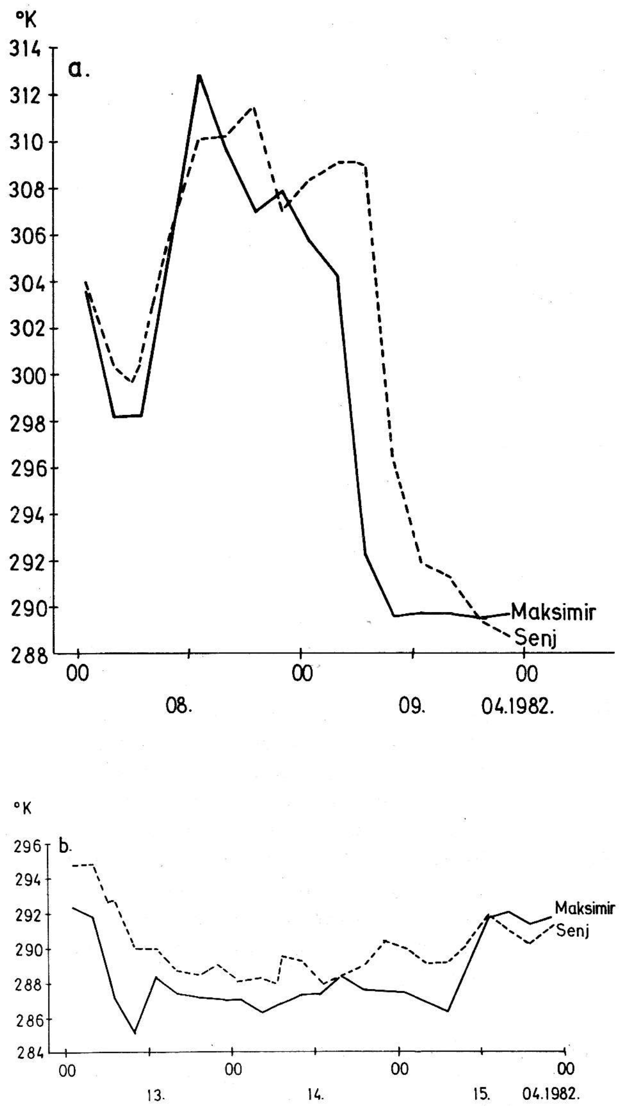


Fig. 3. Hourly courses of surface equivalent potential temperature for Zagreb-Maksimir and Senj, a) 8-9 April, b) 13-15 April

Sl. 3. Dnevni hod prizemne ekvivalentne temperature za Zagreb-Maksimir i Senj, a) 8-9.4. b) 13-14. 5. 1982

Daily courses of various elements in Split for the period 8 - 10 April is shown in Fig. 5. NE winds appear here for a very short period late in the evening on 9 April, but they were of a low speed. The wind increased when the direction turned easterly. The only sign of frontal passage was the lower temperature maximum on 10 April which occurred with the pressure minimum and increased relative humidity.

Daily courses of the same elements in Dubrovnik (not shown here) indicate no bora presence with prevailing E winds at night and stronger southerlies at daytime. Temperature maxima were also only a little disturbed indicating that the frontal system did not influence the weather in Dubrovnik in contrast with the frontal situation of 11 March briefly discussed in section 3.3 (Jurčec, 1988).

2.3. Vertical time cross-section

Figs. 6 and 7 present the time cross-sections for Karlovac and Zadar at three-hourly intervals obtained by special 1/2-minute readings of original soundings described by Poje in this Volume. The most interesting feature during the bora period of 9 and 10 April is a lowering of westerlies below which easterly winds are rather weak. The wind reversal occurs gradually. NE winds were found in the lowest 1 km layer on 10 April in Karlovac when the bora was still observed in Senj, but with a relatively weak wind speed.

In Zadar the lowest stability was observed prior to the bora onset (Fig. 4b). A neutral layer in Fig. 7a, which could be identified as a "dead" region in S85 model, apparently extends from the ground to an altitude of

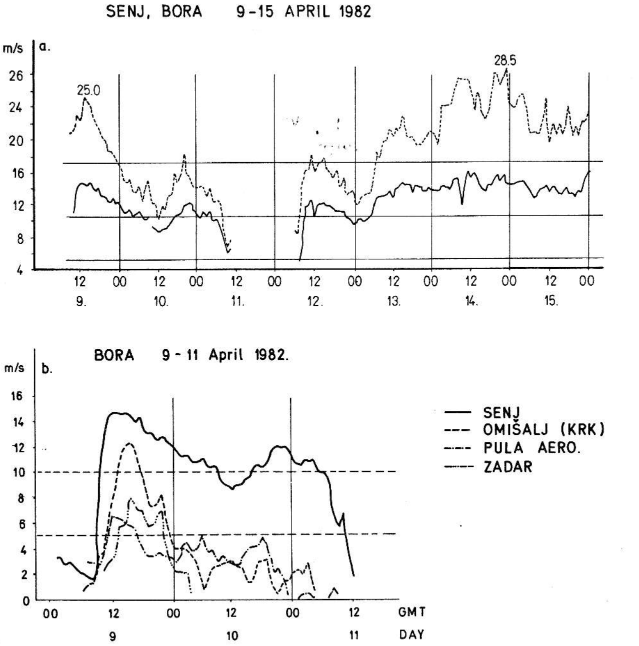


Fig. 4. **Daily courses for wind speed a) hourly mean values and gusts 9-15 April 1982 for Senj, b) comparison of mean hourly values with the other northern Adriatic stations.**

Sl. 4. **Dnevni hod brzine vjetra a) srednje satne vrijednosti i mahovi 9-15. 4. 1982 za Senj, b) Usporedba srednjih satnih za nekoliko stanica sjevernog Jadrana.**

about 1.5 km. This is approximately the same depth as a neutral layer in Pula shown by θ - profiles in Fig. 8. Such a dead region remains bound to a shallow layer near the surface and gradually becomes thinner until it finally ceases to exist at the end of the day when the bora also ceased at all locations except Senj.

Physically this could be interpreted that low level mixing does not allow a strong surface maximum wind speed to persist due to a redistribution of momentum, since a sudden strong sinking, soon after the bora onset, leads to a zero-perturbation layer in the S85 model as will be discussed in the next section. Of course, our observation cannot lead to more conclusive results until some (possibly radar) measurements are available to follow the development of the hypothesized dead region down to the ground level.

The postfrontal situation on 14 April indicates a deeper bora layer and directional changes to southerlies above the inversion layer which was also lowering but with weakening winds aloft.

2.4. Low tropospheric profiles of stability and bora wind component

The essential parameter for the application of hydraulics considered in the next section is the Scorer parameter, l, as a ratio of static stability to the wind velocity. The stability is expressed in terms of Brunt-Vaisala frequency

Fig. 8b shows vertical θ-profiles for Zagreb and Pula 06-18 GMT in the low troposphere, and Fig. 9 for Karlovac 12-18 GMT with the calculated profiles of N from the significant levels in sounding. Zagreb's profile indicates a large θ decrease from 06 to 12 GMT, and an almost constant profile afterwards.

A mathematical description of severe downslope winds in S85 assumes a constant stratification in the upstream layer (bora depth). It is seen from the θ - profiles that this is justified for 06 GMT whereas the other soundings in Zagreb and Karlovac indicate smaller stability close to the neutral stratification in the lowest 1 km layer. However, we consider this shallow feature as a result of boundary layer processes also reflected in the wind profiles shown in Figs. 9 and 10. This is a consequence of a regular daily mountain breeze clearly followed on the mean wind and temperature profiles in Zagreb and Pula during the ALPEX SOP (Jurčec, 1986). Furthermore, detailed stability profiles in Karlovac, particularly at 15 GMT, shows that in such a transient frontal situation shallow unstable layers may appear which cannot be representative for a steady state

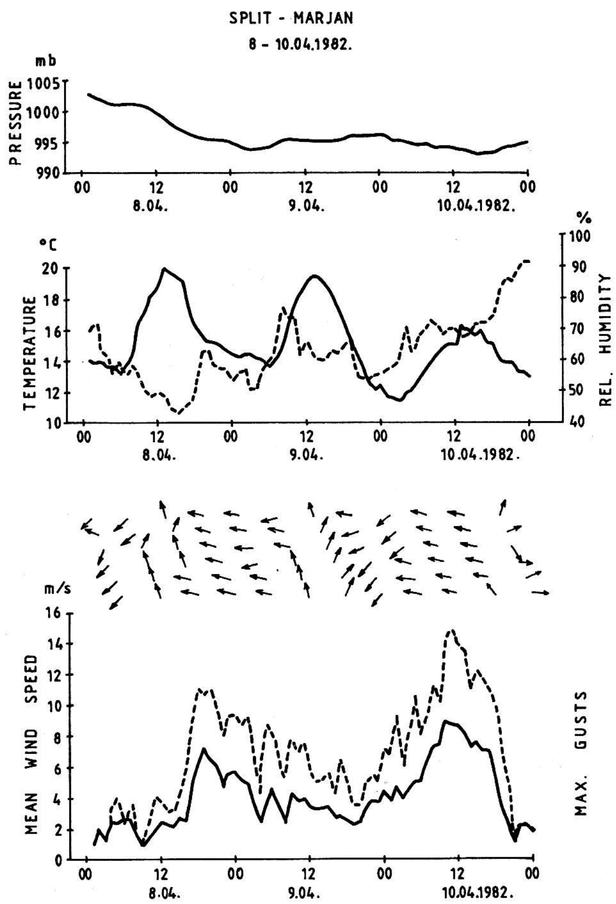


Fig. 5. **Daily courses for pressure, temperature, relative humidity, wind speed and direction for Split-Marjan, 8-10 April 1982.**

Sl. 5. **Dnevni hod tlaka zraka, temperature, relativne vlage, brzine vjetra i smjera vjetra za Split-Marjan, 8-10. 4. 1982.**

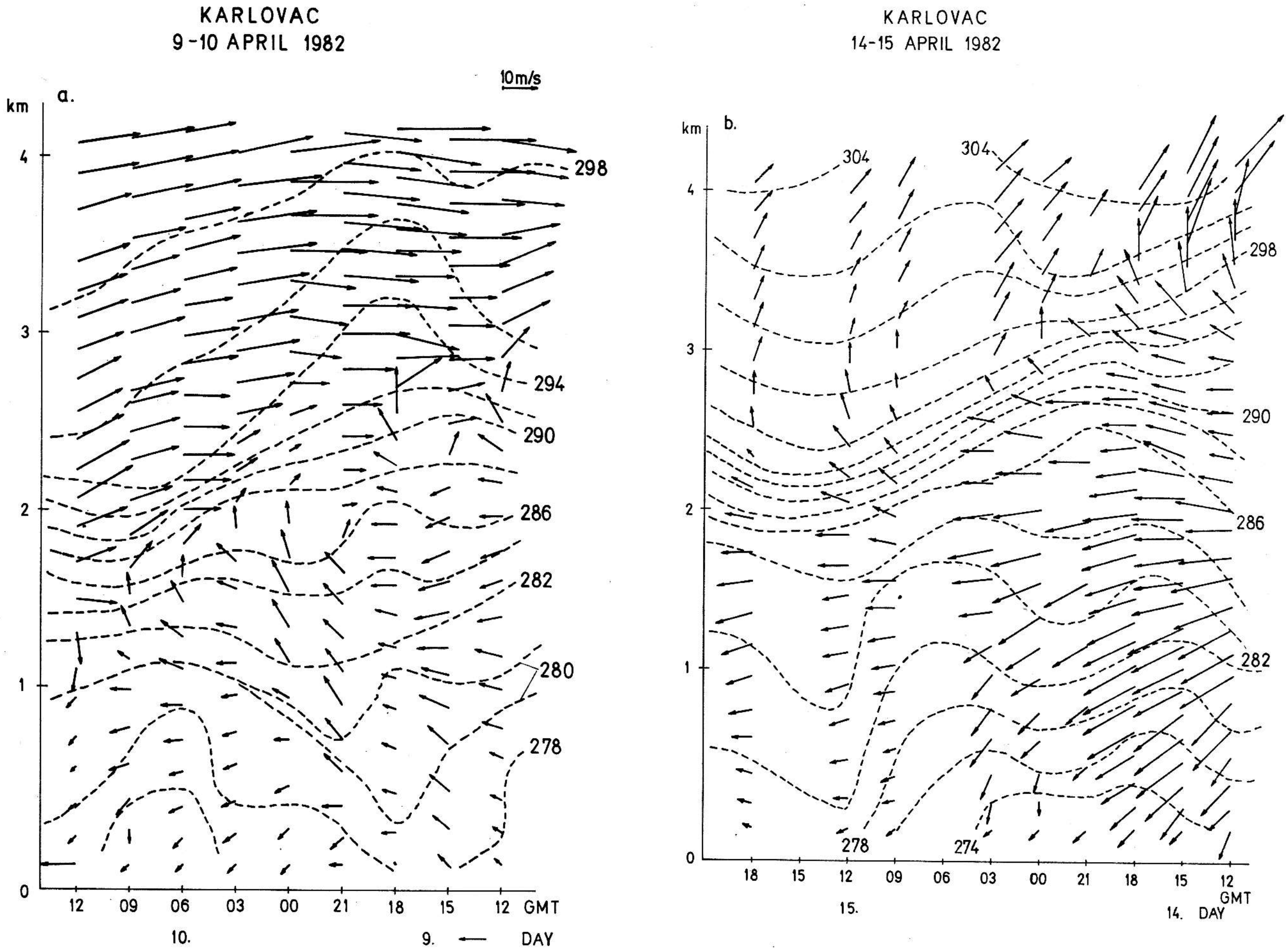


Fig. 6. **Time cross-section at three-hourly intervals, 1/2-minute reading signals for Karlovac 9-10 April and 14-15 April 1982, wind and isentropes.**

Sl. 6. **Vremenski vertikalni presjek u trisatnim intervalima, 1/2-minutni signali za Karlovac 9-10. 4. i 14-15. 4. 1982, vjetar i izentrope.**

upstream condition. We will therefore neglect them also in the calculation of mean bora layer stability. This neglect is probably no more serious than the existence of multilayer N-structure and the low-level jet profile which should be included in the improved time-dependent bora modeling when studying the bora evolution.

The bora component, u_B, perpendicular to the coastal mountains is taken as the wind direction $45^{\circ} \pm 90^{\circ}$. Parts of these profiles in Karlovac drawn by heavier lines in Fig. 9 indicate the directions 15 - 105° considered as the bora direction by Smith. They also appear approximately between 1 and 2 km in Zagreb's profiles in Fig. 10 for the period of 12 - 18 GMT. Such a jet-like structure does not appear in 06 sounding in Zagreb where the maximum velocity is found at the ground with a rapid decrease with height. The same u_B profiles are seen at 12 and 18 GMT in Pula corresponding to the characteristic profile for a downstream accelerated low-level flow in Smith's model as will be shown later.

A further characteristic of the upstream wind structure seen in Fig. 10b is a weak and relatively **constant wind speed** up to 2 km altitude but a very strong **directional** shear up to 3 km in Zagreb, also characteristic for a 2 km deep layer in Pula at 12 and 18 GMT. This deserves the attention of researchers for the future bora modeling since the low-level opposing flow and the jet existence was shown as important mechanism for trapping energy at low levels (Crook, 1988; Smith, 1976).

2.5. Humidity profiles

We expect that most of the bora cases will be sufficiently well aproximated by a dry tropospheric state. This may not be the case in the frontal bora structure. We will, therefore, briefly describe low-tropospheric humidity profiles although they will not be taken into consideratin among the present hydraulic parameters in the next section.

It is already seen from the profiles of equivalent potential temperature in Zagreb and Pula (Fig. 8b) that differences in θ_e between 06 and 12 GMT are larger than for dry θ - profiles. θ_e in Zagreb is almost constant in a layer 2 km deep with a larger increase of θ_e up to 3 km where the time-changes are smallest. Such a constant θ_e in time is found in Pula at 2 km with the larger differences 12 - 18 GMT in the lowest layers.

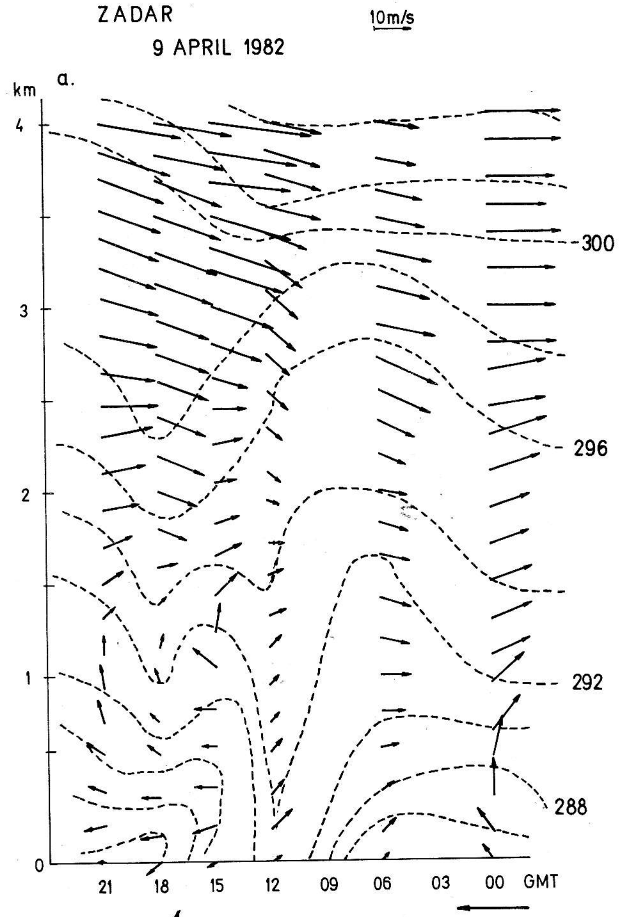
The humidity profiles are better pronounced in terms of the mixing ratio in Fig. 11, where the small temporal changes of r at 3 km in Zagreb and at 2 km in Pula as well as an increase of surface humidity in Pula at 12 GMT are clearly seen. These features would change the stability profiles in the low troposphere and it would obviously require the humidity inclusion in the final version of frontal type bora.

3. APPLICATION OF HYDRAULIC THEORY

3.1. Introduction

"Hydraulics" refers to the basic theory of hydrostatic current flowing over an obstacle which under these circumstances experiences a drag force. The state of this force depends on varius flow parameters. "High drag" states are identified with the local phenomenon of severe downslope windstorms and the "transitional" flow.The latter is defined in terms of a local Froude number, $F = U/(g'H)^{1/2}$ where H is the layer depth, U the local fluid velocity and g' the reduced gravity, $g'=g\Delta\theta/\theta$ (Pettre, 1984).

The essential ingredient for validity of hydraulic analogy is a reflecting upper boundary condition controlling the wave energy which remains or leaves the system. There are several mechanisms proposed to account for this reflection and its association with the development of strong downslope winds.



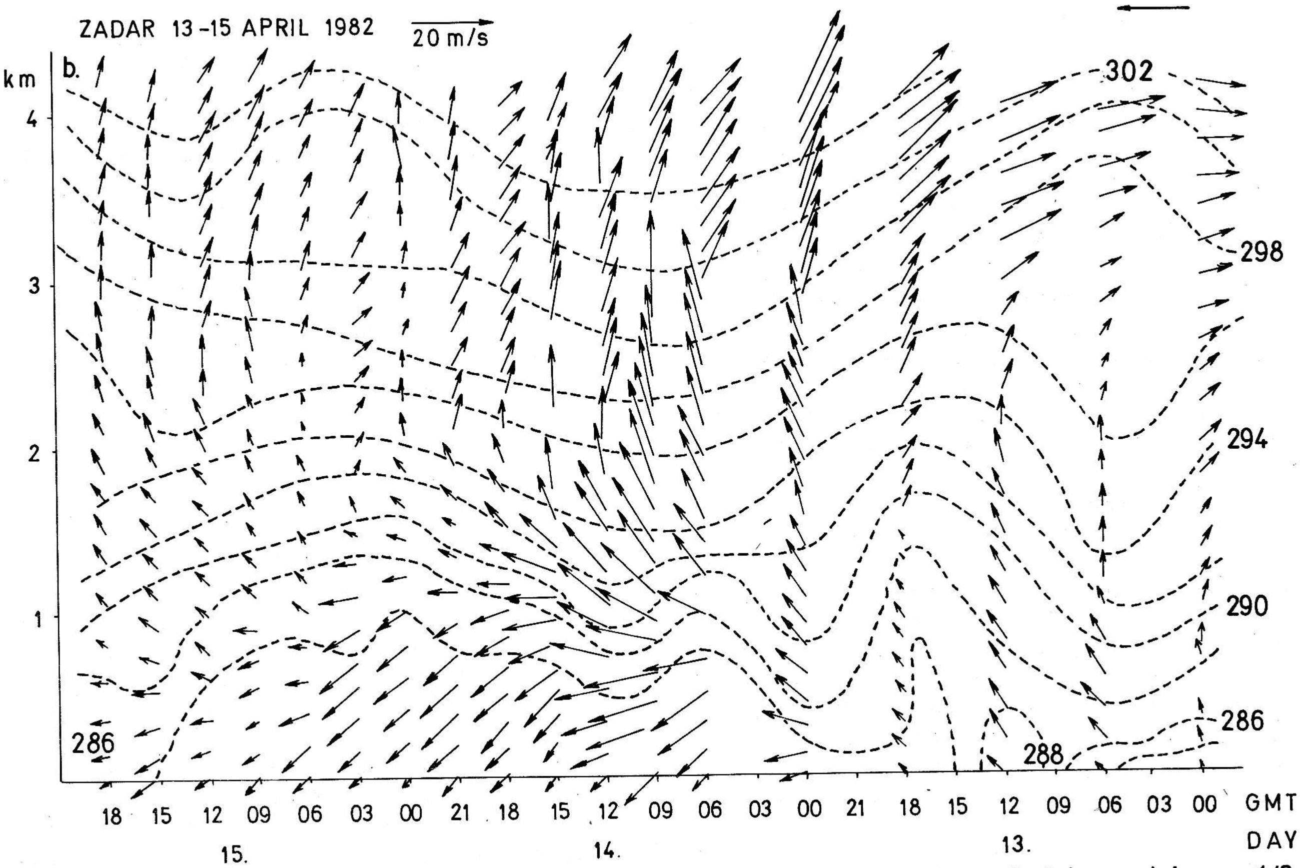


Fig. 7. Time cross-section for 1/2-minute reading signals for Zadar on 9 April, 13 - 15 April 1982, wind and isentropes.

Sl. 7. Vremenski vertikalni presjek za 1/2 minutne intervale za Zadar.

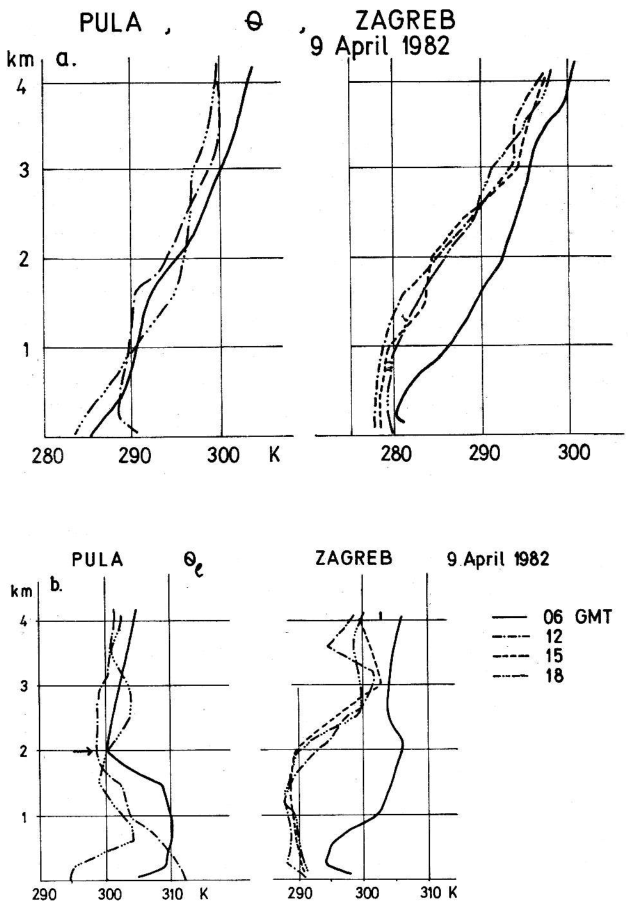


Fig. 8. Vertical profiles for Zagreb and Pula, 9 April 1982, a) potential temperature, θ, b) equivalent potential temperatgure, θ_e.

Sl. 8. Vertikalni profili za Zagreb i Pulu, 9. 4. 1982, a) potencijalna temperatura, θ_e b) ekvivalentna potencijalna temperatura, θ_e.

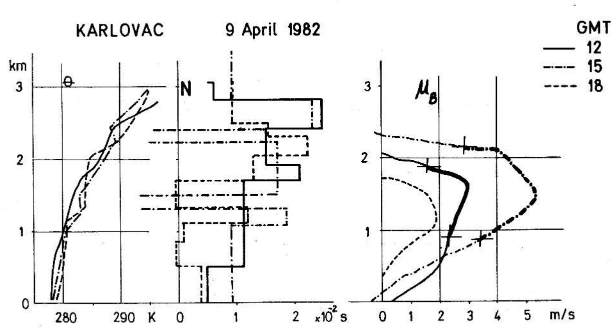


Fig. 9. Vertical profiles of potential temperature, θ, stability, N, and bora component, u_B, for Karlovac, 9 April 1982.

Sl. 9. Vertikalni profili potencijalne temperature, θ, stabilnosti, N, i komponente bure u_B (45 ± 90°) za Karlovac, 9. 4. 1982.

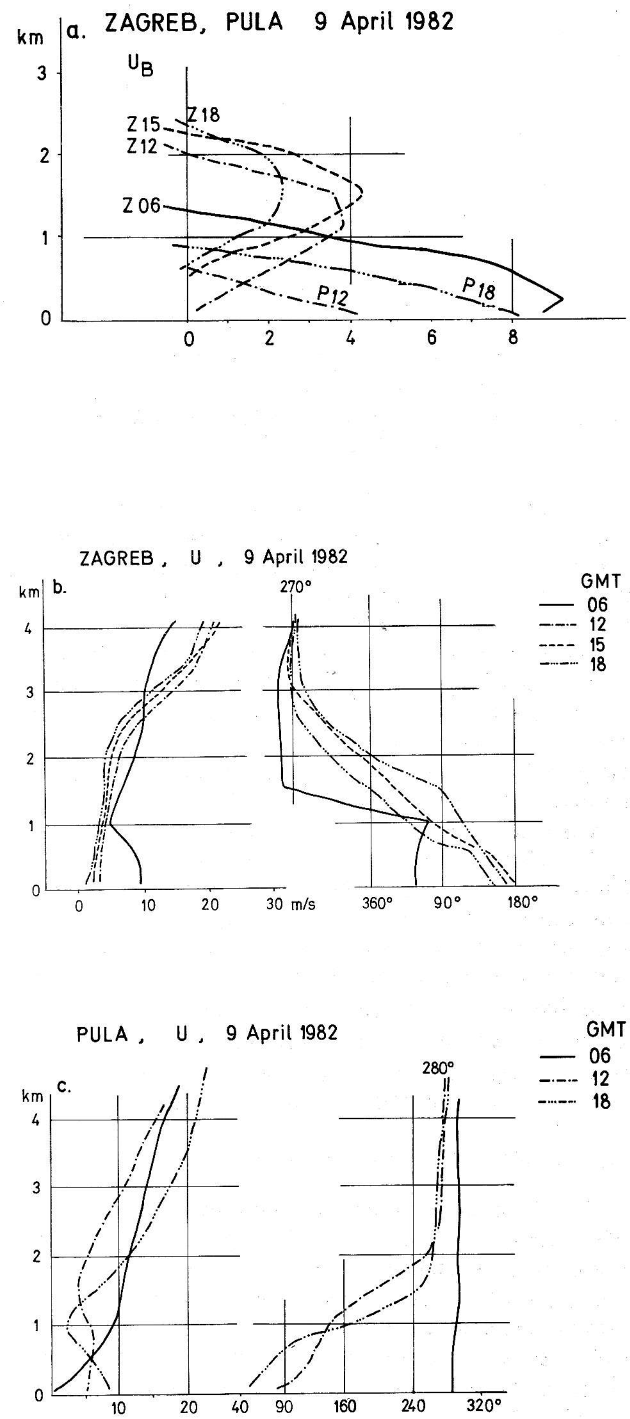


Fig. 10. Vertical profiles for Zagreb and Pula, 9 April 1982 at indicated observation times (GMT), a) bora component, u_B, for Zagreb (Z) and Pula (P), b) wind speed and direction for Zagreb, c) wind speed and direction for Pula.

Sl. 10. Vertikalni profili za Zagreb i Pulu, 9. 4. 1982. u označenim terminima (GMT), a) komponenta bure, u_B, za Zagreb (Z) i Pulu (P), b) brzina i smjer vjetra za Zagreb, c) brzina i smjer vjetra za Pulu.

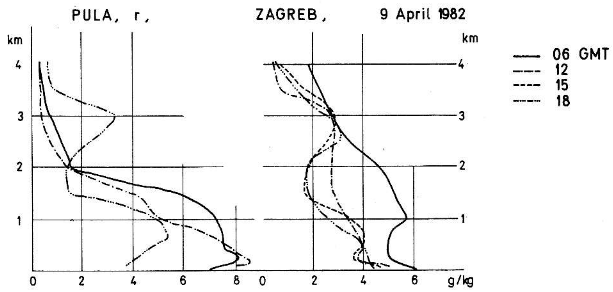


Fig. 11. Vertical profiles of mixing ratio for Zagreb and Pula.
Sl. 11. Vertikalni profili omjera miješanja za Zagreb i Pulu.

Probably the most attractive way to study these problems is by means of numerical experiments which allow a detailed presentation of the atmospheric flow structure, but these results are more difficult to interpret than those obtained analitically.

The best known are the experiments by Clark and Peltier (1984) which connect the downslope winds with a wave breaking region characterized by strong mixing and a local reversal of the cross-mountain wind. They suggest that the upward propagating wave energy is trapped below this "self-induced critical layer" causing an essential increase in the wave amplitude.

An overview of this problem is given by Durran (1986), Durran and Klemp (1987) and Bacmeister and Pierrehumbert (1988). In a series of numerical experiments these authors made an evaluation of Smith's and Clark and Peltier's theories through mountain wave simulation. The results have shown conditions similar to those postulated by Smith and reveal strong similarities between the ideal steady states and the simulated time-dependent flow.

3.2. Smith's internal hydraulic model

Fig. 12 shows schematically the basic elements of the S85 model. θ_e represents the streamline (critical isentrope) originating at the level H_e which splits over the mountain with a rapidly descending lower branch. The region encompassed by the split streamlines is turbulent with a potential temperature θ_c decoupling a highly disturbed and accelerating low-level flow from the disturbance-free region aloft. The upstream flow has a constant speed U and stability N.

3.3. Hydraulic parameters on 9 April

The basic parameters considered suitable for the analysed case calculated from the available data in Zagreb and Karlovac are given in Table 1a.

a) **The level of split streamline - bora layer depth, H_o**

There is some ambiguity in the definition of bora layer upper boundary which would concide with H_o - level and descending split isentrope with a constant upstream velocity U. In a postfrontal situation H_o could be usually defined by both temperature and wind structure, but in a frontal case this may not be so simple.

Considering the analysis of wind and temperature profiles discussed in 2.4 we have defined the H_o - level as the top of a positive bora component, u_B, (Figs. 9c and 10a). All heights are rounded off to the nearest 50 or 100 m. The mean value of H_o representing the bora layer, is of 2 km altitude with a minimum of 1400 m, which are the lowest values in the bora cases during ALPEX. With H_o specified we define the mean static stability as a weighting average in this layer but neglecting the lowest boundary layer value and some shallow unstable layers in Karlovac as indicated earlier. If in the same manner we would take the average of the bora wind component this would result in a very low value for the wind speed. We have therefore taken U close to the u_B maximum as can be seen in Figs. 9 and 10.

The vertical wavelength $L_z = 2\pi U/N$ is less than 3 km and looks reasonable for such a case.

We will now consider the predicted values by specifying the maximum nondimensional mountain height $h_m = h_m{}^* l = 1.0$. This is in the S85 model the largest value for which solution exists in cases when the final terrain height is the same as upstream ("positive mountain").

H_o can be calculated for the critical mountain height $h = h^*$ and the vertical displacement function $\delta = \delta^*$ at $\partial h/\partial\delta = 0$ from the SS87 (see also Vučetić in this Volume). For $h = 1.0$, $\delta^* = -1.27$ and $H^*_o = 4.74$. In these cases the maximum heights, given by the inverse value of the Scorer parameter, l^{-1}, are listed in Table Ia in the fifth column. This indicates the mountain heights between 300 and 450 m, much below the coastal Adriatic mountain ridges.

The predicted H_o is in most cases lower than the empirical H_o defined by u_B-component which seems reasonable. At the point x_1 in Fig. 12 with this specification we have $H_1 = \pi/2$ and $\delta_{c1} = -\pi$. This could be obtained from the graphical solution presented in S85. H_1 is about 1 km, in a rather good agreement with the observed descending of θ_c isentrope between Zagreb and Pula.

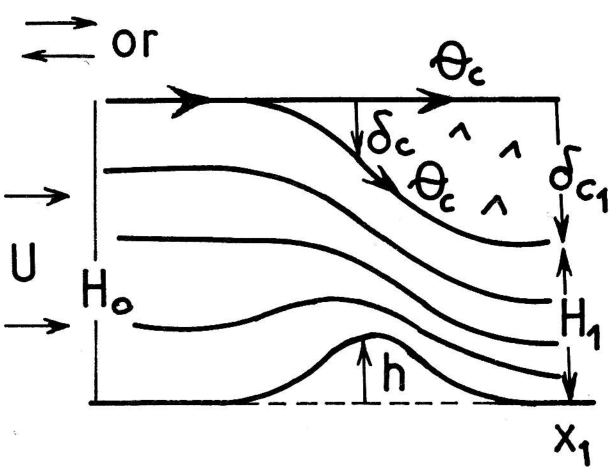


Fig. 12. Schematics of Smith's (1985) model for severe downslope winds.
Sl. 12. Šematski prikaz Smithovog (1985) modela za zavjetrinski vjetar

Table 1. Hydraulic parameters 9 April 1982, 11 March and 12 - 15 March 1982
Tab. 1. Hidraulički parametri 9 travnja 1982, 11 ožujak i 12-15 ožujak 1982

9 APRIL GMT	H_l [m]	N $10^{-2}[s^{-1}]$	U $[ms^{-1}]$	l^{-1} h_m [m]	L_z [m]	θ_c [K]	F_c U/NH_o	$\hat{h}$ h=800m	δ [m], predicted for h_m =1.0	H_o^*	H_1	δ_{c1}	μ_s
a. Zagreb													
06	1400	1,51	7	450	2800	289	0,33	1,7 (0,65)	-570	2100	700	-1400	29
12	2000	1,30	4	300	1900	285	0,15	2,6	-380	1400	500	- 900	17
15	2200	1,10	4	370	2300	286	0,17	2,2	-470	1750	600	-1150	17
18	2300	1,30	4	300	1900	288	0,17	2,6	-380	1400	500	- 900	17
Karlovac													
12	2000	1,30	4	300	1900	285	0,15	2,6	-380	1400	500	- 900	17
15	2200	1,31	5	400	2400	289	0,17	1,3	-500	1900	650	-1250	21
18	1800	1,00	3	300	1900	284	0,17	2,7	-380	1400	450	- 950	12
b. Zagreb													
11 March 18	3500	1,19	14	1180	7400	288	0,34	0,68 (0,26)	-1500	5600	1900	-3700	58
12-15 March	3400	0,97	11	1100	7500	285	0,33	0,73	-1400	5200	1750	-3450	38

Table 2. Calculated vertical profile of the perturbation velocity μ (x_1, z) from (3) for 9 April 1982, 06 GMT in Zagreb
Tab. 2. Teorijski vertikalni profil brzine perturbacije u (x_1, z) za 9. travanj 1982, 06 GMT za Zagreb.

z	(m)	0	100	200	300	400	500	600	700
u	(ms^{-1})	29.0	28.4	26.9	24.4	21.0	17.0	8.7	7.7

b) The perturbation velocity profile

The last column in Table 1 shows the value of maximum perturbation velocity at the ground calculated from the S85 relation

$$u\ (x., z) = U\ (1 - \hat{\delta}_{c1} \cos lz) \qquad (1)$$

As an example the vertical profile of μ at 06 GMT in Zagreb for each 100 m level is given in Table 2.

From (1) u = U at $lz_c = \pi/2$, z_c = 707 m, which is the height H_1. Unfortunately we cannot check these values, but considering the wind profile in Pula, and maxima gusts in Senj this prediction is quite acceptable.

c) The mountain drag

Having H_o and H_1 we can follow S85 method in the calculation of pressure drag on the mountain, D, as a measure of the strength of the transitional flow. The expression for this drag is derived from a control volume momentum budget.

Taking $\rho = 1$ kg m^{-3}, N = 0.0151 s^{-1}, $H_o - H_1$ = 1400 m
D = 104 x 10^3 kg s^{-2}

This is equivalent to an average pressure difference of about 1 hPa across the 1 km high mountain. Contrary to the case of 6 March (shown by Bajić in this Volume) the value of D is not sufficient to explain the total pressure perturbation in the bora layer. It could be only interpreted as a relatively small contribution to the total pressure difference across the barrier produced by displacement of the lower branch of the stable layer involved in the hydraulic flow. The factor which probably dominates in the total pressure gradient is in this case the upstream blocking of surface cold air (Smith, 1978) wihich at the same time makes it difficult for the cold dense air to climb over the higher mountains. This could explain the stronger bora in Senj in respect to the other locations in frontal bora cases associated with very cold air outbreak. The maximum measured pressure difference for Ogulin-Senj (see Fig. 2b) on this day was 7.1 hPa at 15 GMT.

d) Discussion of similarities between the ideal steady state, simulated time-dependent flow and the observed frontal bora features

Considering a priori that a steady state model with constant wind and stability profiles cannot define the upstream bora layer structure for the frontal condition, the undertaken calculation of the hydraulic parameters in this bora case was belived to show the significant differences in respect to those for which the validity of the steady state hydraulic model was established.

Surprisingly this was not the case. The analysis was instructive in a number of ways, and the results quite remarkable. In particular:

- The calculated parameters were not too far from those in the postfrontal (approximately steady state) situations for which the theory in S85 already proved successful. The reason is a fast moving front with pronounced flow separation quantitatively expressed by the surface trajectories shown by Chen and Smith (1987). Thus, the postfrontal situation was soon established with the particular flow characteristics described by the hydraulic parameters and their physical significance.

- It seems that relatively small corrections are needed to bring the predicted value of H_o to the empirically estimated bora layer height. Relatively large vertical displacement of the lower dividing streamline δ_c for such a shallow layer defined by environmental wind reversal (representing the breaking level) could be easily modified to extend close to the surface. This could probably be achieved most effectively by considering an asymmetric mountain profile which would be a more realistic presentation of the coastal mountain shape.

- The greatest air speed near the ground corresponds well to the modeling profile in the perturbation layer, but besides the lee side such a profile was also found in the upstream flow prior to the frontal passage. This feature, as well as a blocking effect on the mountain pressure drag are neglected in the simple steady hydraulic theory. However, it was shown by numerical experiments (Bacmeister and Pierrehumbert, 1988) that hydraulic analogy partially extends to time-dependent flow in which the critical line is initially below the position required by the S85. In such a condition the incoming flow is adjusted by a strong upstream surge, the critical line is lifted and the surface wind is drastically reduced. These results suggest a need for inclusion of oreigenic blocking or some other mechanism which could also account for the development of the low-level jet inside the bora layer.

- For higher H_o there are significant differences since the wave has more time to disperse in the horizontal before encountering the critical level. This leads to the essential differences between the shallow bora layer case and a case with uniform ambient wind.

3.4. Comparison with the frontal bora case of 11 March 1982

Frontal conditions over the Alpine region could be very different and we should not expect the same characteristics for various frontal bora cases. For comparison we present here the frontal case of 11 March, and the postfrontal period, the strongest ALPEX SOP bora case on the middle Adriatic (Jurčec, 1988).

The basic local characteristics of this bora case are the same: a rapid increase of bora speed, large temperature drop and brief bora duration. However, the bora of 11 March occurs in conjunction with an Alpine lee cyclogenesis on that day followed by another cyclogenesis on 13 March. Thus, the postfrontal bora in that case was of the "cyclonic" type with essential differences in the bora onset, intensity, duration and weather characteristics along the Adriatic coast.

The hydraulic parameters are given in Table 1 b, in the first row for the frontal case of 11 March and in the second row are the mean values for the postfrontal state at eight selected observations where the inversion was present capping the bora depth. These are two different definitions for the bora depth since in the case of 11 March there was no inversion in Zagreb's sounding and the bora depth, H_o, was estimated by the height of $u_B = 0$ as in the case of 9 April. It is seen from the Table that at 18 GMT the H_o was 3500 m, and the predicted H_o for the maximum height allowed by the model was much heigher at 5600 m.

During most of the postfrontal period, 12 - 15 March, NE winds spread throughout the troposphere and H_o was defined by the inversion level which was in the mean at 3400 m. Large values of predicted H_o and deflection parameter δ_c result from the large wind speed which gives a small value for the Scorer parameter and therefore a smaller effective mountain height h in respect to the frontal case on 9 April with weak winds and large $\hat{h}$.

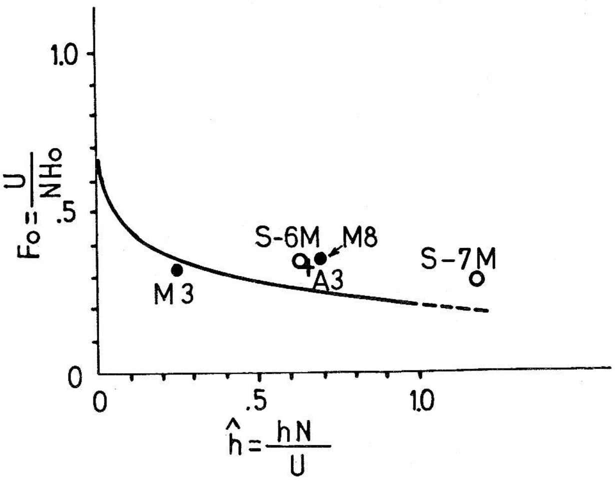


Fig. 13. A comparison of upstream conditions with the prediction of Smith's theory under critical conditions for uniform stabiliy. Smith's (1987) results for 6 and 7 March are plotted with the open circles: 9 April 1982, 06 GMT for h = 300 m (A3) and h = 800 (A8), and 11 March 1982, 18 GMT for the same heights of 300 m (M3) and 800 m (M8). Data is from Table 1.

Sl. 13. Usporedba prognoze Smithovom teorijom u kritičnim uvjetima s jednolikom stabilnosti. Unešeni su i rezultati Smitha (1987) za 6 i 7 ožujak. A3 je za h = 300 m, a A8 za 800 m. M je za situaciju 11 ožujka 1982 s istim oznakama. Podaci su u Tablici 1.

The calculations were also repeated for the mountain height h_m = 800 m used by Smith. The predicted mean values in this case are:

H_o = 4700 m, δ = -1200 m, δ_{c1} = -2800 m, H_1 = 1900 m

In some observations H_o differs more than 2 km stressing the influence of the mountain height on the predicted H_o in the stronger inflow regime. However, the deflection of split streamline is also large in this case and the perturbation height H_1 does not change significantly.

The value of δ_{c1} corresponding to h_m = 800 m for the same background wind speed of 11 m s^{-1} would decrease the predicted perturbation velocity at the ground to 39 m s^{-1} which is close to the maximum gust in Split for this situation. Such an agreement is of course fortuitous but the physics here is interesting since the observations without the wind reversal gives us no idea how to estimate bora depth empirically.

Still not clear is the role of the upstream condition for stronger bora in the middle Adriatic in respect to the northern coast. It is possible that the downstream condition with the Adriatic mesocyclone, generated by the cold front from the north, greatly contribute to the bora speed and gusts.

3.5 Critical Froude number and effective mountain height

A relationship between upstream bora layer depth, stratification, wind and mountain height provided by hydraulic theory could be expressed ty two nondimensional numbers $\hat{H}_o = H_oN/U$ and $\hat{h}$ = h N/U as shown in SS87. The first is the inverse of the Froude number and physically express the ratio of the bora depth H_o to the hydrostatic vertical wavelength of the internal waves. The value of $\hat{h}$ is known to play a role in steepening and wave breaking. According to Miles and Huppert (1969) if h is in the range of $0 \le \hat{h} \le 0.85$ the internal waves generated by flow over barrier will not break (or will not be supercritically steepened). Slight changes, however, in the mountain height or the wind speed may lead to a marked increase in steepening.

For each specified $\hat{h}$ S85 gives only one $\hat{H}_o$ (+ 2 π n). This graph is plotted in Fig. 13 with Smith's results for two bora days 6 and 7 March with h = 800 m. Our results for the frontal cases 11 March, 18 GMT and 9 April, 06 GMT have been calculated for Zagreb for h = 300 m and h = 800 m (also shown in Table 1a). Three points in Fig. 13 fall together: 6 and 11 March (h = 800 m) and 9 April (h = 300 m). The latter for h = 800 m results in a large $\hat{h}$ regime, preventing a laminar mountain wave field, whereas for 11 March h = 300 m gives a very small effective height of 0.26 for the same Froude number close to 0.33.

This points out to the known facts related to three-dimensional effects that 1) the variation of mountain height along the coast for the same upstream stability and wind profile may change the flow regime dramatically, 2) the differences in the upstream condition (N/U) are not equally favourable for the bora at the northern and southern Adriatic coast.

4. SUMMARY AND CONCLUSION

The main conclusion from the present study is that, unexpectedly, the frontal bora type in spite of apparent unsteadiness due to frontal movement and the complex atmospheric structure could be successfully presented by the internal hydraulic theory of Smith (1985) succesively followed by the calculated hydraulic parameters. It is shown that the actual frontal stage is brief causing a sudden bora speed increase, but also a rapid decay except at localities influenced by lower mountain passes where three-dimensional channeling effects are responsible for bora strenght and longevity such as observed in Senj.

The initial upstream acceleration on 9 April is caused by a frontal process following an oreigenic blocking on the northern side of the Alps, flow splitting and the low-level currents moving **around** the Alpine barrier. Such a NE current is opposing the higher level westerly flow **across** the Alps and may be considered as an enhanced mechanism for trapping the low-level internal gravity waves and developing a low level jet inside the bora layer.

Smith's model predicts in this case a large effective mountain height, h = $\hat{h}$N/U, resulting from the high stability and weak wind speed, although the modeling mountain heights are very low. Qualitatively, the results suggest that a slow moving shallow and dense air mass could not climb the higher mountain except during a short period of faster moving frontal air. The postfrontal relatively weak incoming flow results in a strong low-level acceleration which could be expected from the point of view of mass flow conservation. An estimation of pressure gradient caused hydrostatically by horizontal temperature gradient due to descending isentropes shows that this effect cannot account for a large part of total pressure gradient. The latter is probably in such a frontal case mainly due to a blocking of dense surface air.

Contrary to the shallow bora layer case of 9 April, the case of 11 March indicates a frontal bora class characterized by a deep bora layer with stronger incoming winds and lower effective mountain height. A brief presentation of hydraulic parameters indicates that the theoretical approach could be even more useful in such a case since there is no obvious empirical parameter which would indicate how deep the bora layer and the accelerating perturbation depth is when the northerly wind extends throughout the troposphere. Since the supply of colder air in this case was soon exhausted the inversions, even if existed, were weak and at the high altitudes.

An interesting speculation by Smith on the basis of ALPEX data analysis in comparison with Boulder storms is that they may have a common dynamical basis. It seems, however, that stronger incoming wind counteracted by a greater mountain height upstream of the middle Adriatic may preferably place such a situation in the same class with the Boulder flow. The conclusions must await the analyses of some **severe bora** cases (v > 17 m s^{-1}) from the archive data since none of these cases occurred during the Alpine experiment. The improved models with asymmetric mountains, three-dimensional effects, variable wind and stability profiles, blocking, etc. are needed for better understanding the structure and possible resemblance of bora and "bora-like" winds with the other downslope winds in various parts of the world.

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KRATAK SADRŽAJ

Poznato je da svaka fronta vezana uz prodor hladnog zraka sa sjevera uzrokuje buru na Jadranu, barem na sjevernoj obali. Kako prolaz fronte preko nekog područja definira tranzientno stanje atmosfere, moglo bi se unaprijed pretpostaviti da se takvo stanje atmosfere ne može prikazati jednim stacionarnim modelom. To znači da se Smithova hidraulička teorija, koja se pokazala uspješnom za objašnjenje mehanizma bure u postfrontalnim situacijama (vidi Bajić i Vučetić u ovom broju Rasprava), ne bi mogla primijeniti na slučajeve "frontalnog tipa" bure. Međutim, pokazalo se da je primjena hidrauličke teorije iznenađujuće dobra i korisna s nekoliko aspekata:

a) Izračunati parametri za slučaj bure od 9. travnja 1982. bitno se ne razlikuju od postfrontalnih, što se može vidjeti na sl. 13. Razlog tome je u brzo pokretnoj fronti, obilaženju struje oko Alpa i vrlo izraženim trajektorijama pri tlu (Chen i Smith, 1987). Na taj način je postfrontalno stanje vrlo brzo uspostavljeno i karakteristike ove situacije su opisane empiričkim i prognostičkim hidrauličkim parametrima.

b) Neki teoretski rezultati ne daju vrlo vjernu sliku atmosferskog stanja, ali se kvalitativno može objasniti fizikalni proces koji ujedno sugerira i poboljšanje modela. Teorija je posebno korisna u slučaju kada se NE smjer vjetra proteže kroz cijelu troposferu pa se empirički ne može odrediti sloj bure.

c) Rezultati ukazuju da su nužne relativno male korekcije da se dođe do boljeg podudaranja između prognostičkih i empiričkih visina sloja bure u navjetrini. Analizom izentropa na sl. 7 za Zadar ukazuje se na relativno dubok sloj miješanja, od tla do visine 1.5 km, neposredno pred početak bure, što se u narednim terminima istog dana smanjuje ali ostaje vezan uz tlo. Pretpostavlja se da je taj sloj izrazito turbulentan pa se može identificirati Smithovim "mrtvim" područjem koji se prema prognostičkim rezultatima u Tablci 1.a nalazi između 500 i 2000 m. Ako bi se taj sloj spustio do tla, kako analize sugeriraju, ne bi bilo sloja jakog laminarnog strujanja, a turbulencija i miješanje kroz dublji vertikalni "mrtvi" sloj doveli bi do znatnog smanjenja brzina vjetra, što je na lokalitetu Zadra i opaženo.

d) Model daje najveću brzinu vjetra pri prolazu same fronte, a maksimum je zabilježen pri tlu. To odgovara opaženom profilu komponente bure, u_B, (na sl. 10.a) u Puli, ali takav profil pokazuje i sondaža Zagreba prilikom prolaza fronte. S jedne strane to opovrgava zavjetrinski "padajući" vjetar kao mehanizam bure po kojem bi se akceleracija javljala padom zraka niz planinu, dok s druge strane takav profil ne odgovara niti hidrauličkom konstantnom vjetru u sloju bure na strani navjetrine. Objašnjenje za ovo neslaganje dao je Smith pretpostavkom efektivne visine planine, $\hat{h}$ = h N/U, gdje je h visina prepreke, N stabilnost, a U brzina vjetra, čiji omjer definira Scorerov parametgar l = N/U. Maksimalno moguć $\hat{h}$ u modelu Smitha (1985) s kontinuiranom stratifikacijom je jednak jedinici, i na taj način smo u Tablici 1 računali prognostičke veličine. Ako bi se h povećao, što je u modelu fizikalno nemoguće, došlo bi do prilagođavanja navjetrinskog strujanja. To su eksperimentalno dokazali Bacmeister i Pierrehumbert (1988) numeričkim eksperimentima vremenski-ovisnog toka preko planine. Ti

rezultati sugeriraju uvođenje orografskog blokinga u model bure, što bi smanjilo efektivnu visinu planine i omogućilo veću maksimalnu visinu planine, h_m, koja je za naš slučaj u Tablici 1. a premala i ne prelazi 450 m. S druge strane, uvođenje blokinga bi vjerojatno omogućilo simulaciju niske mlazne struje unutar sloja bure mehanizmom refleksije gravitacionih valova na gornjoj površini sloja bure, pa time zadržavanjem i povećanjem valne energije u sloju bure.

Kvalitativno, rezultati sugeriraju da se plitka i hladna zračna masa, koja se sporo giba srednjim vjetrom u sloju bure. 4-5 m s^{-1}, ne može popeti na više planine, kao što je moguće u kratkom vremenskom periodu za vrijeme prolaza fronte. No ovako slabo strujanje ima za posljedicu jaku akceleraciju u nižem sloju troposfere što se i može očekivati sa stanovišta sačuvanja toka. Procjena gradijenta tlaka preko planine uvjetovane hidrostatski uslijed spuštanja izentropa (sl. 12), pokazuje da taj efekt ne može objasniti ukupni gradijent tlaka, pa se pretpostavlja da je tome uzrok blokiranje hladnog zraka nakon prolaza fronte.

Nasuprot situaciji od 9. travnja sa plitkim slojem bure u navjetrini, slučaj bure od 11. ožujka ukazuje na frontalni tip s vrlo dubokim slojem bure i jakom navjetrinskom strujom što uzrokuje nižu efektivnu visinu planine h. Primjena teorije za izračunavanje hidrauličkih parametara je u tom slučaju još korisnija jer se sjeverni vjetar proteže uglavnom kroz cijelu troposferu pa se empirički iz vertikalne razdiobe vjetra ne može odrediti sloj bure. S obzirom da ne postoji nagomilavanje hladnog zraka, visinske inverzije, ukoliko i postoje, vrlo su slabo izražene.

Na kraju se navodi interesantnim spekulacija Smitha po kojoj bi ALPEX slučajevi bure i zavjetrinske oluje u Boulderu imale istu dinamičku osnovu. Međutim, prema našoj analizi bure 11. ožujka, s jakom strujom u navjetrini preko Bosanskih planina ispred srednjeg dijela Jadrana, čini se da bi bure toga tipa sa sjevernim vjetrom kroz cijelu troposferu imale više sličnosti s olujama u Boulderu, nego bura na sjevernom Jadranu. Daljnje analize s arhivskim podacima jakog vjetra trebale bi dati odgovore i na neka pitanja sličnosti bure na Jadranu s zavjetrinskim vjetrom u raznim dijelovima svijeta.