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SEVERE BORA ON THE MID - ADRIATIC

Olujna bura na srednjem Jadranu

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Abstract - The Adriatic severe bora can partly be explained by the two-dimensional hydraulic theory, as one of the possible mechanisms of a strong surface downslope wind. A comparison of the application of the hydraulic theory shows a similar severe bora mechanism on the northern and mid-Adriatic, with the exception of the Senj area where special bora effects have been observed. As the theory could not completely explain Adriatic bora, this required a study of a three-dimensional bora structure. The results have been achieved through analyses of the interaction of the upstream bora structure (sounding measurement at Zagreb and Belgrade) and the downstream bora structure at Split. The only available aerological data at Split date back to the period 1959-1963 and can be used for a comparison of estimated hydraulic parameters on the lee side.

Key word index: Severe bora, hydraulic theory, three-dimensional analysis.

Sažetak - U radu je pokazano da dvodimenzionalna hidraulička teorija, kao jedan od mogućih mehanizama jakog zavjetrinskog vjetra pri tlu, može djelomično objasniti pojavu olujne bure na Jadranu. Neposredna usporedba primjene hidrauličke teorije ukazuje na jednak mehanizam olujne bure na sjevernom i srednjem Jadranu s izuzetkom na području Senja gdje dolaze do izražaja lokalni efekti. Pošto ova teorija nije u potpunosti mogla objasniti olujnu buru na srednjem Jadranu, to je zahtijevalo istraživanje trodimenzionalne strukture bure. Ovi rezultati dobiveni su na osnovi analize interakcija navjetrinske strukture atmosfere, iz radiosondažnih podataka Zagreba i Beograda u terminima 00 i 12 UTC kao i zavjetrinske strukture u 6 situacija s olujnom burom u jedinom raspoloživom periodu visinskih mjerenja u Splitu (1959-1963). Aerološki podaci Splita poslužili su za usporedbu s procijenjenim parametrima u zavjetrini.

Ključne riječi: Olujna bura, hidraulička teorija, trodimenzionalna analiza

INTRODUCTION

The severe bora wind on the northern Adriatic coast has been in the centre of interest for the last ten years, specially since the Alps experiment (ALPEX-SOP) in March and April 1982. The results of ALPEX bora mostly coincide with the assumptions of the hydraulic theory (Smith, 1984, 1987). Smith's theoretical results essentially changed the traditional view on the bora as a "fall wind". Further research in many bora cases (Bajić, 1988, 1991; Jurčec, 1988, 1989; Ivančan-Picek and Vučetić, 1990; Tutiš, 1988 and Vučetić, 1988) shows that the hydraulic model can explain the occurrence of bora on the northern Adriatic. It is well known, however, that a severe bora wind can occur all along the Adriatic coast. Preliminary bora research on the mid-Adriatic (Jurčec and Visković, 1989; Bajić, 1989) shows a thicker upstream bora layer compared to the same layer on the northern Adriatic. Due to the complexity of the orographic situation on the lee side of the mid-Adriatic it remains an open question if the hydraulic theory can be successfully applied on severe bora cases all along the coast. Therefore, the aim of the paper is to study the application of the hydraulic theory to the mid-Adriatic bora.

In this paper, the vertical atmospheric structure is analysed in 6 situations with severe bora wind of $v_{mean} \geq 17.0\,\mathrm{m\,s^{-1}}$ in the period 1959-1963 on the basis of sounding data in Split. The measurements in Split made possible a comparison of theoretical results obtained by application of the hydraulic theory and observations. In addition to data from Zagreb, aerological data from Belgrade were used for the first time to study the upstream bora layer. During this analysis some questions arose: Are the sounding measurements at Zagreb and Belgrade representative of upstream bora layer in the mid-Adriatic? Is there any essential difference in the vertical atmospheric structure between Zagreb and Belgrade? The answers to these questions are the first attempt to confirm the basic characteristic flow during the occurrence of the mid-Adriatic bora.

HYDRAULIC THEORY APPLICATION

A short review of the hydraulic theory

The basic characteristics of the hydraulic theory are briefly illustrated in cases of continuous atmospheric stratification, one and two-layer models.

One-layer model

Long (1953) was the first to consider theoretically and experimentally the application of the hydraulic theory to a uniform flow across the mountain with a discontinuity in density. It assumes a two-dimensional hydrostatic steady flow with two homogenic fluids of different density. The lower neutral layer is covered with a very thin temperature inversion. In that case the model is reduced to a one-layer model and the motions and continuity equations for shallow water are valid. Only the disturbed lower layer falls over the obstacle and there are no imposed pressure gradients of the upper layer. As this rarely occurs in the real atmosphere, the hydraulic theory can not be often applied. The vertical wind profile during a bora event is often similar to the assumptions of the theory, as a wind above the bora layer is light or reversed. Therefore, there is no pressure gradient on the cold lower layer.

According to the hydraulic theory for single layer model, a certain relationship must exist among the upstream wind U_0, the stability N_2^2 (N_2 - the Brunt-Väisälä frequency), the mountain height h, the depth of the upstream layer H_0 and the depth of the temperature inversion d:

$$\frac{h}{H_0} = 1 + \frac{1}{2}F_0^2 - \frac{3}{2}F_0^{2/3} \qquad (1)$$

$$F_0 = \frac{U_0}{\sqrt{g'H_0}} \ , \quad g' = N_2^2 d \ , \quad N_2 = \frac{g}{\rho}\frac{\partial \rho}{\partial z}$$

F_0 is the Froude number representing the ratio of the wind speed and the velocity of the long gravity waves.

From the equations of momentum and mass conservation Bainse (1987) obtained the relations of depends on F_0 and H_0:

$$\frac{h}{H_0} = \left[8\left(F_0^2+1\right)^{3/2}+1\right]\left[16F_0^2\right]^{-1} - \frac{1}{4} - \frac{3}{2}F_0 \qquad (2)$$

$$F_0 = \left[\frac{h}{H_0} - 1\right]\left[\frac{1+h/H_0}{2h/H_0}\right]^{1/2} \qquad (3)$$

The first curve is presented on Figure 1b by AF and the second curve by BC. To the left of the curves AB and AF the flow is either supercritical ($F_0 > 1$) or subcritical ($F_0 < 1$). To the right of BC the obstacle height is sufficiently large to completely block the flow. In a partially blocked case, flow over the obstacle crest is controlled by the local condition $F_c = 1$. A hydraulic jump may be attached on the upstream (region ABCD) or downstream (region ADE). In the region EAF the flow may be either partially blocked or supercritical, depending on the initial conditions.

Continuous stratification

The analyses of aircraft measurements during bora occasions on the northern Adriatic in the ALPEX period 1982 helped Smith to construct a new hydraulic model using Long's equation for the continuous stratification N_0 and uniform upstream flow U_0 (Smith, 1985). It is presumed that the critical streamline at the level H_0 splits over the mountain with the lower branch descending rapidly, by δ_c, towards the lee side. Above H_0 a weak flow is present, at least in comparison with the strong perturbance below. Between the split streamlines the air is well mixed so that the density in that region is constant. The descending of the critical streamline is obtained by:

$$\hat{\delta}_c = \frac{1}{\sqrt{2}}\left[\hat{h} + \hat{h}\left(\hat{h}^2 + 4\right)^{1/2}\right]^{1/2} \qquad (4)$$

$$\hat{\delta}_c = \delta_c l \qquad \hat{h} = hl$$

The Scorer parameter l is the maximum horizontal wave number with which steady linear gravity waves can propagate in the vertical. If the Scorer parameter decreases with height, there will be a range of wave number over which gravity waves can have a periodic vertical structure only near the ground. $\hat{h}$ is the effective mountain height.

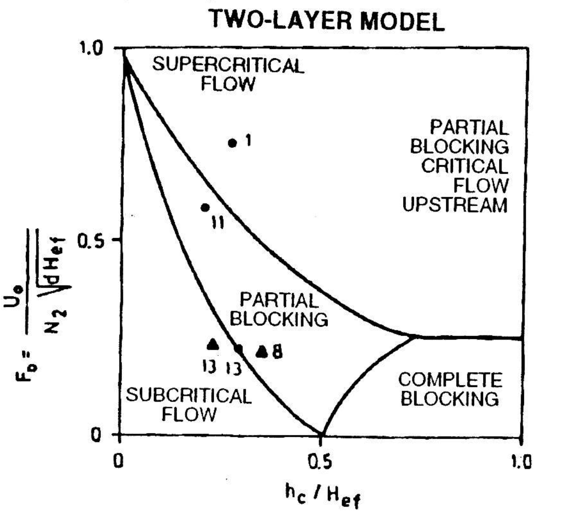
The vertical profile of velocity perturbations $u_T(x_1,z)$ and the height of H_1 (the descending layer on the lee side) is obtained from the relation:

$$u_T(x_1,z) = U_0\left(1 - \hat{\delta}_{c1}\cos lz\right)$$

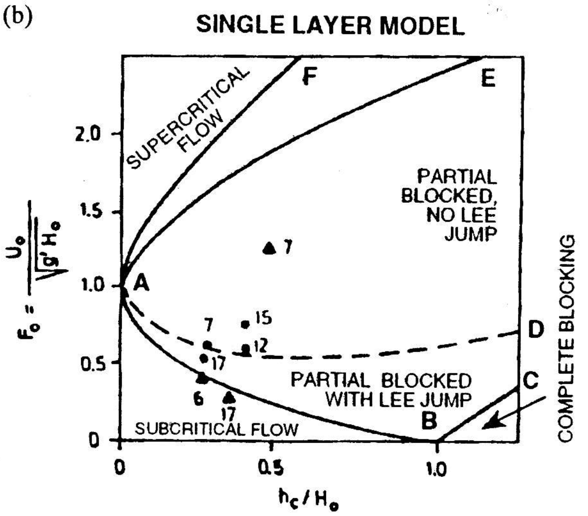
$$\hat{H}_1 = \frac{\pi}{2} \qquad \hat{\delta}_{c1} = \frac{\pi}{2} - \hat{H}_0 \qquad (5)$$

$$\hat{H}_1 = H_1 l, \quad \hat{H}_0 = H_0 l, \quad \hat{\delta}_{c1} = \delta_{c1} l$$

(a)



(b)



POINTS	DATA		ZG	BG
1	17. 1. 1959.	00 UTC	T	
2'	18. 1. 1959.	00 UTC		C
3	5. 11. 1961.	12 UTC	C	
4	29. 1. 1962.	12 UTC	C	
5	30. 1. 1962.	00 UTC		C
6	31. 1. 1962.	00 UTC		S
7	31. 1. 1962.	12 UTC		S
8	14. 3. 1962.	12 UTC	C	T
9'	15. 3. 1962.	00 UTC		C
10'	15. 3. 1962.	12 UTC		C
11'	16. 3. 1962.	00 UTC	T	C
12'	2. 12. 1962.	12 UTC	S	C
13	3. 12. 1962.	00 UTC		T
14	21. 1. 1963.	12 UTC	C	
15	22. 1. 1963.	00 UTC	S	
16'	23. 1. 1963.	12 UTC		C
17	24. 1. 1963.	00 UTC		S

T - Two-layer model
S - Single layer model
C - Continuous stratification

●, ○ ($\hat{h}=1$) ZG - Zagreb

▲, Δ ($\hat{h}=1$) BG - Belgrade

(c)

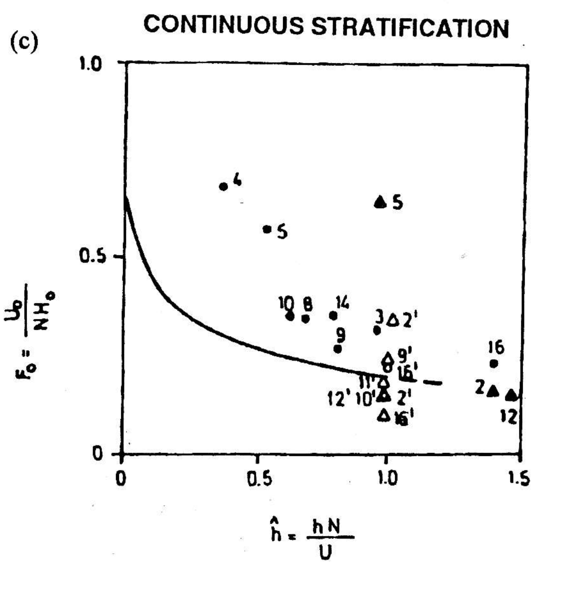


Figure 1. A comparison of bora conditions above Zagreb and Belgrade with predicted values according to the hydraulic theory for: (a) two-layer model (Smith and Sun, 1987), (b) one-layer model (Long, 1953) and (c) continous stratification (Smith, 1985).

Slika 1. Usporedba stanja iznad Zagreba i Beograda za vrijeme bure s procijenjenim vrijednostima prema hidrauličkoj teoriji za: (a) dvoslojni model (Smith i Sun, 1987), (b) jednoslojni model (Long, 1953) i (c) kontinuiranu stratifikaciju (Smith, 1985)

The theory has shown that the descending streamline begins where the mountain rises and that it accelerates above the mountain crest. The surface lee wind is a few times stronger than the initial flow.

Smith (1985) supposed that transitional flows for the effective mountain height higher than 1 are not possible because of the complete blocking on the windward side. In 1989 Smith suggested that if $h > 1$ the ideal flow is modified because of a partial blocking of the cold air in the surface layer. For higher ridges it is supposed that a layer may form upstream of sufficient depth d, to maintain the effective depth

$$\hat{h}' = \hat{h} - \hat{d} = 0.985 \approx 1 \qquad (6)$$

Two - layer model

An improvement of the theory was brought about by Smith and Sun (1987). The non-steady state solutions for the stratified two-layer model flow over a ridge proposed by the authors fit any distribution of stability. In parameter space these solutions lie between the interfacial case of Long and the constant stratification case of Smith. The vertical profile of stability consists of two layers with stability N_1 and N_2. In order to simplify that, it is presumed that the lower layer is neutral ($N_1 = 0$ and $l_1 = 0$). The fluid selects a certain critical streamline in the upper layer to serve as the top of the disturbed flow.

If H_a is the depth of the lower layer, d the depth of the upper layer and H_b the total depth in the upstream region the following ratios are defined:

$$r = \frac{d}{H_a} \qquad R = \frac{d}{H_b} \qquad (7)$$

Knowing the empirical values of h, H_a and d, we may apply the theory in order to obtain the predicted values h^*, H_a^* and d^*.

For an analogous definition of the Froude number F_0, as in the one-layer model, Smith and Sun presumed that a thick stable layer might be approximated by a thin density interface of equal strength located at its mean position. This is why they introduced the effective altitude $H_{ef} = H_a + 0.5\,d$ and the Froude number equals

$$F_0 = \frac{U_0}{\sqrt{g' H_{ef}}} \qquad (8)$$

The wind regime of the two-layer model $R = 0.5$ (Baines, 1987, Fig. 1a) has analogous areas of subcritical, supercritical and partial blocking to the one-layer model.

HYDRAULIC PARAMETERS IN SEVERE BORA CONDITIONS ON THE MID - ADRIATIC

Detailed statistic analyses of severe bora cases in the mid - Adriatic area emphasise the duration and intensity of some special bora situations duration and intensity (Vučetić, 1991). For further research six severe bora situations (1959 - 1963, Fig. 2), were chosen according to the following criteria:

a) maximum mean hourly wind speed in the direction from N to E ≥ 17.0 m s^{-1}

b) maximum gust wind ≥ 35 m s^{-1}

c) at least one day with a mean hourly wind speed ≥ 10.0 m s^{-1} per bora event.

In all the situations observed the severe bora lasted for 241 hours at Senj, 98 hours in Split and only 1 hour in Dubrovnik. Considering the maximum mean hourly wind speed, but not the maximum bora gusts, these situations cover the longest and strongest bora cases in Split (since the existence of anemographic measurement).

A detailed synoptic and mesoscale analysis of the surface and vertical atmospheric structure on indicates the thermodynamic characteristics of severe bora on the mid - Adriatic. The basic surface characteristics of severe bora along the Adriatic coast have been followed by noting the daily courses of wind speed and air temperature at Senj, Split and Dubrovnik (Figs. 3 and 4). As already mentioned, according to the hydraulic theory the fluid selects a critical streamline to split the upper and lower layer in the troposphere. The altitude where this streamline is located defines the top of the upstream bora layer. In this paper, H_o is the height of the upper-level inversion in the layer in which the positive $u_B = 45° \pm 90°$ bora component prevails. The hydraulic theory assumes a uniform upstream flow and so the weighted average of all the significant layers was calculated to obtain the mean wind speed in the upstream bora layer. In the same way, the mean Brunt-Väisälä frequency was averaged. 800 m was taken as the maximum mountain height.

All three models of the hydraulic theory, depending on the vertical profile of stability, were applied to the aerological data in Zagreb, Belgrade and Split during the severe bora on the mid-Adriatic. Table 1 contains the results of this application.

The situation on 15 - 20 January 1959

An abrupt bora onset was associated with a drastic fall of air temperature (14.1°C / 7 hours in Split, Fig. 4). Cold and dry air from the north very quickly covered all the Adriatic area with a low relative humidity which reached a minimum of 14% in Dubrovnik on 18 January. Such changes caused a pronounced cold air outbreak on the Adriatic Sea after the frontal passage,

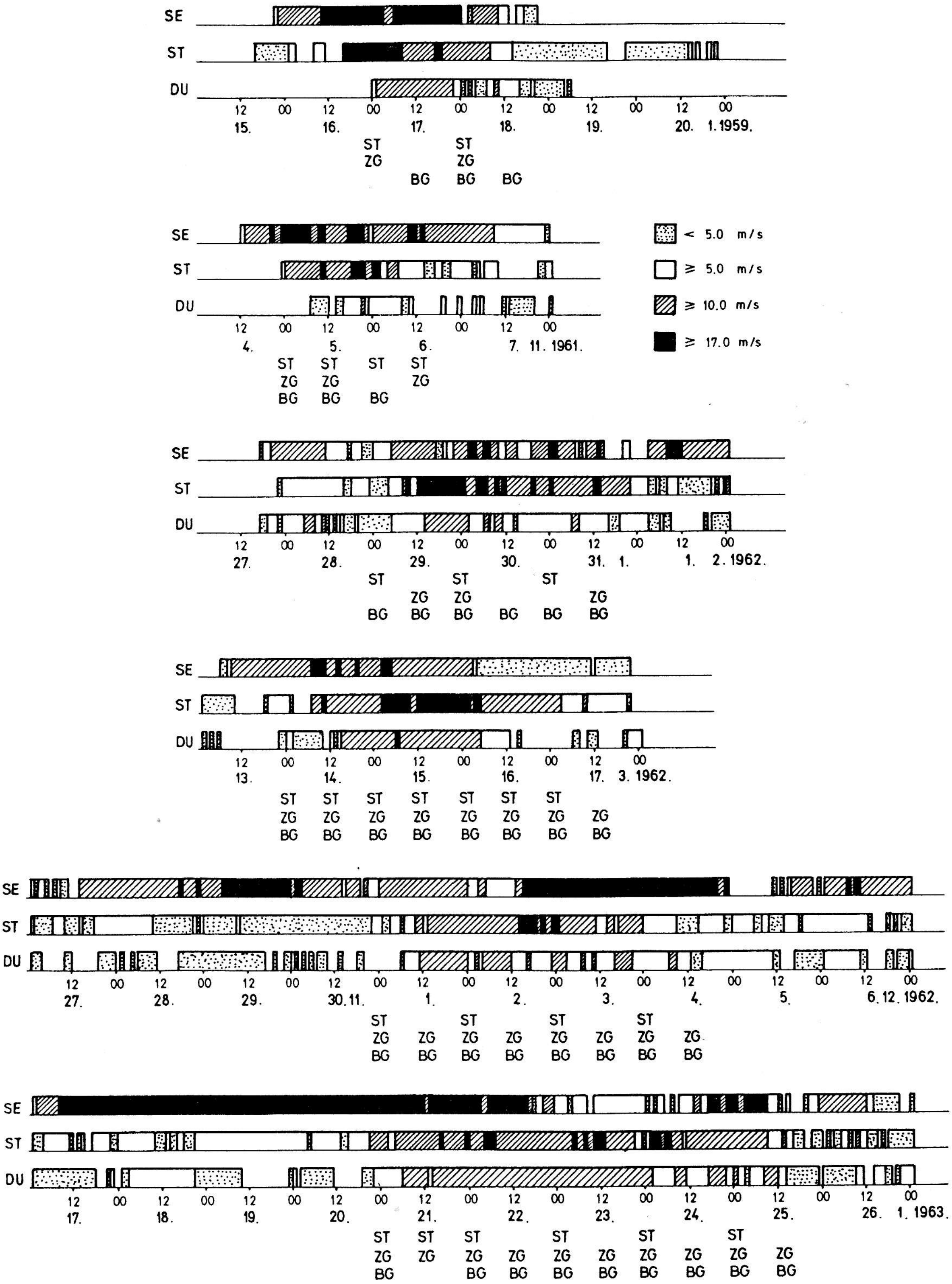


Figure 2. The daily courses of bora occurrences at Senj, Split and Dubrovnik for the period 1959-1963. ZG, ST, BG mean the existence of aerological data in Zagreb, Split and Belgrade.

Slika 2. Dnevni hodovi bure u Senju, Splitu i Dubrovniku u razdoblju 1959-1963. ZG, ST i BG označavaju postojanje aeroloških podataka u Zagrebu, Splitu i Beogradu.

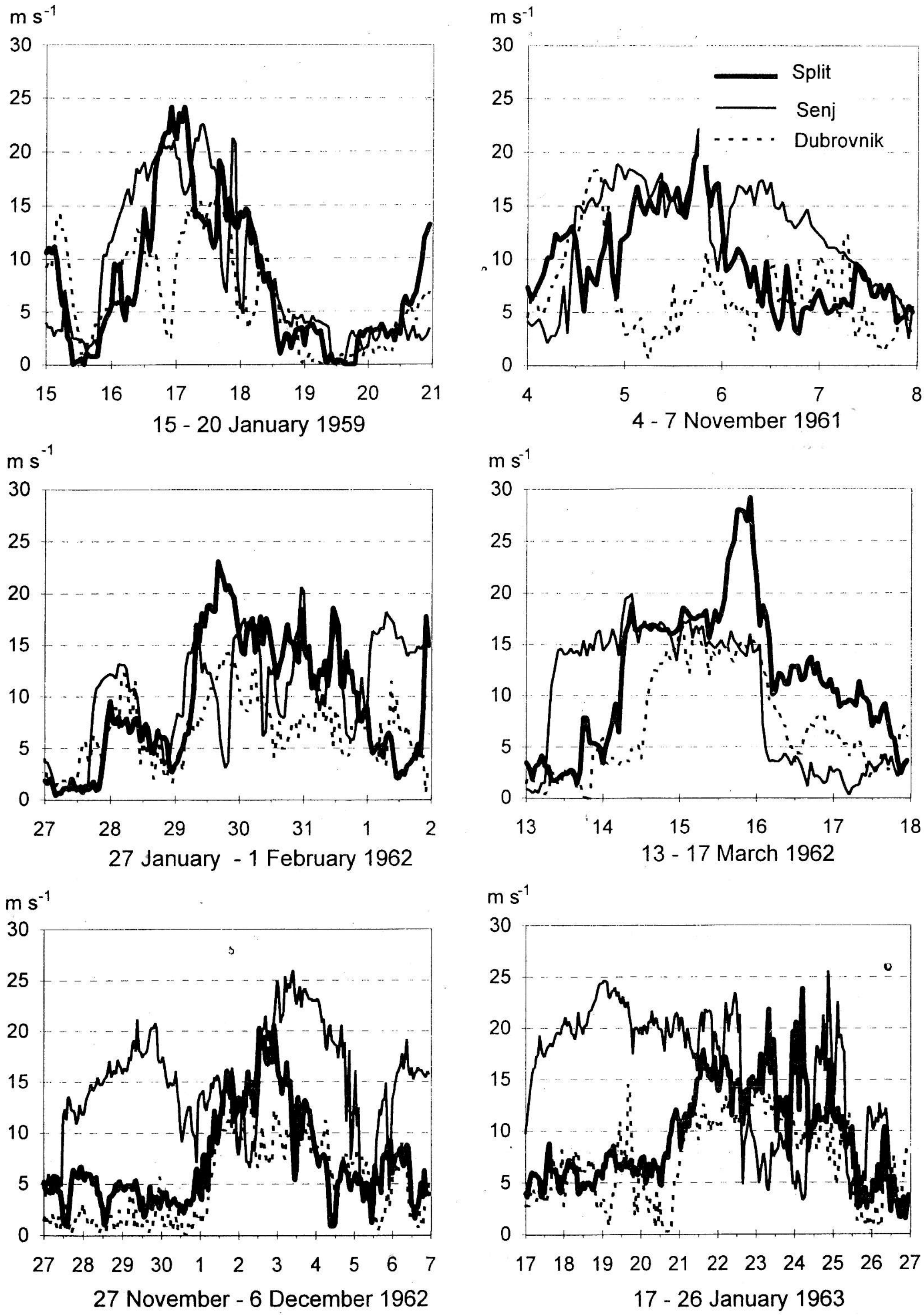


Figure 3. The daily courses of the mean hourly wind speed for severe bora situations at Senj, Split and Dubrovnik in the period 1959-1963.

Slika 3. Dnevni hodovi srednje satne brzine vjetra u situacijama s olujnom burom za Senj, Split i Dubrovnik u razdoblju 1959-1963.

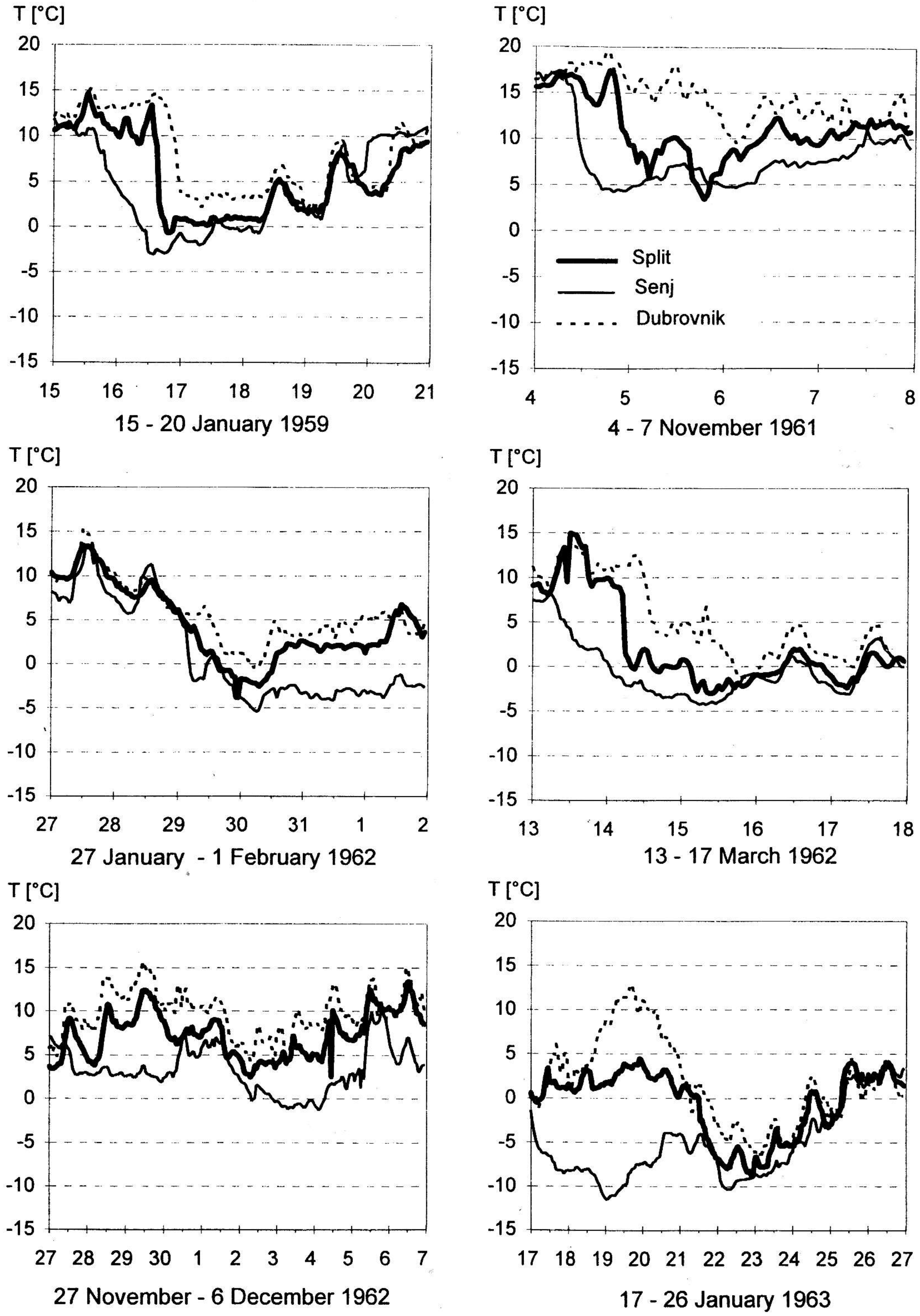


Figure 4. The daily courses of air temperature for severe bora situations at Senj, Split and Dubrovnik in the period 1959-1963.

Slika 4. Dnevni hodovi temperature zraka u situacijama s olujnom burom za Senj, Split i Dubrovnik u razdoblju 1959-1963.

which was related to a shallow fast movement of the cyclone in the western Mediterranean (Fig. 5). On 17 January the upper troposphere was characterised by a very strong SW-W jet, the axis of which being located northward of bora region. The bora event was accompanied by a typical fast cut-off process. The upper-level trough was characterised by a large amplitude and a short wavelength. The maximum wind speed was transferred into the bora layer and the surface bora reached severe strength on the mid-Adriatic. On the next day, the upper-level ridge intensified above the northeastern Atlantic and the NE tropospheric wind speed increased, whereas the surface bora suddenly decayed.

On 17 January a strong wind shear with maximum wind speed occurred inside the bora layer. Above Zagreb the wind turned to ESE in the second upper level inversion. In Split the NE flow extended throughout the troposphere and on the tropopause the wind abruptly turned to NW. At an altitude of 600-700m over Belgrade a weak W wind occurred. As a consequence the bora layer, with a pronounced N-component, did not extend from the surface.

On the vertical profile of the Brunt-Väisälä frequency (18 January at 00 UTC) small variations of N with height are presented. Therefore, a constant atmospheric stratification could be assumed.

The NE wind in the upstream bora layer decayed

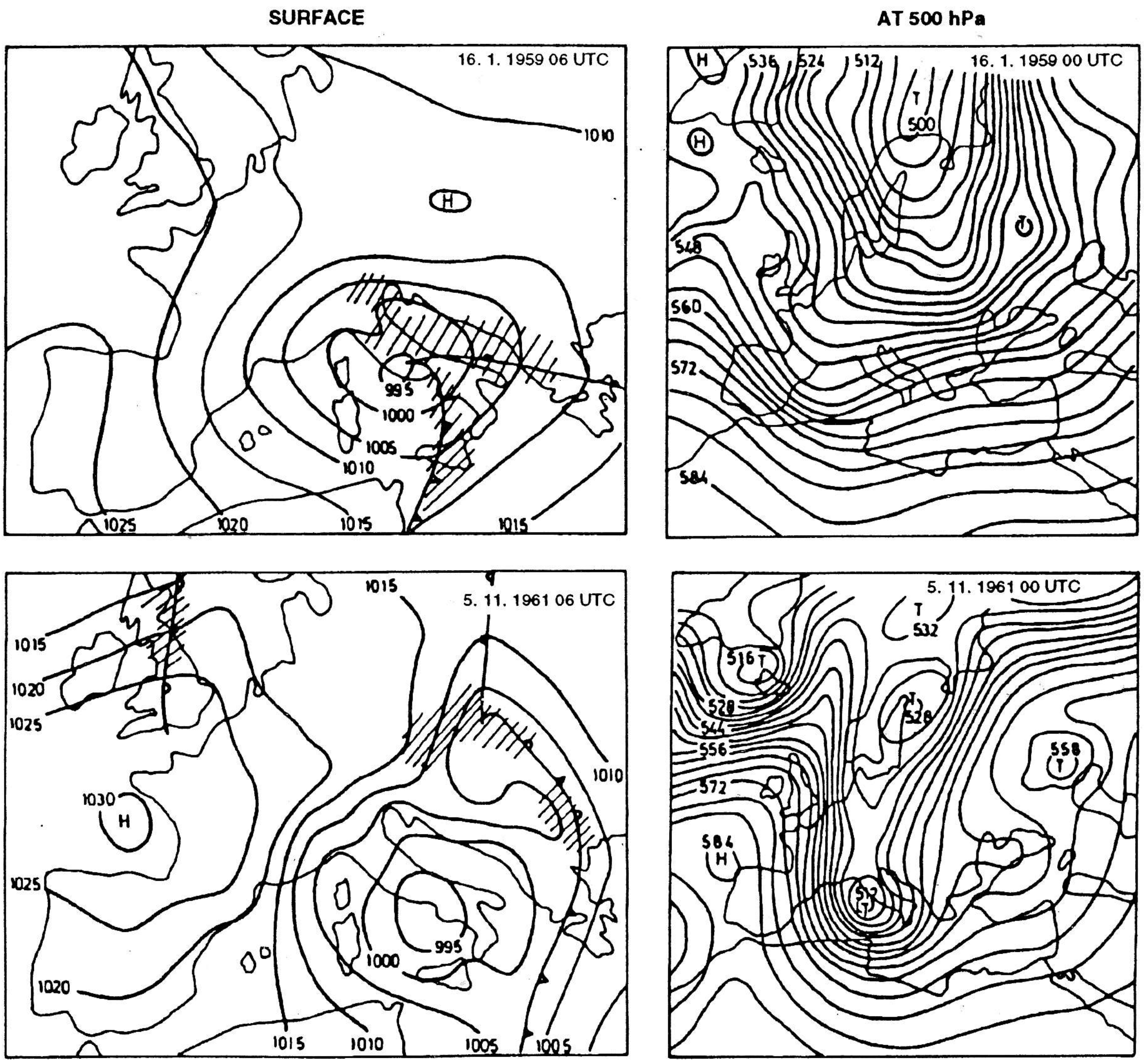


Figure 5. Analysis of the surface synoptic situation over Europe at 06 UTC (left) and AT 500hPa at 00 UTC (right) for severe bora situations in the period 1959-1963.

Slika 5. Prizemna sinoptička analiza iznad Europe u 06 UTC (lijevo) i AT 500hPa u 00 UTC (desno) za situacije s olujnom burom u razdoblju 1959-1963.

reducing the bora component u_B and causing $\hat{h}>1$. According to Smith's theory (1985) a transient flow across the mountain is not possible. In order to enable the incoming flow to fall over towards the Adriatic, at the same wind speed and stability either, $\hat{h}$ has to equal 1 or the mountain height should not be exceed 500 m (Tab. 1).

The predicted results are in good agreement with the observations such as the height of upstream bora layer and the maximum surface perturbation velocity (Eq. 3) could be compared with the maximum bora gust in Split. The theoretical pressure difference is close to the real value of Δp between the continental and coastal areas. The Froude number depending on $\hat{h}$ (Fig. 1c) agrees with the theoretical values. However, the theory overestimates the height of the streamline descending towards the sea ($\delta^*_c \approx$ 1500-1800 m). According to the data in Split the descend was 750-900 m, this is why the downstream bora layer was twice as thick as estimated.

The situation on 4-7 November 1961

The severe bora observed in Split had a frontal character associated with a cool air outbreak from the Atlantic (Fig. 5). The absence of a normal diurnal temperature variation was marked at Senj and in Split. It is visible that the cool air arrived only to the mid-Adriatic (Fig. 4). As a consequence, the occurrence of a brief severe bora was observed at Senj and in Split. In Dubrovnik the wind speed did not exceed 10.0 ms^{-1} (Fig. 3). The bora region was in front of an upper-level cyclone, in the strong uniform S-SE flow which extended to the lower tropospheric layer in Belgrade (Fig. 1). As there was no bora layer above Belgrade the hydraulic parameters on this location were not calculated.

The maximum wind speed in Split occurred in the surface layer. The theoretical profile of $u_T(x_I,z)$ obtained by sounding over Zagreb follows the vertical profile of the empirical values of u over Split (Fig. 7). The predicted values of u_T are overestimated, but the estimated surface wind speed agrees with the maximum bora gust of 36.5 ms^{-1} in Split.

The hydraulic parameters were determined for 5 November at 12 UTC, immediately before the severe bora onset in Split. The vertical variation of N was almost constant. The estimated hydraulic parameters for continuous stratification case show that point 3 (Fig. 1c) is close to the theoretical curve F_0 depending on $\hat{h}$. The predicted values of Δp^* are significantly underestimated for the mid-Adriatic. This application of the theory shows that some parameters can be well estimated in case of a brief severe frontal type bora.

The situation on 27 January-1 February 1962

In this situation, severe bora lasted for 23 hours. The onset impulse of the bora caused a cold and dry air outbreak leading to a cut-off process in the upper troposphere, similar to the first situation. The basic feature of this process is a deep trough above central Europe and a pronounced ridge over the northeastern Atlantic leading to the well-known blocking circulation. Since this case was quasi-stationary with shallow but strong anticyclone in the surface layer (1040 hPa in its centre), this caused a long-lasting bora condition along the Adriatic coast (Figs. 3 and 6). The surface cyclone activity in the western Mediterranean intensified the bora component to gale force. During the severe bora on 29/30 January the eastern part of the bora area was under the influence of the front side while the western part was under the influence of the back side of the upper-level cyclone. That provoked a different tropospheric wind direction above Belgrade (a strong S wind) and Zagreb. The NE wind over Zagreb extended throughout the entire troposphere with a maximum wind speed inside the bora layer (Fig. 6). In Split the wind aloft decayed and turned to S.

In Figure 1c point 5 is significantly displaced from the theoretical curve $F_0(\hat{h})$. It can be seen that the available upper data above Zagreb and Belgrade on 30 January were not representative as upstream bora condition over the mid-Adriatic. On the following day, the temperature and wind structure over Zagreb and Belgrade were similar and better results were obtained fitting the one-layer model. Points 6 and 7 in Figure 1b. indicate a possible hydraulic jump on the lee side as a consequence of a subcritical upstream flow (F_0=0.41 for Belgrade) and a supercritical downstream flow (F_0=1.05 for Split). The predicted pressure difference provided better results for the northern Adriatic area than for the mid-Adriatic. The theoretical curve of $u_T(x_I, z)$, according to the Zagreb sounding follows the vertical profile of u_B above Split. In the case of the $u_T(x_I, z)$ values of the Belgrade sounding no similarity can be noticed (Fig. 7).

The situation on 13-17 March 1962

The considered situation presents the strongest and longest-lasting bora event in Split (25 hours), where bora resembled a hurricane. The maximum mean hourly wind speed reached 29.2 ms^{-1}. This is the absolute maximum wind speed measured in Split and along the coast. At Senj 28.9 ms^{-1} were registered on 12 December 1967. The situation on March 1962 is very interesting as it is the only considered case of severe bora occurrence in Dubrovnik. On 15 March, a wide surface anticyclone formed above Europe and a very deep cyclone over the Tyrrhenian Sea (985 hPa in the centre). Such surface distribution of the baric system built up a very large pressure difference across the Dinaric Alps (Δp=19.7 hPa). Similar to the bora storm of January 1962 the type of blocking circulation maintained a lasting bora along the Adriatic. The upper-level situation was quite similar to the other bora storms mentioned above: the NW-W jet and a dynamic unstable upper-level trough lead to a cut-off process above northern Africa. Due to the effects of the upper-level cyclone, a strong uniform S flow aloft developed in the upstream and downstream bora region. The bora decay on 16/17 March was linked to a typical upper-level ridge above the northeastern Atlantic and to an increase in the NE wind speed aloft on the windward side.

The vertical temperature structure in the continental and coastal regions during the severest bora case in Split was very complex with 2 to 3 upper-level inversions in the low troposphere. The vertical temperature gradient (1.5-2°C/100m) above Zagreb, before the bora onset, and in Split during the gale (16 March at 00 UTC) provoked extremely stable layers with the Brunt-Väisälä frequency ~ 4×10^{-2} s^{-1}. As a very complex stability profile prevailed a multi-layer model had to be used for hydraulic parameters estimations. In order to simplify the calculation, a continuous stratification was assumed.

The upstream bora layer above Zagreb was the thickest (3-3.5km), in all the bora events considered, with a strong wind shear and a maximum wind speed inside it (35ms^{-1} at a 2.4km altitude on 16 March at 00 UTC).

The mean wind speed of 18.5 ms^{-1} inside the upstream bora layer is close to the assumed value of 20ms^{-1} which is often used in theoretical research of severe downslope winds. Therefore, this special severe bora case in Split can be used to understand the bora dynamics in relation to other severe storms in different parts of the world. A weaker flow (5-7ms^{-1}) inside the bora layer above Belgrade led to an effective mountain height greater than 1 and thus was presumed $\hat{h} = 1$. In a mountain pass (as for example Vratnik near Senj) it is possible to assume that h is smaller than the mountain height. The long-lasting bora in Senj proves that (Vučetić, 1988). With a high mountain range (the Dinaric Alps) it is justified to presume (Smith, 1989) that in quasi-stationary situations the cold surface air accumulated upstream maintains $\hat{h} \sim 1$ and reduces h for the depth of the blocked air.

When considering the blocked pattern on a large scale, cold air occupied the Pannonian Plane and at this bora stage it is justified to assume $\hat{h} \sim 1$. Points 9',10' and 11' in Figure 1c are close to the theoretical curve for continuous stratification. The same conclusion applies to points 8, 9 and 10 which were obtained by to the Zagreb soundings.

Thus, the hydraulic theory can explain the mechanism of severe storm in Split, in the case of a uniform surface wind speed. The theoretical value of the perturbation velocity at the surface agrees with the bora gust of 42.2 ms^{-1} in Split. The vertical profile $u_T(x_1,z)$, however, according to Zagreb and Belgrade data illustrates again a strong wind shear in the lower troposphere in relation to the u_B component above Split.

Table 1. Hydraulic parameters for Zagreb, Belgrade and Split for severe bora situations in the period 1959-1963.

Tablica 1. Hidraulički parametri za Zagreb, Beograd i Split u situacijama s olujnom burom u razdoblju 1959-1963.

Two-layer model

	H_a [m]	d [m]	r	N_2 [s^{-1}]	U_B [ms^{-1}]	l_2^{-1} [m]	h	H_a^* [m]	d^* [m]	h^* [m]	F_o	F_o^*	H_{ef} [m]	H_{ef}^* [m]
16 March 1962 00 UTC														
Zagreb	2119	1516	1.40	0.015	18.5	1268	0.63	3804	3018	254	0.59	0.31	2877	5313
3 December 1962 00 UTC														
Zagreb	1131	1538	1.36	0.015	15.4	1002	0.80	2986	3006	180	0.58	0.28	1900	4489
Belgrade	1438	2258	1.57	0.014	7.2	506	1.58	1316	1493	961	0.21	0.29	2567	2063

Single layer model

	H_o [m]	d [m]	N_o [s^{-1}]	U_B [ms^{-1}]	l^{-1} [m]	h	F_o	h/H_o	H_o^*	F_o^*	$(h/H_o)^*$
16 March 1962 00 UTC											
Split	2829	98	0.042	15.3	364		0.69				
22 January 1963 00 UTC											
Zagreb	1991	159	0.031	13.0	420	1.91	0.75	0.40	921	0.28	0.87
Split	2580	80	0.049	10.0	208		0.46				
24 January 1963 00 UTC											
Zagreb	3119	454	0.022	15.3	695	1.15	0.58	0.26	6667	0.41	0.12
Belgrade	2485	139	0.031	4.9	158	5.06	0.27	0.32	1951	0.35	0.41
Split	1665	385	0.023	12.5	536		1.12				

Continued.

Continuous stratification

	H_o [m]	N [s^{-1}]	U_B [ms^{-1}]	l^{-1} [m]	$\hat{h}$	$\hat{h}'$	H_o^* [m]	δ_c [m]	δ_{cl} [m]	H_l^* [m]	u [ms^{-1}]	F_o	F_o^*	Δp [hPa]	Δp^* [hPa]
18 January 1959 00 UTC															
Zagreb	2679	0.017	8.0	477	1.68	1.00	2590	-610	-1841	749	38.9	0.18	0.18	6.6	6.3
Belgrade	709-2476	0.017	9.5	567	1.41	1.00	2925	-756	-2035	890	43.6	0.32	0.19	5.8	7.2
Split	1709	0.015	9.9	663							+38.4	0.39		10.7	
5 November 1961 12 UTC															
Zagreb	2689	0.010	8.2	828	0.97		3874	-1030	-2574	1300	33.7	0.31	0.21	5.8	3.6
Belgrade	-	-	-	-	-		-	-	-	-	-	-	-	11.2	-
Split	1450	0.011	10.0	938							+36.5	0.65		13.9	
30 January 1962 00 UTC															
Zagreb	2754	0.008	12.2	1567	0.51		5597	-1270	-3136	2461	36.6	0.57	0.28	5.6	4.1
Belgrade	1376	0.014	12.2	892	0.90		4030	-1052	-2629	1401	48.2	0.65	0.22	5.4	7.4
Split	2938	0.009	11.6	1349										11.2	
15 March 1962 00 UTC															
Zagreb	3448	0.012	12.4	994	0.80		4259	-1081	-2698	1561	46.1	0.29	0.23	9.6	5.9
Belgrade	2088	0.014	7.2	515	1.55	1.00	2730	-659	-1921	809	34.1	0.25	0.19	12.6	4.5
Split	1843	0.016	5.0	307							+42.2	0.17		13.9	
15 March 1962 12 UTC															
Zagreb	3726	0.013	17.3	1311	0.61		5015	-1190	-2956	2059	56.3	0.35	0.26	7.9	9.1
Belgrade	2109	0.014	5.1	375	2.13	1.00	2205	-480	-1615	589	27.1	0.18	0.17	11.5	3.7
Split	1930	0.015	11.4	784							+42.2	0.41		15.5	
16 March 1962 00 UTC															
Belgrade	2380	0.015	7.2	467	1.71	1.00	2550	-598	-1817	733	35.2	0.20	0.18	12.1	4.8
3 December 1962 00 UTC															
Split	2615	0.013	4.3	327								0.13		17.1	
22 January 1963 00 UTC															
Belgrade	919	0.005	2.7	5000	0.16		12708	-2082	-4854	7854	5.3	5.44	0.39	12.8	6.0

List of symbols:

-	bora layer does not exist
*	theoretical values
+	absolute maxima bora gust at Split

continous stratification

H_o	upstream bora layer height
N	stability of bora layer
U_B	mean wind speed in the upstream bora region
$l=N/U_B$	Scorer parameter
h	mountain height $\hat{h}=hl$ h=800 m
δ_c	vertical displacement of the critical streamline over the mountain crest
δ_{cl}	vertical displacement of the critical streamline on the lee side
$H_l^*=H_o^*+\delta_{cl}$	predicted downstream bora layer height
u	predicted surface bora wind
$F_o=U_B/NH_o$	upstream Froude number
Δp	pressure difference between the upstream and downstream bora region

Zagreb	$\Delta p=p(ZG)-p(Senj)$
Split	$\Delta p=p(Sl.Brod)-p(ST)$
Belgrade	$\Delta p=p(BG)-p(Dubrovnik)$

two-layer model

H_a	depth of the neutral lower layer
d	depth of the stable upper layer
N_2	upper layers stability
$F_o=U_B/N_2^2dH_{ef}$	Froude number with the effective height $H_{ef}=H_a+0.5d$

single layer model

$F_o=U_B/g'H_o$	Froude number

$h/H_o=1+0.5F_o^2-1.5F_o^{2/3}$

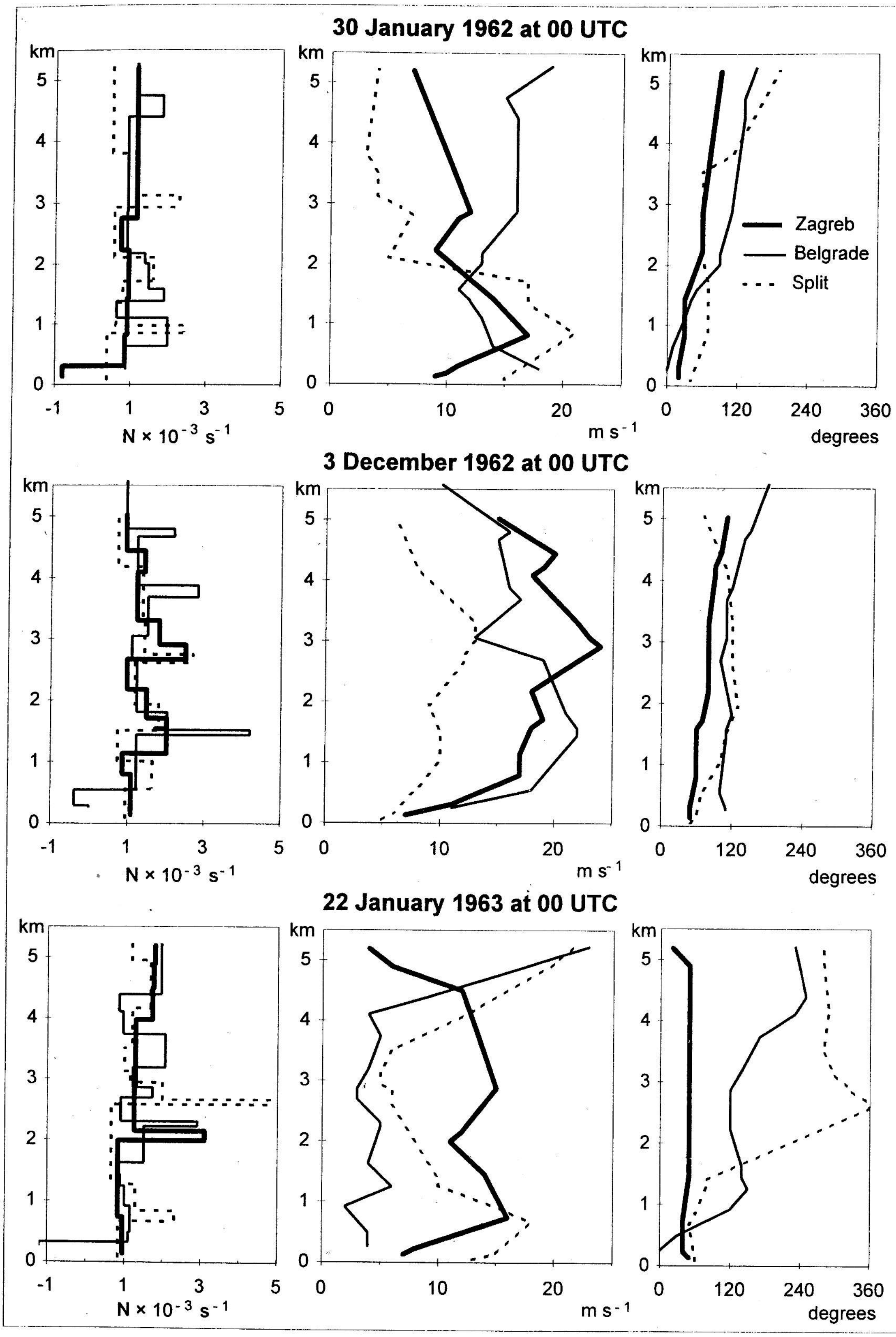


Figure 6. Vertical profiles of stability *N*, wind speed and direction for bora situations in the period 1959-1963.

Slika 6. Vertikalni profili stabilnosti *N*, brzine i smjera vjetra za situacije s olujnom burom u razdoblju 1959-1963.

The situation on 27 November - 6 December 1962

In that period, severe bora occurred at Senj on 29 November and 3 December. It is interesting to point out that during the first bora storm at Senj a weak bora prevailed in Split (Fig. 3). The reason for that is a light wind inside the shallow upstream bora layer which could not pass across the broad and high Dinaric Alps. The mountain pass Vratnik and the narrow barrier close to Senj allowed an advection of cold air from the mainland and caused severe bora only at this location (Vučetić, 1988). The severe bora event in Split on 2 December was associated with the large pressure difference between a strong and wide anticyclone above central Europe and a shallow cyclone over the Tyrrhenian Sea. The position of the upper-level cyclone above the western Mediterranean provoked a different upper wind direction above Zagreb (NE wind) and Belgrade (W-WS wind). In this bora case there were also two upper-level inversions upstream, but their intensity was twice smaller than in the previous situation. The depth of the upstream bora layer varied between 2.5-3.5 km.

The vertical stability profiles show a layer-like structure above Zagreb and Belgrade (3 December at 00 UTC, Fig. 6). Points 12 and 13 for Zagreb in Figure 1 belong to the area of partial blocking on the upstream side. The current was subcritical above Belgrade and on the lee side, which is confirmed by the small values of the Froude number (Tab. 1).

As in the previous cases, large differences appear between the estimated and empirical values of the pressure difference across the Dinaric Alps. The measurement value was 16 hPa and the theoretical only 4 hPa.

The situation on 17-26 January 1963

As in the previous situations, except November 1961, the bora onset was connected with a very cold and dry air outbreak so that the minimum relative humidity was 19% in Split and 15% in Dubrovnik, while the air temperatures were -8.8°C and -6.3°C, respectively (Fig. 4). A typical large scale blocking pattern maintained a long bora duration along the Adriatic coast (124 hours at Senj). Between the 22 and 24 January a very interesting event occurred. The strengthening of the NE current aloft in Zagreb on 22 January provoked a rapid surface bora decay at Senj. It also caused bora speed variations on the mid-Adriatic but the bora in Split kept its gale force. It can be explained by a greater similarity in the circulation over Split and Belgrade (W-WS wind) than in that over Zagreb (Fig. 6) which caused a narrow upper-level trough above the bora region.

On 24 December, the bora at Senj intensified while the NE flow in the upper troposphere above Zagreb decayed. The bora layer above Zagreb was not so thick as in the two previous bora stages. Above Belgrade, the bora layer was not extended from the surface. A light W wind prevailed in the boundary layer. On the 22 and 24 January a neutral layer was covered with a very thin stable layer above Zagreb.

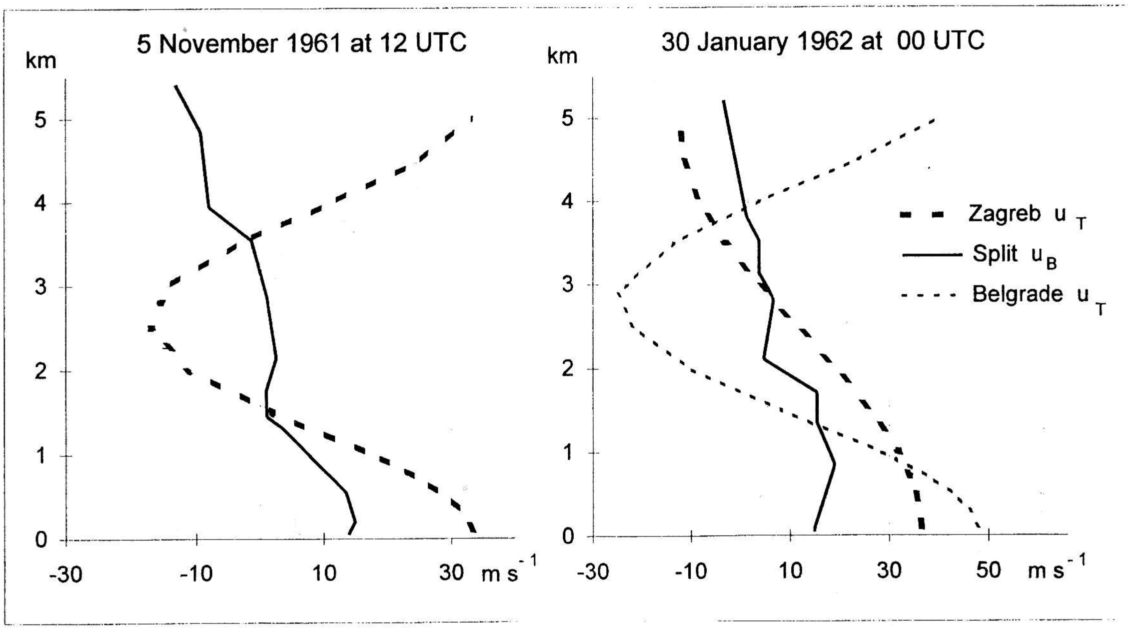


Figure 7. Vertical profiles of the theoretical perturbance of velocity u_T, according to Zagreb and Belgrade aerological data and the bora component u_B in Split for severe bora situations in the period 1959-1963.

Slika 7. Vertikalni profili teorijske brzine u_T prema aerološkim podacima Zagreba i Beograda i komponenta bure u_B u Splitu u situacijama 5. studenog 1961. u 12 UTC i 30. siječnja 1962. u 00 UTC.

These profiles of N meet the presumptions of the one - layer model (Fig. 1b, Tab. 1). A very interesting event occurred in Belgrade on 22 January. A small value of $\hat{h}=0.16$ was obtained because of a small stability and a weak wind in the thin bora layer. This means, that instead of a hydraulic flow in the lower troposphere, there was a vertical propagation of gravity waves throughout the atmosphere.

On the following day, an accumulation of very cold air (-10°C to -15°C) occurred in Zagreb up to 500m and in Belgrade up to 1 km accompanied by a weak wind (2-3 ms^{-1}). Therefore, the estimated hydraulic parameters were calculated with $\hat{h}=1$ (Tab. 1, point 16 in Fig. 1c) similarly to the situation on March 1962.

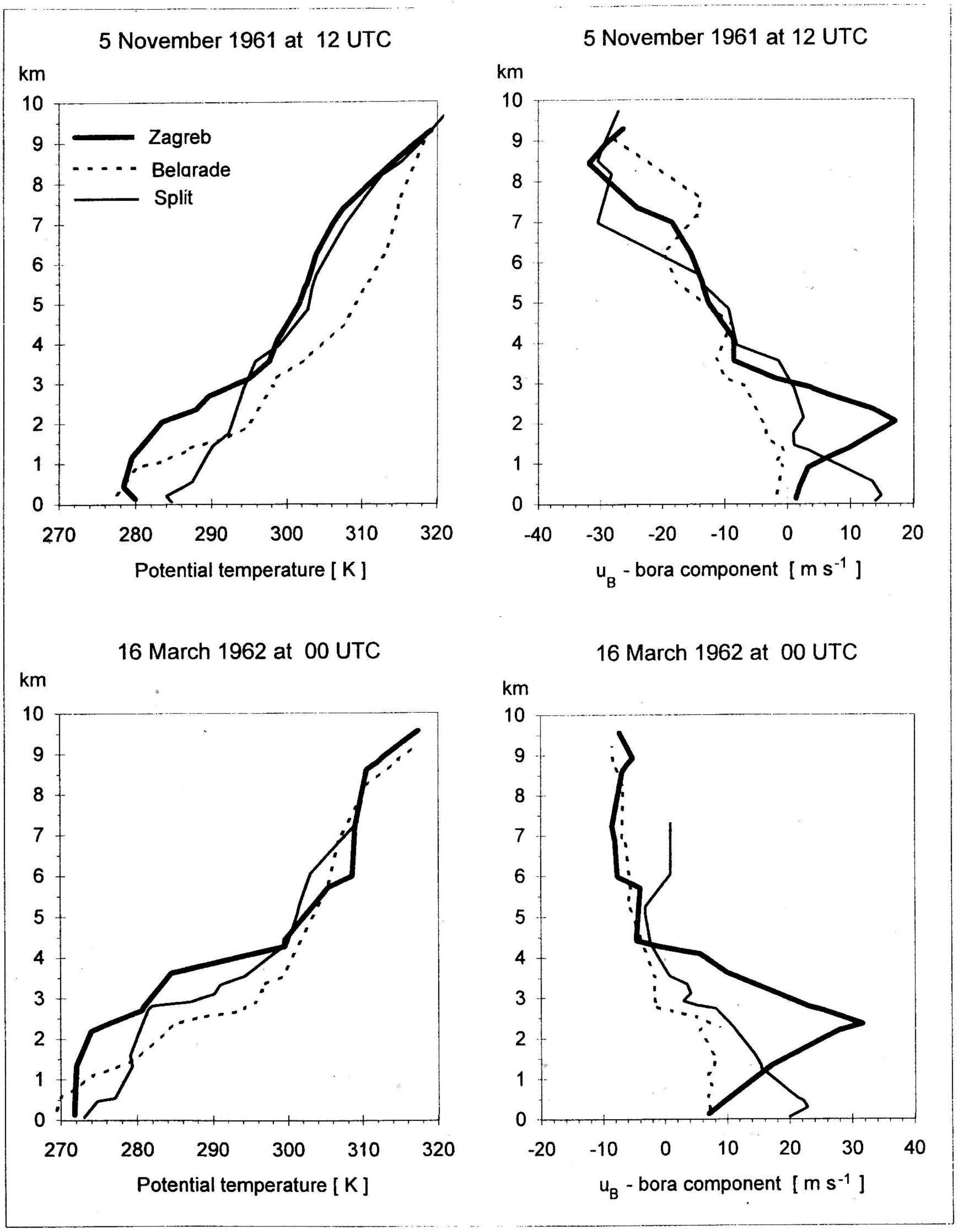


Figure 8. Vertical profiles of potential temperatures (θ in K) and u_B - bora components for Zagreb, Belgrade and Split on 5 November 1961 at 12 UTC and on 16 March 1962 at 00 UTC.

Slika 8. Vertikalni profili potencijalne temperature (θ u K) i u_B- komponente bure u Zagrebu, Beogradu i Splitu za 5. studeni 1961. u 12 UTC i 16. ožujak 1962. u 00 UTC.

On 24 January, a possibility of a hydraulic jump existed on the lee side (point 17, Fig. 1b) which is in accordance with the observed Froude number, the subcritical upstream flow (F_o=0.58 for Zagreb and F_o=0.27 for Belgrade) and the supercritical downstream flow (F_o=1.12 for Split).

Considering the complex upstream structure of the real atmosphere in the most severe bora storms on the mid-Adriatic the hydraulic theory with continuous stratification (8 cases for Zagreb and 11 for Belgrade) seemed the most acceptable. A layer-like vertical structure with two upstream layers of different stability was noticed in 3 cases above Zagreb and in 2 cases above Belgrade, whereas a neutral layer covered with thin inversion appeared in 4 and in 3 cases, respectively.

This analysis indicates that the occurrence of persistent severe bora along the Adriatic requires a thick bora layer with a strong mean wind speed (>10 m s^{-1}) inside it and a pronounced inversion above. It indicates a similar mechanism for the persistence of the severe bora in quasi-stationary situations on the northern and mid-Adriatic.

Although it was excepted that the aerological data above Belgrade would better present the upstream bora region of the mid-Adriatic better than those above Zagreb, in most cases the vertical atmospheric structure above Split resembled the structure above Zagreb. This is reason why Zagreb data are generally acceptable for the upstream conditions in bora cases on the northern and mid-Adriatic.

The application of the hydraulic theory on quasi-stationary situations has helped to successfully estimate the maximum speed of the surface lee wind and the height of the critical streamline on the lee side. The predicted pressure differences across the mountain, only when provoked by a hydrostatic equilibrium as a consequence of a descending critical streamline, could not explain the total pressure gradient. In most cases Δp was significantly greater than Δp^* because the orographic blocking effect intensified the horizontal pressure gradient across the Dinaric barrier after a cold air outbreak. The application of the hydraulic theory demonstrates the nature of the physical process of a strong downslope wind. On the mid-Adriatic, where a complex orographic situation prevails the complexity of the real atmosphere is difficult to explain only through the two dimensional model. Therefore, in the following chapter the bora problem is approached through three-dimensional analyses.

THREE-DIMENSIONAL ANALYSIS OF THE BORA STRUCTURE

In this paper two different situations of severe mid-Adriatic bora (5 November 1961 at 12 UTC and 16 March 1962 at 00 UTC) have been singled out resulting from the application of the hydraulic theory and the results of the analysis. The first situation was a brief, severe frontal type bora, while in the second situation an upstream blocking pattern and a deep cyclone above the Tyrrhenian Sea caused the strongest and longest-lasting bora in Split. The previous analysis of the up and downstream vertical profiles of wind and temperature indicated three-dimensional bora effects.

This is why we analysed the three atmospheric structure on the basic of the sounding data for Zagreb, Belgrade and Split.

Two important points can be noticed on the vertical profiles of potential temperature (Fig. 8). The first point is represented by the lower base of the stable layer up and downstream which corresponds to the amount of θ=284 K in the first and θ=276 K in the second case. Slightly below, the NE wind reaches its maximum value over Zagreb and Split. The flow rapidly decreases toward Belgrade and wind shear is less noticeable over the eastern part of the observed area. On 5 November the NE wind did not occur above Belgrade, but a weak W wind was prevailing up to 1 km altitude.

The second interesting point in the lower layer of the troposphere is the intersection of the potential temperature curves over Zagreb and Split (θ=294.5K in the first and θ=300K in the second case) which corresponds to the altitude of the critical streamline (the upper boundary of the bora layer). The wind on the upper isentropic level abruptly changes to the ESE direction.

Although they deal with different cases, Figures 9a and 10a are quite similar. The lower isentropic level slopes steeply from Zagreb to Split with a somewhat lower inclination towards Belgrade. The upper θ-level is at a relatively constant altitude (of 2.8 km in the first and 4.3 km in the second case) between Zagreb and Split and separates the lower and higher tropospheric layers. According to Smith's hydraulic theory a vertical decoupling of the low-level streamline should be present. However, the 294.5K and 300K level descending by ~1 km towards Belgrade implies a horizontal split streamlines around an obstacle and marked three-dimensional effects.

Such difference in the distribution of wind fields on the observed isentropic level brought about dynamic changes inside and above the bora layer. The kinematic method was therefore used to define horizontal divergence and relative vorticity along the θ-levels. The point grid 12×7 with $\Delta x = 27$ km and $\Delta y = 36.5$ km over the observed area was accurate enough to define these value from the aerological data from Zagreb, Split and Belgrade.

An analysis of horizontal divergence and relative vorticity at θ-level in the bora layer in both situations showed a prevalence of anticyclone vorticity with a downslope movement over the western part and an upslope movement over the eastern part inside the bora layer and divergent flow components at the top of the layer (Figs. 9 and 10). The first and the second term in the relation of horizontal divergence have opposite sign which means that stretching along one axis is compensated by shrinking along the other and there is attendant deformation.

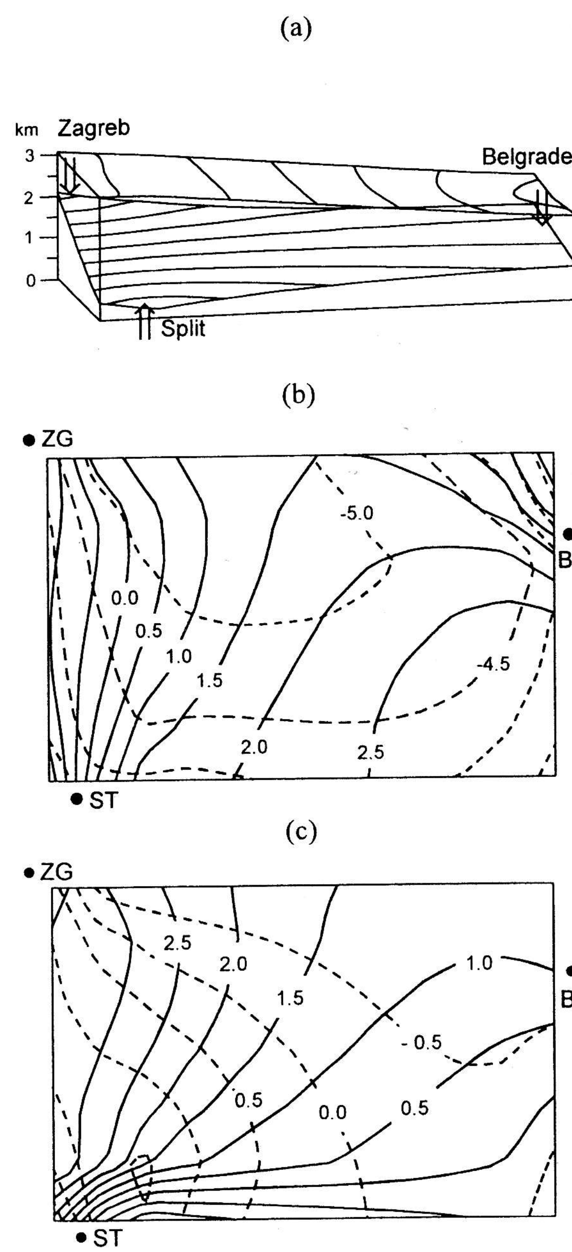
The maximum value of the anticyclone vorticity ($-5 \times 10^{-1}\ s^{-1}$) in the lower troposphere in the northwestern area observed on 5 November (Fig. 9b) presents well-known horizontal split streamlines around the eastern Alps and cold air penetrates the Adriatic area. In the second case, on the contrary an intensive anticyclone vorticity occupies the entire Pannonian Plane (Fig. 10b). Thus, it is obvious that the cold air arrived directly from the north of Europe. This is confirmed by a prevalent N wind component in the upstream bora region. A negative vorticity of slight intensity also dominated on the upper isentropic level (Fig. 10c). Therefore, on 16 March a strong anticyclone circulation spread as far as the middle-layers of the troposphere, which did not happen on 5 November. From what has been said it is clear that an intensive development of the synoptic situation is necessary for a long-lasting severe bora occurrence along the mid-Adriatic. A wide and strong anticyclonic activity over the mainland results in long bora duration. A large mesoscale difference in pressure (Δp 15 hPa) over the Dinaric mountain range, between a continental anticyclone and a deep cyclone over the southern Adriatic intensifies the bora component to gale force.

Although the application of the two-dimensional hydraulic theory on severe bora in the mid-Adriatic (16 March 1962) has contributed to the knowledge of the bora as a gale force wind, it could not comprise all the complexity of the real atmosphere on the mid-Adriatic backed by the high and wide mountain range of the Dinarides. The three-dimensional analysis has pointed out the stability variations in space and vertical flows not only between the mainland and the Adriatic but also between the western and eastern part of the upstream bora region. These results, therefore, show that by taking into consideration the three-dimensional and orographic effects it would be possible to explain the occurrence of severe bora on the Adriatic.

CONCLUSION

The analysis of six severe bora cases in Split have shown that the initial bora impulse causes a cold and dry air outbreak towards the Adriatic. The large pressure gradient between a strong and wide continental anticyclone and cyclone activity above the western Mediterranean or Tyrrhenian Sea intensifies the bora component. The pronounced upper-level ridge above the northeastern Atlantic, the axis of which is in the NE-SW direction, increases the NE tropospheric wind directly causing a surface bora decay. The upper situation during severe bora is characterised by a trough of large amplitude which is developed in an upper-level cyclone by a cut-off process. The position of the trough or cyclone directly influence the up and downstream flow aloft.

5 November 1961 at 12 UTC



ZG - Zagreb BG - Belgrade ST - Split

Figure 9. A three-dimensional illustration of isentropic levels 284K and 294.5K (a); horizontal divergence (solid line, $10^{-5}\ s^{-1}$) and relative vorticity fields (dashed line, $10^{-5}\ s^{-1}$) on isentropic levels 284K (b) and 294.5K (c) for 5 November 1961 at 12 UTC

Slika 9. Trodimenzionalni prikaz izentropskih ploha 284K i 294.5K (a); polja horizontalne divergencije (puna crta, $10^{-5}\ s^{-1}$) i relativne vrtložnosti (isprekidana crta, $10^{-5}\ s^{-1}$) na izentropskim plohama 284K (b) i 294.5K (c) za 5. studeni 1961. u 12 UTC.

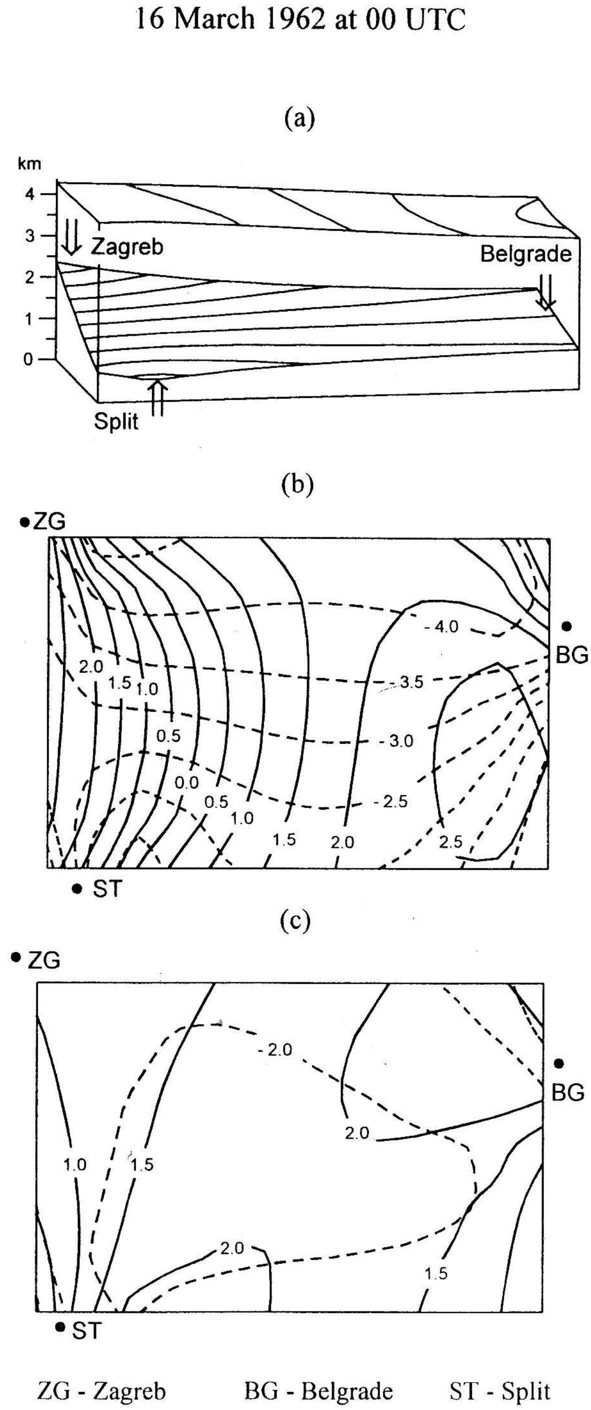


Figure 10. A three-dimensional illustration of isentropic levels 276K and 300K (a); horizontal divergence (solid line, 10^{-5} s^{-1}) and relative vorticity fields (dashed line, 10^{-5} s^{-1}) on isentropic levels 276K (b) and 300K (c) for 16 March 1962 at 00 UTC.

Slika 10. Trodimenzionalni prikaz izentropskih ploha 276K i 300K (a); polja horizontalne divergencije (puna crta, 10^{-5} s^{-1}) i relativne vrtložnosti (isprekidana crta, 10^{-5} s^{-1}) na izentropskim plohama 276K (b) i 300K (c) za 16. ožujak 1962. u 00 UTC.

The analysis of the considered bora stages indicates some characteristic types of upper wind:

a) The centre of the upper-level cyclone is located in the north of the upstream bora area and it is influenced by the NW-W jet. A brief severe bora occurs only at Senj. The bora layer is shallow with a weak NE wind on the windward side and the flow can not fall over a wide obstacle towards the mid-Adriatic.

b) The bora area is under the influence of the front side of an upper-level trough in a strong uniform flow aloft from S.

c) A weak NE tropospheric wind occurs upstream if the back side of the trough is above the bora area. The maximum wind speed is inside the bora layer. In both cases a thick bora layer and a strong NE wind in the lower troposphere cause severe bora in Split.

d) A very narrow upper-level trough over the bora region leads to a reversed upper wind above Zagreb (NE wind) and Belgrade (SW wind). If the upper-level ridge simultaneously intensifies above the north-eastern Atlantic, the speed of the NE wind aloft increases only above Zagreb, the Senj's bora decays, but not the bora on the mid-Adriatic. In this case the upper circulation above Split resembles the circulation above Belgrade and not the one above Zagreb. Therefore, in such a case the Zagreb aerological data are not representative of the mid-Adriatic upstream bora region. For this reason aerological measurements should be introduced somewhere on Slavonija (for example Slavonski Brod) and soundings in Split should be restored.

Brief severe boras on the northern and mid-Adriatic are associated with a fast movement of a cut-off process above the Adriatic and those are frontal type boras.

This analysis has shown that severe bora is the consequence of a large-scale situation above Europe and the Mediterranean. Differences in the mechanism of severe bora maintenance on the northern and mid-Adriatic exist in situations with a strong NW upper wind and a shallow bora layer. In those cases a severe bora occur only at Senj.

It has also been shown that during severe bora on the mid-Adriatic, besides surface or elevated inversions, one or two upper-level inversions were reflected in the upstream region. Such inversions separate the higher and lower atmospheric air flow and make the lower fluid behave according to the hydraulic law. The data support the same mechanism for severe bora generation and its continuance in quasi-stationary situations on the northern and mid-Adriatic.

Severe bora on the mid-Adriatic, where the broad and high Dinaric mountain range opposes the upstream flow, is connected to a thick bora layer above Zagreb ($\overline{H}_0$=2.8 km) within which a strong NE air flow occurs ($\overline{U}_0$=12.1 m s^{-1}). The upper boundary of this layer splits over the mountain (Split $\overline{H}_l$=1.8 km with $\overline{U}$=9.1 m s^{-1}) in agreement with the modelling assumption but it has also been found that this isentropic layer descends to the east toward Belgrade ($\overline{H}_0$=2.3 km with $\bar{U}_0=7.3\,m\,s^{-1}$) which can not be accepted in two-dimensional models.

Thus, although the application of the hydraulic theory with small variations of surface bora intensity successfully estimated the maximum bora velocity and the downstream bora layer height, analyses show that the two-dimensional hydraulic theory could not completely explain bora occurrence on the mid-Adriatic. This required a study of a three-dimensional bora structure which was carried out by analysing aerological data from Zagreb, Belgrade and Split.

It has been shown that the upstream structure of the lower troposphere over Belgrade does not always indicate a NE flow perpendicular to the mountain range, as the usual case is in the northern Adriatic (Zagreb).

An anticyclonic relative vorticity field prevails in the bora layer along the steeply sloping isentropic level toward the Adriatic, appears over the western part of the bora region and convergence field over its eastern part. This is obviously a sign of a three-dimensional upstream structure in the mid-Adriatic bora flow.

Consequently, this analysis emphasises, the spatial and temporal variations of the wind field and stability during bora occurrence not only along the NE bora flow, but also perpendicular to this flow in the upstream area. This study, therefore, concludes that a complete picture of the bora structure and consequently its dynamics can only be achieved by applying three-dimensional models and the corresponding wind and temperature fields.

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REFERENCES

Baines P.G. (1987) Upstream blocking and airflow over mountains. *Ann. Rev. Fluid Mech.* **19**, 75-97.

Bajić A. (1988) The strongest bora event during ALPEX-SOP. *Rasprave-Papers* **24**, 1-9.

Bajić A. (1989) Olujna bura na srednjem Jadranu. *Vijesti PMC* **1**, Split, 13-19.

Bajić A. (1990) Severe bora on the northern Adriatic, Part II: Time and space variations. *Rasprave-Papers* **25**, 13-24.

Bajić A. (1991) Application of the two-layer hydraulic theory on the severe northern Adriatic bora. *Meteorologische Rundschau* **44**, 129-133.

Glasnović D. and Jurčec V. (1990) Determination of upstream bora depth. *Meteorol. Atmos. Phys.* **43**, 137-144.

Ivančan-Picek B. and Vučetić V. (1990) Bora on the northern Adriatic coast during the ALPEX SOP 20-25 March 1982. *Rasprave-Papers* **25**, 1-12.

Jurčec V. (1988) The Adriatic frontal bora type. *Rasprave-Papers* **23**, 13-25

Jurčec V. (1989) Severe Adriatic bora storms in relation to synoptic developments. *Rasprave-Papers* **24**, 11-20.

Jurčec V. and Visković S. (1989) O uzrocima bure u Splitu. *Vijesti PMC* **35**, 20-26.

Long R.R. (1953) Some aspects of the flow of stratified fluid, A theoretical investigation. *Tellus* **5**, 42-58.

Smith R.B. (1985) On severe downslope winds. *J. Atmos. Sci.* **42**, 2598-2603.

Smith R. B. (1987) Aerial observations of the Yugoslavian bora. *J. Atmos. Sci.* **44**, 269-297.

Smith R.B. (1989) Hydrostatic airflow over mountain. *Adv. Geoph.* **31**, 1-41.

Smith R.B. and Sun J. (1987) Generalized hydraulic solutions relevant to severe downslope winds, *J. Atmos. Sci.* **44**, 2934-2939.

Tutiš V. (1988) Bora on the Adriatic coast during ALPEX SOP on 27-30 April 1982. *Rasprave* **23**, 45-56.

Vučetić V. (1988) Bora on the northern Adriatic 12-18 April 1982. *Rasprave* **24**, 27-44.

Vučetić V. (1991) Statistical analysis of severe Adriatic bora. *Hrv. Met. Časopis* **26**, 41-51.

Vučetić V. (1992) The strongest bora event on the mid-Adriatic. *22 ITAM*, 7-11 Sept. Toulouse, 55-59.