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RASPRAVE 25, Zagreb 1990, str. 25 - 36

UDK 551.555.4 : 551.543.5
Originalni znanstveni rad

MOUNTAIN DRAG AND SURFACE PRESSURE VARIATIONS DURING SEVERE ADRIATIC BORA STORMS

Planinski otpor i promjene prizemnog tlaka zraka za vrijeme olujne bure na Jadranu

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Primljeno 5.veljače 1990, u konačnom obliku 11.svibnja 1990.

Abstract: The observed sea-level pressure variations in Senj and pressure difference Zagreb-Senj are presented for 197 observations in 17 case studies considering only the most severe bora storms in Senj from the period 1957-1986. Using Smith's (1985) hydraulic theory with the continuous stratification model, mountain drag is calculated predicting the pressure difference across the mountain in these bora events.

It is shown that the theory can predict well the pressure difference in cases when the atmospheric state is close to the idealized modeling structure. However, due to constraints in the presented model there is a relatively small sampling of such cases, although the real atmosphere allows some reasonable modifications of hydraulic parameters which would be unnecessary if the flow were truly two-dimensional and steady.

Key words: severe bora, hydraulics, mountain drag, surface pressure variations, hydrostatic bora layer, Adriatic storms.

Sažetak: Prikazane su promjene prizemnog tlaka zraka u Senju i razlike tlaka Zagreb - Senj za 197 termina motrenja u 17 slučajeva s ekstremnim olujnim burama u Senju u periodu 1957 - 1986. Primjenom Smithove (1985) hidrauličke teorije računat je planinski otpor koji prognozira razliku tlaka preko planine u promatranim pojavama bure.

Pokazano je da se primjenom teorije mogu dobro prognozirati razlike tlaka u slučajevima kada je stanje atmosfere blizu idealiziranoj strukturi atmosfere modela. Međutim, zbog ograničenja prikazanog modela s kontinuiranom stratifikacijom dobiva se mali uzorak takvih situacija, premda realna atmosfera dozvoljava neke razumne modifikacije hidrauličkih parametara koje ne bi bile nužne da je tok dvodimenzionalan i stacionaran kako je aproksimiran u modelu.

Ključne riječi: olujna bura, hidraulika, planinski otpor, prizemne promjene tlaka, hidrostatski sloj bure, jadranske oluje.

1. INTRODUCTION

Among various problems associated with the local phenomenon of severe downslope windstorms, understanding the pressure drag on mountains is important due to its effect on larger scale flow as well for its general significance in fluid dynamics.

Study of the Adriatic bora flow and associated pressure gradient is particularly attractive, since ALPEX aerial observations have indicated flow acceleration upstream of the mountain ridge. This led Smith (1982) to modify a simple bora model of "fall wind" with acceleration only when the air is moving downslope, by introducing an internal hydraulic mechanism for the bora.

On the basis of ALPEX observations and numerical simulations of severe wind flow by Clark and Peltier (1984), Smith (1985) derived an idealized picture of severe wind configuration and constructed a new theory of severe downslope winds.

In a series of papers (Smith, 1987; Bajić, 1988, 1989; Jurčec, 1988; Tutiš, 1988; Vučetić, 1988; Jurčec and Visković, 1989; Ivančan-Picek and Vučetić, in this issue) the hydraulic theory was successfully applied to the ALPEX bora cases. However, these bora cases in spring are generally of persistent postfrontal bora type characterized by weaker intensity. During ALPEX SOP severe bora speed, usually defined as exceeding 17 m s^{-1}, appeared in Senj only for several hours.

In this paper we are concentrated on attempts to predict the drag on a mountain as a consequence of 2-D hydraulic flow associated with the most severe bora storms in Senj for the period 1957 - 1986. Case studies of these events (Jurčec, 1989a) revealed their association with fast upper level development and cut-off processes. Therefore, we can a priori expect that only particular cases for limited time intervals during the bora period could represent a stationary phase appropriate for consideration of Smith's steady - state model.

2. THEORY

A well known feature of atmospheric flow over orography is the asymmetry in the surface pressure field with high pressure upstream of the mountain and low pressure in the lee. Contrary to this gradient by which the atmosphere acts on the mountain, the mountain exerts a force on the flow which is directed upstream. This phenomenon of mountain drag is a particular case of "pressure drag".

The total force **F** which acts on an obstacle in a moving fluid is given by the surface integral

$$\mathbf{F} = \int_s \tau \cdot \mathbf{n} dA - \int_s p \mathbf{n} dA \qquad (1) \qquad (1)$$

where n is the unit vector normal to the surface element dA, τ is the viscous stress tensor, and p is the pressure (Bannon, 1985).

The first integral in (1) is the contribution to the drag due to viscous stress usually called surface friction, whereas the second integral is mountain drag which depends on pressure distribution over the surface.

The total drag, **D**, on the obstacle is defined as a component of **F** in the direction opposite to the mean flow

$$\mathbf{D} = \mathbf{U} \cdot \mathbf{F}$$

where **U** is a constant unit vector in the direction of mean flow of the fluid.

Smith's (1978) drag measurements on the Blue Ridge Mountain indicated that mountain drag is as important as the skin friction for this region.

Hafner and Smith (1985) transformed the surface integral into flux integral and assuming a constant locally averaged pressure gradient Δp, determined the horizontal pressure drag vector **D** by the product of Δp and the volume V = A h. A represents the unit horizontal area, and h is the height of the mountain. The pressure gradient is obtained as

$$\Delta p = \frac{\mathbf{D}}{h} \qquad (2)$$

Smith (1985) derived an expression for drag from a control volume momentum budget using the 2-D hydraulic model (Smith, 1985). The density and pressure field are defined in such a way that h = 0 on the windward side and in the lee. Smith's model considers height H_0 in the undisturbed upstream flow at which the pressure is constant, p*, and there is no disturbance above H_0. The streamline or Θ - surface which originates at H_0 splits over the mountain and the lower branch descends rapidly. Between the split streamlines the air is well mixed and strong turbulence helps to decouple the bora layer from a weak or reversed flow aloft. The descending isentropes in the lower part of inversion produce a horizontal temperature gradient, which is hydrostatically related to a surface gradient and a flow acceleration. Below the lower streamline the flow is hydrostatic, nondissipative, Boussinesq and steady. The upstream flow is assumed to have constant stability N and speed U, so that the Scorer parameter ℓ = N/U is constant in the upstream bora layer with undisturbed pressure p* at H_0. The pressure along the lower branch of the split streamline is $p\,(x, H_0 + \delta) = p^* - \rho g \delta$, where δ is the vertical displacement of the lower dividing streamline.

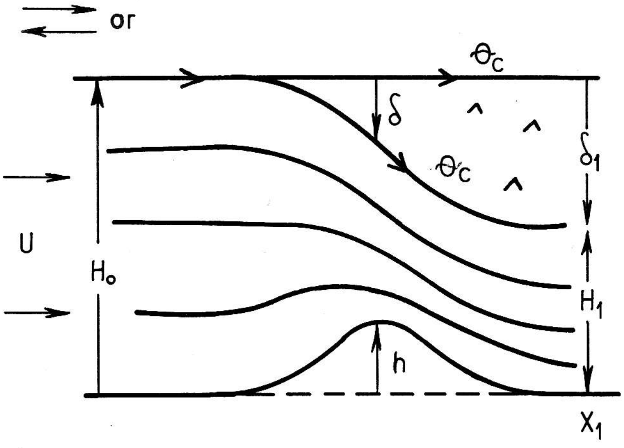

Fig. 1. Schematics of Smith's (1985) hydraulic model for severe downslope winds.

Sl. 1. Shematski prikaz Smithovog (1985) hidrauličkog modela za jake zavjetrinske vjetrove.

We will consider the simplifications introduced by Smith for which the terrain height is the same upstream and downstream of the obstacle, and the new stream has the properties $H_1 = \pi/2$ ($\pi = 3{,}14$) and $\delta_1 = \pi/2 - H_0$ for the point x_1 indicated in Fig. 1.

With this assumption D is obtained as a sum of three terms: the first one contains the difference of the horizontal pressure force on the layer upstream and downstream of the obstacle, second is the difference of momentum flux at the same points and third is the pressure force on the layer from the mixed region. The formula has the form

$$\mathbf{D} = \frac{\rho N^2}{6} (H_0 - H_1)^3 \qquad (3)$$

which can also be written as (Bacmeister and Pierrehumbert, 1988):

$$\mathbf{D} = \rho U^3 \hat{\delta}_1^3 / 6\,N \qquad (3')$$

indicating that larger wind speed and larger vertical displacement on the lee side (stronger horizontal temperature gradient) will result hydrostatically in a larger pressure gradient on the surface across the mountain.

As an example we can take $\rho = 1$ kg m^{-3}, $N = 0{,}01$ s^{-1}, $U = 10$ ms^{-1}, and h = 1000 m. A nondimensional effective height $\hat{h} = \ell h \leq 1{,}0$, which is the limiting value in the Smith's model, and transitional flow for mountains higher than $\hat{h} = 1{,}0$ is not possible.

In this example $H_o = 3\pi/2 = 4,7$, and $H_o = 4700$ m, $\delta_1 = \pi$ and from (3)

$$D = 10^3 \times 30,959/0,06 = 515986 \text{ kg s}^{-2}$$

and from (2) we can obtain the pressure difference across the mountain Δp, as

$$\Delta p = 5,1 \text{ hPa}$$

If we take h = 800 m as used by Smith and in most of the applications of this model, with the same U and N, then $\Delta p = 4,2$ hPa. If we increase N to a hydrostatic value close to $0,02 \text{ s}^{-1}$ (see section 4.2), $\hat{h}$ is much above 1,0, and for $U = 10 \text{ m s}^{-1}$ maximum N is $0,0125 \text{ s}^{-1}$ to give $\hat{h} = 1,0$ and $\Delta p = 5,1$ hPa. On the other hand for N = 0,02 and h = 800 m, $\hat{h} \leq 1,0$ requires that $U \geq 16 \text{ m s}^{-1}$, and for these speeds $\Delta p \geq 13,2$ hPa. Thus, various combinations of values U (10 - 16 m s^{-1}) and N (0,01 - 0,02 s^{-1}) give results 5,1 to 13,2 hPa which are realistic values for severe bora cases, as will be shown in the next section.

3. OBSERVATIONS OF PRESSURE VARIATIONS IN SENJ AND PRESSURE DIFFERENCE ZAGREB - SENJ

For this study we have selected 17 cases from the period 1957 - 1986 with the most severe bora storms in Senj defined by a mean hourly wind speed exceeding 17 m s^{-1}. The observed pressure difference is presented for the distance Zagreb - Senj (about 120 km) which is for all 197 observations in these cases (twice a day at 00 and 12 UTC) in the average 6.4 hPa. Absolute maxima are registered in the case of 3 December 1983, 12 UTC, 14,6 hPa and in the case of 3 December 1962, 00 UTC, 14.1 hPa. The latter case is presented with more detailes in Table 2 and Fig. 4.

All values of Δp are plotted in Fig. 2 together with graphs of sea level pressure variations in Senj, which intends to indicate how stationary a particular case study is. There are cases when the pressure gradient is very large only for one observation during the entire bora period (e.g. in a case of 1977, and two cases of January and November 1979). These are frontal bora cases described also by Bajić in this issue.

Fig. 2 shows that the correlation between surface pressure in Senj and Zagreb - Senj pressure difference are generally not too high.

Rapid pressure rise toward the end of the bora period appearing in most cases is common and results from a continuous cold air supply. This may become deep in a postfrontal thermal trough with winds turning to northerlies and intensifying in the upper troposphere. This destroys the hydraulic flow through the coupling of the upper and lower troposphere causing a decrease in pressure gradient and bora decay.

Contrary to the large pressure variation in most of these cases one may find slow changes of Δp for a bora period of several days such as the cases of 1968 and 1971. It will be seen, however, that this is not a guarantee that the flow is hydraulic and well predicted by the considered model.

4. RESULTS OF THE APPLICATION OF SMITH'S MODEL TO DRAG CALCULATIONS

4.1. Long-lasting severe bora cases

First we apply the hydraulic theory to the cases of long-lasting bora in 1963, 1968, 1969 and 1971 shown in Fig. 2, requiring that model's criterion $\hat{h} \leq 1,0$ (h = 800 m) is satisfied.

From the total number of 108 observations in these cases there are 31 which fulfill this condition and they are listed in Table 1. The last three columns in this Table indicate: heights of the inversion layer, H_i, from the Zagreb's sounding, potential temperature differences at the bottom and top of this layer, $\Delta\Theta$, as a measure of inversion strength, and the Froude number $Fr = U/\sqrt{g\ H}$, where $g' = g\,\Delta\Theta/\Theta$ is the reduced gravity.

The stability is calculated as a weighted average of Brunt-Väisälä frequency N inside the bora layer from the Θ - profile at significant levels as they appear in the sounding.

The empirical bora height H_e is taken as a depth from the surface to an altitude where the upstream (in Zagreb) wind direction is no longer from the NE quadrant (0 - 90°), but does not enter the stratosphere with very high stability. Thus, for the cases marked by "TROP" we take $H_e = 9$ km although the NE bora direction extends to the stratosphere. This is usually found either briefly at the bora onset or at the end of the period when the bora is ceasing. The mean empirical height without six TROP-cases — is a little above 3 km, usually taken as the empirical value for the bora depth. The theoretical mean of H_o very well agree with the mean H_e of 4420 m.

The other mean values of hydraulic parameters also present surprisingly good results with very small difference in the observed and calculated value of Δp. A large discrepancy between the observed and predicted H_o and Δp is found only in the case of 1968 when the depth of the bora layer after the first (TROP) observation sharply decreased to about 1,5 km, with a weakening bora flow. This is an example in which the application of the considered continuous stratified model is questionable since a low wind speed and small stability below a strong inversion could be more suitably presented by a single layer case (Smith, 1987). However, caution is needed in considering a "shallow bora layer" with a strong inversion since it may reflect local effects in Zagreb's low-level structure instead of the upstream flow characteristics. For example, in the case of 9 January 1971, Table 1 indicates that in spite of a strong inversion the result of Δp is very accurate, but H_e extends throughout the troposphere and the values of N and U are not largely influenced by the state below the inversion. This is demonstrated in Fig. 3 for this case where the wind speed has decreased to an almost calm condition. It seems therefore that a deep layer with uniform but not too strong NE flow may well be accomodated to the modeling structure giving a chance to the flow to select a proper dividing streamline which would result in a well-predicted pressure drag. This is a very interesting result drawn from the continuous stratification model since it shows that **the bora could begin in a uniform NE flow in the upstream region with proper**

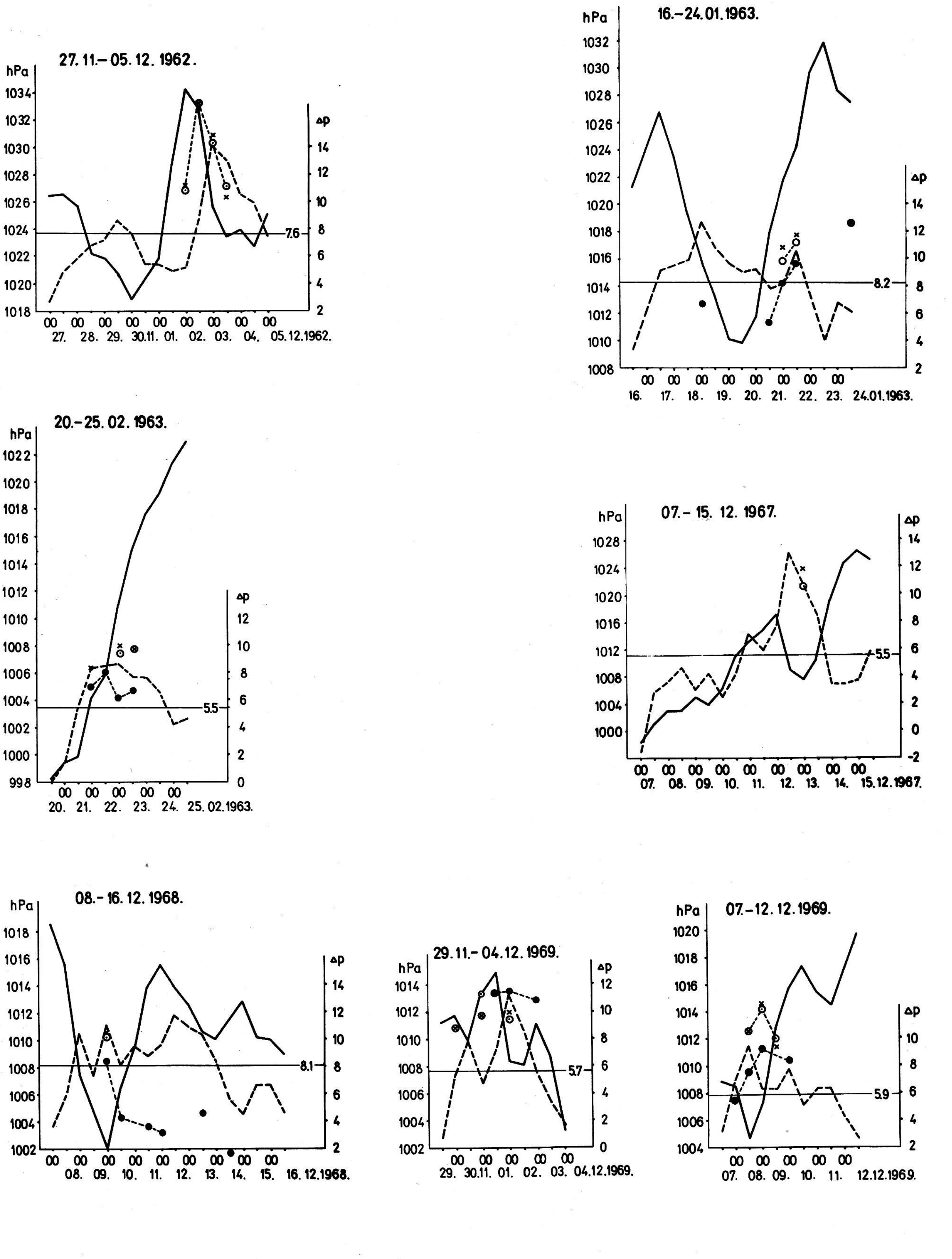

Fig. 2. Temporal changes of sea-level pressure in Senj (solid lines) and sea-level pressure difference Zagreb-Senj (dashed lines) for 17 case studies of severe bora wind in Senj, selected from the period 1957-1986. The theoretical values for Δp from Table 1 (*) and Table 2 (x for Δp_1 and o for Δp_2) are also shown for the corresponding days.

Sl. 2. Vremenske promjene prizemnog tlaka zraka u Senju (pune linije) i razlike prizemnog tlaka Zagreb-Senj (crtkane linije) za 17 slučajeva olujne bure u Senju izabrane iz razdoblja 1957-1986. Teoretske vrijednosti za Δp su također prikazane za odgovarajuće dane iz Tabele 1 (*) i Tabele 2 (x za Δp_1 a simbol o za Δp_2).

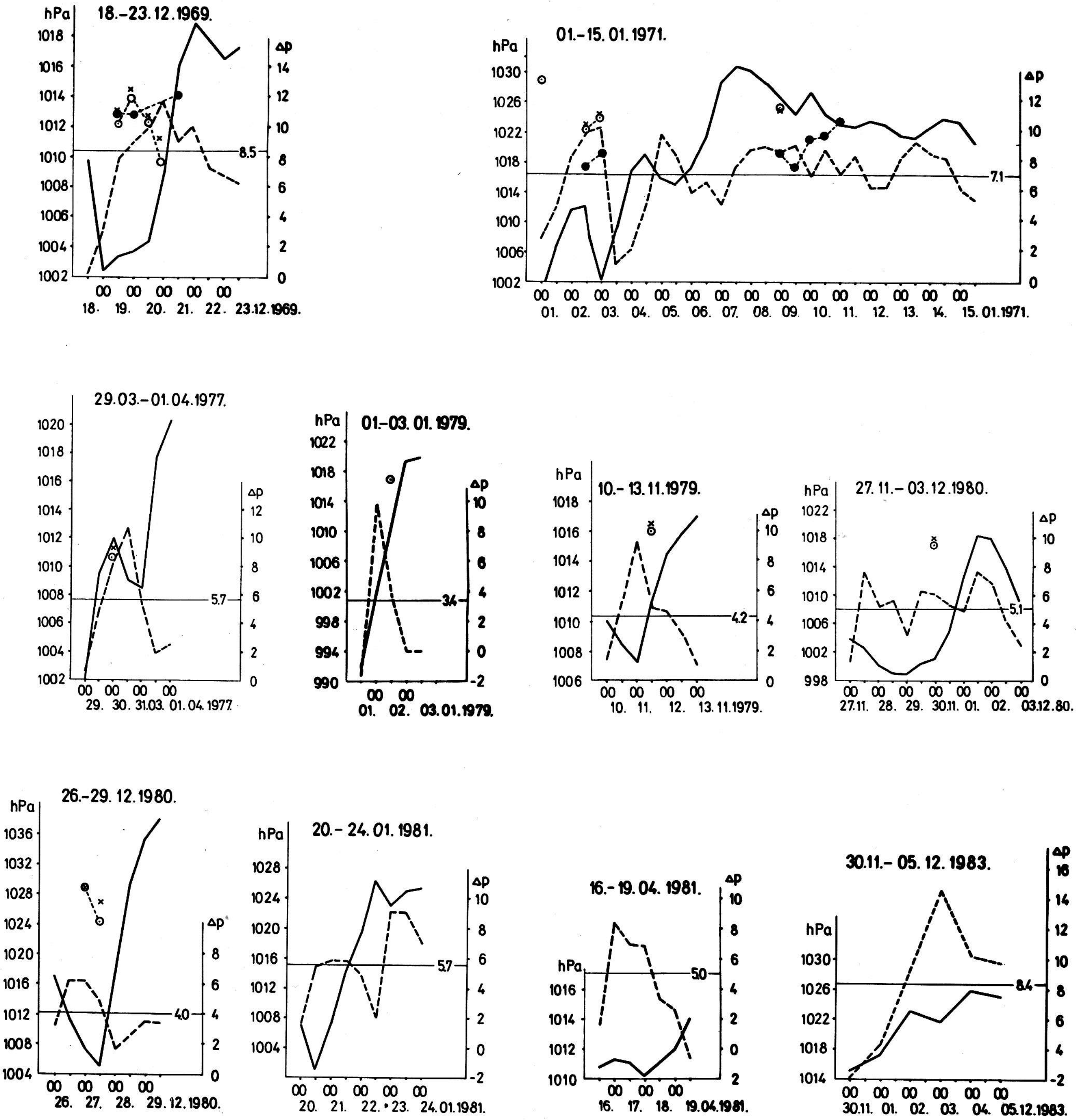

Fig. 2. Continuation
Sl. 2. Nastavak

stratification and wind speed to induce a high drag and a corresponding pressure gradient. This gives a push to the initial high acceleration observed at the bora onset, **but unless the upper-level flow weakens or the low-level stratification strengthens, the bora and associated pressure drag could not be maintained.**

However, with the constraint of $\hat{h} \leq 1.0$ the investigated sample is reduced to about 30 percent of the total number of observations even for the selected long-lasting bora cases, or to about 15 percent of all severe bora cases (197) considered.

The basic problem is a very complex low-level atmospheric structure which probably should be simplified but retaining the basic flow characteristics suitable for the presentation by the model.

4.2. The "hydrostatic bora layer" and the "bora wind component"

We will now consider all 17 case studies with 197 observations of severe bora in Senj, while making a more

Table 1. Hydraulic parameters for 31 long-lasting bora cases in Senj for which $\hat{h} \leq 1.0$. H_e is the empirical height for which the wind speed U has direction between 0 - 90°. N is Brunt Väisälä frequency in 10^{-2} s^{-1}, ℓ the Scorer parameter N/U, $\hat{h}$ is non-dimensional height for h = 800 m, H_0 is the theoretical bora layer height, Δp the theoretical pressure difference, and Δp_0 the observed pressure difference Zagreb - Senj. H_i is the inversion height, $\Delta\Theta$ the inversion strength, and F_0 the Froude number.

Tabela 1. Hidraulički parametri za 31 termin iz slučajeva dugotrajne bure u Senju za koje je $\hat{h} \leq 1{,}0$. H_e je empirička visina sloja bure definirana smjerom vjetra između O - 90°. N je Brunt-Väisäläeva frekvencija u 10^{-2} s^{-1}, ℓ^{-1} je inverzna vrijednost Scorerovog parametra (ℓ = N/U), $\hat{h}$ je bezdimenzionalna visina za h = 800 m, H_0 je teoretska visina sloja bure iz modela, Δp je teoretska razlika tlaka, a Δp_0 je stvarna razlika tlaka Zagreb - Senj. H_i je visina inverzije, $\Delta\Theta$ je razlika potencijalne temperature na dnu i na vrhu sloja inverzije kao intenzitet inverzije, a F_0 je Froudov broj.

							Predicted		Zgb-Senj			
	UTC	H_e (m)	U (ms^{-1})	N $10^{-2}s^{-1}$	ℓ^{-1} (m)	$\hat{h}$	H_0 (m)	Δp (hPa)	Δp_0 (hPa)	H_i (m)	$\Delta\Theta$ (K)	F_0 $U/\sqrt{g'H}$
1963												
19.1.	00	2300	12	1.46	822	0.97	3800	6.9	12.6	1850	8.5	0.51
21.1.	12	3000	11	1.22	902	0.89	4000	5.4	7.9	2460	8.5	0.40
22.1.	00	5500	14	1.27	1102	0.73	4600	8.1	8.2	1990	4.1	0.81
22.1.	12	9000	20	1.00	2000	0.40	6800	10.2	10.4	1700	3.3	1.39
22.2.	00	5500	14	1.13	1239	0.65	4850	7.0	8.4	2010	6.3	0.67
22.2.	12	5300	13	1.52	855	0.94	3900	8.1	8.4	1850	5.0	0.72
23.2.	00	4200	11	1.39	791	1.00	3700	6.2	8.6	1760	2.3	0.92
23.2.	12	3000	12	1.44	833	0.96	3850	7.2	7.7	1210	7.3	0.68
1968												
10.12.	00	TROP	15	1.37	1095	0.73	4550	8.5	11.1	1120	14.3	0.63
10.12.	12	8000	10	1.07	934	0.86	4100	4.4	8.3	1370	10.5	0.45
11.12.	12	1500	10	0.98	1020	0.78	4300	3.7	8.9	1910	9.3	0.40
12.12.	00	1500	8	0.98	816	0.98	3800	3.2	9.7	2190	10.3	0.29
13.12.	12	1500	10	1.20	833	0.96	3850	4.7	11.0	1400	17.2	0.34
14.12.	00	1300	6	0.71	845	0.95	3900	1.7	8.5	1290	15.7	0.23
1969												
1.12.	12	3600	18	1.49	1208	0.66	4800	11.3	7.2	3360	3.8	0.87
2.12.	00	3000	15	1.82	824	0.97	3850	11.5	11.3	2090	4.9	0.80
3.12.	00	4500	17	1.48	1149	0.70	4700	10.9	5.4	2490	3.1	1.04
8.12.	00	2600	10	1.24	806	1.00	3800	5.3	6.9	1710	6.5	0.51
8.12.	12	3000	12	1.50	800	1.00	3800	7.6	9.4	2610	5.9	0.52
9.12	00	3000	16	1.39	1151	0.70	4650	9.3	6.3	2400	7.1	0.66
10.12.	00	TROP	14	1.44	972	0.82	4200	8.5	7.7	1590	5.2	0.83
19.12.	12	2500	14	1.69	828	0.97	3900	10.9	7.8	1870	3.8	0.89
20.12.	00	2000	17	1.65	1030	0.78	4300	10.9	9.0	2710	4.2	0.87
21.12.	12	3500	16	1.86	860	0.93	3950	12.1	9.0	2360	4.4	0.85
1971.												
2.1.	12	1500	13	1.45	897	0.89	4000	7.7	10.0	2430	10.6	0.44
3.1.	00	2500	15	1.52	987	0.43	4200	8.6	10.3	2210	12.3	0.49
9.1.	00	TROP	15	1.37	1095	0.73	4550	8.5	8.6	1050	18.7	0.57
9.1.	12	TROP	14	1.47	952	0.84	4150	7.7	9.0	820	16.8	0.64
10.1.	00	TROP	16	1.47	1088	0.74	4500	9.6	7.0	770	5.7	1.28
10.1.	12	4500	16	1.69	947	0.84	4100	9.9	8.7	990	3.2	1.51
11.1	00	2500	18	1.56	1154	0.69	4600	10.8	7.1	1420	3.9	1.30
MEAN		4420	14	1.38	1008	0.80	4300	8.1	8.8	1800	7.9	0.74

Table 2. Hydraulic parameters for $\hat{h} \leq 1.5$, with predicted "hydrostatic bora layer height". Symbols are as in Table 1, but index 1 is for empirical H_e and 2 is for height at which bora wind component U_B (45 ± 90°) vanishes. x indicates days appearing in both Tables.

Tabela 2. Hidraulički parametri za $\hat{h} \leq 1{,}5$, sa prognoziranim visinama "hidrostatskog sloja bure". Simboli su isti kao u Tabeli 1, ali je indeks 1 za empiričku visinu H_e, a indeks 2 za vrijednost visine dobivene isčezavanjem komponente bure U_B (45°± 90°). Znak x označuje dane koji se pojavljuju u Tabeli 1 i 2.

	UTC	H_1 (m) 0-90°	H_2 (m) $U_B>0$	U_1 (ms^{-1})	N_1 ($10^{-2}s^{-1}$)	U_2 (ms^{-1})	N_2 ($10^{-2}s^{-1}$)	ℓ_1^{-1} (m)	ℓ_2^{-1} (m)	$\hat{h}_1$	$\hat{h}_2$	H_{01} (m)	H_{02} (m)	Δp_1 (hPa) Zgb.-Senj	Δp_2 (hPa)	Δp_o (hPa)
1962.																
2.12.	oo	6060	9580	13	1.94	12	1.97	660	624	1.21	1.28	3450	3350	11.0	10.8	5.1
2.12.	12	10220	10220	21	1.98	21	1.98	1056	1056	0.76	0.76	4400	4400	17.2	17.2	8.8
3.12.	00	4220	5690	19	1.91	18	1.92	99	917	0.89	0.87	4200	4100	14.8	04.2	14.1
3.12.	12	2150	7160	12	1.90	13	1.93	631	679	1.27	1.18	3350	3500	10.2	11.1	13.0
1963.																
x 22.1.	00	5300	6770	12	1.97	11	1.98	619	540	1.29	1.48	3350	3150	10.8	9.8	8.2
x 22.1	12	9130	11410	13	2.00	12	2.01	660	622	1.21	1.29	3450	3350	11.7	11.2	10.4
24.1.	12	6960	6960	15	1.96	15	1.96	786	786	1.02	1.02	3750	3750	12.9	12.9	6.0
x 23.2.	00	4080	5350	12	1.92	11	1.93	604	554	1.32	1.44	3300	3200	10.0	9.5	8.6
x 23.2.	12	2910	3890	11	1.91	11	1.92	592	588	1.35	1.36	3250	3250	9.8	9.8	7.7
1967.																
13.12.	00	3720	10160	15	1.90	12	1.96	768	607	1.04	1.32	3700	3300	11.9	10.5	10.5
1968.																
x 10.12.	00	11480	12310	11	1.99	11	2.00	568	550	1.41	1.45	3200	3150	10.3	10.1	11.1
1969.																
30.11.	00	1420	1420	10	1.88	10	1.88	532	532	1.50	1.50	3100	3100	8.8	8.8	5.4
1.12.	00	3590	3590	11	1.90	11	1.90	589	589	1.36	1.36	3250	3250	9.6	9.6	4.8
x 2.12.	00	2860	5670	12	1.90	11	1.92	621	547	1.29	1.46	3350	3150	10.0	9.3	11.3
x 8.12.	12	2970	2970	13	1.91	13	1.91	660	660	1.21	1.21	3450	3450	10.6	10.6	9.4
9.12.	00	2920	3040	15	1.90	15	1.90	811	789	0.99	1.01	3750	3750	12.5	12.2	6.3
9.12.	12	4340	5460	11	1.90	12	1.91	558	613	1.43	1.31	3200	3350	9.3	10.0	6.3
x 19.12.	12	2110	2630	13	1.90	13	1.90	700	658	1.14	1.22	3550	3450	11.0	10.5	7.8
x 20.12.	00	1880	3620	15	1.90	14	1.91	789	749	1.01	1.07	3750	3650	12.2	11.8	9.0
20.12.	12	2870	3350	12	1.91	12	1.91	623	613	1.28	1.31	3350	3350	10.2	10.0	9.9
21.12.	00	3410	5550	10	1.91	8	1.92	534	391	1.50	2.05	3100	2750	9.1	7.5	11.6
1971.																
1.1.	00	1920	1920	17	1.89	17	1.89	905	905	0.88	0.88	4050	4050	13.6	13.6	3.0
x 2.1.	12	1420	2430	12	1.91	12	1.92	634	609	1.26	1.31	3400	3300	10.3	10.1	10.0
x 3.1.	00	2200	2840	13	1.91	13	1.91	702	691	1.14	1.16	3550	3550	11.2	11.0	10.3
x 9.1.	00	11850	13130	13	1.98	13	2.00	672	670	1.19	1.19	3500	3450	11.6	11.8	8.6
1977.																
30.3.	00	1580	2110	11	1.89	10	1.89	577	508	1.39	1.58	3250	3050	9.4	8.6	8.3
1979.																
2.1.	12	3650	4080	14	1.95	14	1.95	723	692	1.11	1.16	3600	3550	11.9	11.5	3.7
11.11.	12	1830	3070	13	1.88	12	1.89	676	624	1.18	1.28	3500	3350	10.5	10.0	4.9
1980.																
30.11.	00	2890	3130	12	1.90	11	1.90	605	589	1.32	1.36	3300	3250	9.8	9.6	6.0
27.12.	00	2900	2900	15	1.89	15	1.89	809	809	0.99	0.99	3800	3800	12.3	12.3	6.2
27.12.	12	2870	4080	14	1.90	12	1.91	732	618	1.09	1.29	3650	3350	11.5	10.1	4.8
MEAN		4080	5350	13	1.92	13	1.93	686	653	1.17	1.26	3500	3460	11.8	11.5	8.4

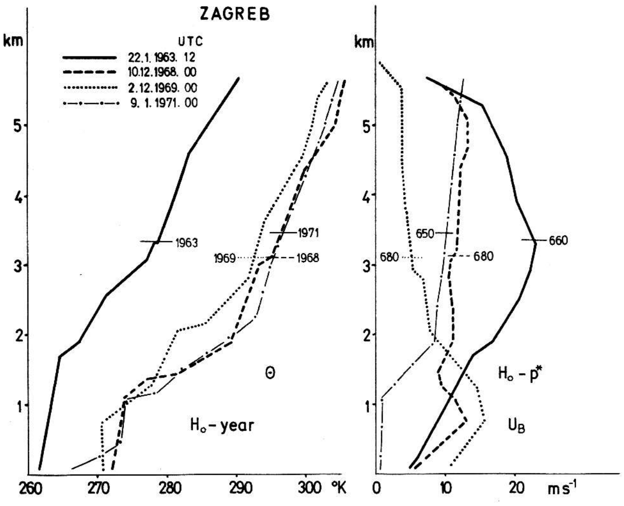

Fig. 3. Vertical profiles of potential temperature (left) and bora wind component (right) for indicated cases. Short lines mark the height of the theoretical bora layer H_{o2} from Table 2 with estimated pressure p* at this height.

Sl. 3. Vertikalni profil potencijalne temperature (lijevo) i komponente bure (desno) za navedene dane. Kratke crtice na krivuljama pokazuju dane i određene godine, kao i teoretske vrijednosti visine sloja bure H_{o2} iz Tabele 2 s procijenjenim tlakom zraka p* na toj visini.

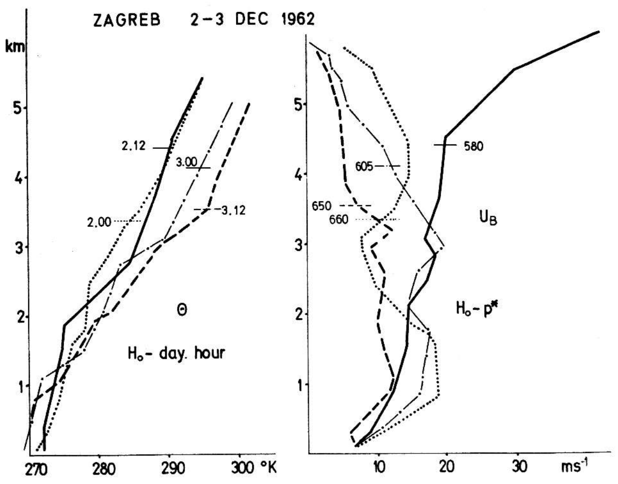

Fig 4. Vertical profiles of potential temperature, Θ, and bora wind component for 12-hourly intervals, 2 - 3 December 1962. Short lines indicate H_{o2} and p* as in Fig. 3.

Sl. 4. Vertikalni profil potencijalne temperature, Θ, i komponente bure U_B za 12-satne intervale, 2 - 3 prosinac 1962. Kratke crtice označuju H_{o2} i p* vrijednosti kao na sl. 3.

objective selection of cases for drag calculations. An attempt at modifying the stability profile intends to remove the local influence on stability imposed by various processes in the boundary layer below 1 km not considered in the modeling structure.

First we require that N obeys hydrostatic approximation which can be obtained from an expression of thermal stability as (Glasnović, 1983; Glasnović and Jurčec, 1990):

$$\frac{\partial p}{\partial \Theta} = -\kappa \frac{p}{\Theta}$$

When introduced to Brunt-Väisälä frequency it gives N close to 0.02 s^{-1}, (as seen in Table 2), which is, therefore, in most cases much larger than the values of N presented in Table 1, but with obviously small temporal variations.

Second, the constant upstream speed U should be in 2-D flow perpendicular to the obstacle, which is not the case if we allow the direction of the stronger wind to vary between 0 and 90°. Particularly in the case of wind turning with height there could be a very large difference between U defined in this way and the "bora component" U_B as 45± 90° (315 - 135°) discussed also by Glasnović and Jurčec (1990). Earlier case studies (Jurčec, 1989) have shown that even a very strong upper-level wind if perpendicular to the U_B-direction has no effect on the surface bora behaviour. If the wind in the bora layer does not diverge much from 45°, the two types of wind estimation and the corresponding heights will be close to each other. This comparison is seen in the first two columns of Table 2 for 31 selected severe bora cases requiring that $\hat{h} \leq 1{,}5$ for h = 800 m. The results indicate that in some cases H_B is more than 5 km higher than H_e. However, both of these heights could extend far into the upper troposphere, or even to the stratosphere, which could not justify their direct use in the definition of the bora layer depth, giving an essential advantage to the consideration of the theoretical values of H_o.

In particular the prediction of H_o based on hydrostatic stability seems very suitable for this purpose, since on the average such a "hydrostatic bora layer" is about 3500 m with rather small variations from case to case.

Due to small differences in U and N from H_e - and H_B-versions the corresponding Δp are very close and in the average both are about 3 hPa larger than the average values in Table 1.

In Table 2 we find 10 cases in which differences between the theoretical and observed Δp is 5 hPa or more, whereas the others, about 10 percent of the total number of cases, can be well presented by the model structure with the hydrostatic bora layer.

Fig. 3 illustrates four cases which appear in both Tables 1 and 2. The first one is 22 January 1963. Table 1 shows that the predicted Δp can be equal to the observed if the U is increased to 20 m s^{-1}, which is the U_B-speed in the vicinity of p*, but since here N = 0,01 s^{-1} this predicts an extremely high ("non-hydrostatic") H_o. With the high hydrostatic stability of N = 0,02 s^{-1} in Table 2 and U = 12 m s^{-1}, Δp is still close to the observed, but H_o is more reasonable and approaches the average hydrostatic H_o.

The case of 10 December 1968 with a strong hydrostatic stability shows good results in Table 2, but H_e extends to the

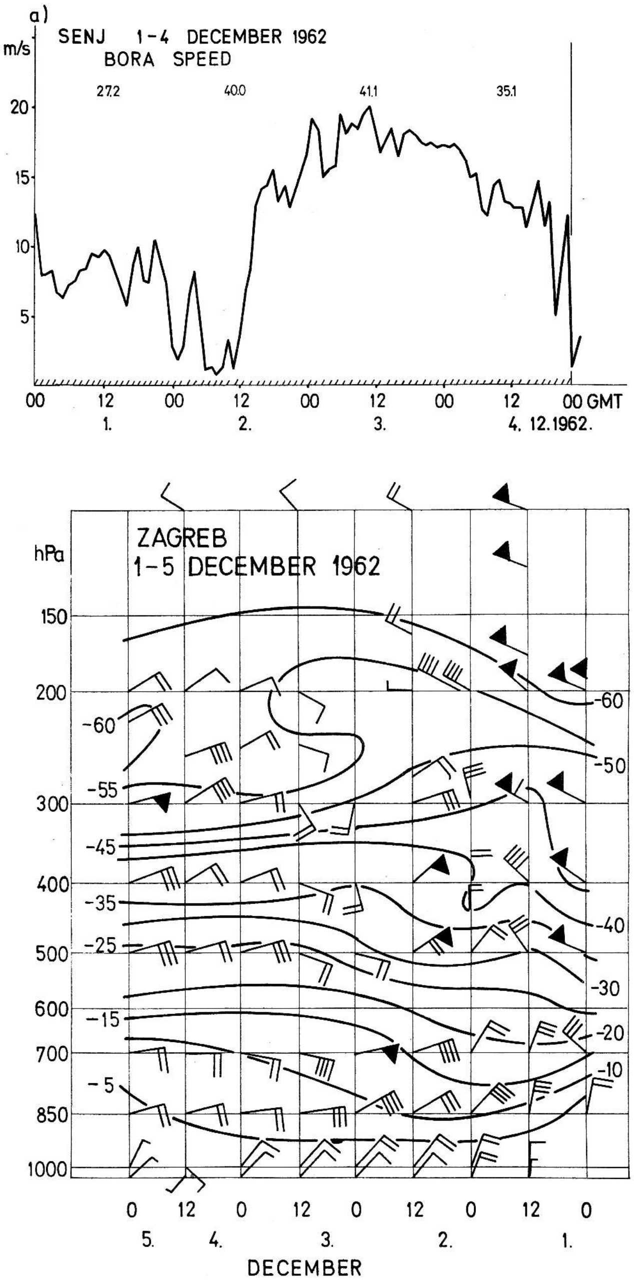

Fig. 5. a) Daily course of surface bora wind in Senj (direction ENE) with indicated maxima gusts on each day (m s^{-1}), and b) time - height cross-section (from right to left) of wind and isotherms for Zagreb, 1 - 5 December 1962.

Sl. 5.a) Dnevni hod bure u Senju (smjer je ENE) s označenim maksimalnim udarima za svaki dan (m s^{-1}), i b) vremenski vertikalni presjek (od desna na lijevo) vjetra i izoterme za Zagreb, 1 - 5 prosinac 1962.

stratosphere. The other observations for this case which appear only in Table 1 with a low H_e, small stability and low wind speed result in the largest errors in this Table. However, in Fig.3 it is seen that the small stability is the result of the boundary layer processes which may not be representative for the upstream bora condition or belong to the layered case.

Similar is the third case of 2 December 1969 but stability close to a neutral state is shallow so that the vertical mean gives N = 0,0182 close to the hydrostatic value of N with a good prediction of Δp in Table 1.

In the last case 9 January 1971 Table 1 shows good results for Δp whereas the hydrostatic stability overestimates Δp with values close to those on the average (last row in Table 2). Fig. 3 shows that in spite of good results in Table 1, the wind and stability profile could not justify the use of continuous stratification in the lower troposphere due to low wind speed and surface inversion. Thus, some of the results, although very good, seem fortuitous, since the proper wind and stability are results of the high tropospheric (and low stratospheric) state and unlikely to influence the surface pressure gradient. This case is also discussed in the next section.

4.3. Case studies and analysis of errors
a) Case of 2-3 December 1962

This case appears only in Table 2 with hydrostatic stability and results in a large error on the first day followed by accurate results for the third observation representing the maximum observed Δp in Table 2.

Fig. 4 shows the Θ-and v - profiles as in Fig. 3 but for this case in consecutive observations of 12-hourly intervals of Zagreb's sounding. It is seen that the large increase in Δp-prediction on 2 December at 12 UTC is caused by an increase in U_B above the top of the hydrostatic layer (580 hPa) which enters the calculation since the NE wind direction extends throughout the troposphere. During the next 12 hours some "adjustment process" has taken place leading to the correct Δp-prediction, although the exact value could also be fortuitous. The reason for such behaviour could not be followed only by the pressure field, therefore in Fig. 5 we present the vertical cross-section of the wind and temperature field in the Zagreb sounding, and the surface bora course in Senj during these days. Evidenty, the large changes in p and Δp in Fig. 2 on these days are accompanied by large upper wind variations which clearly reflect on the bora changes. The highest pressure in Senj with a decreased Δp occurs during the intensification of N - NE upper level winds, whereas the highest Δp on 3 December follows the intensification of low-tropospheric NE flow and upper wind reversal during the strongest bora in Senj. If in this case we take into consideration the changes during the first day and approximate upstream wind and stability by the mean values for 00 and 12 UTC on 2 Dec. inside the hydrostatic bora layer (given by the prediction in Table 2) we will obtain N = 0,013 s^{-1}, U = 14 m s^{-1}, and the result is Δp = 7,5 hPa, which is very close to the observed mean (7.0 hPa) for the day.

b) Case of 19 - 21 December 1969

In this case severe bora in Senj persisted from the morning of 19 December until the morning of 22 December, with a maximum gust of 36.2 m s^{-1} on 21 December at 5.30 UTC coinciding with the maximum observed Δp.

Fig. 6 shows the vertical profiles of wind and stability in the low troposphere for the significant layers from Zagreb sounding, and Table 3 presents the hydraulic parameters for these days which are now modified in respect to those in Table 1 and 2. After having the prediction of hydrostatic

Table 3. Hydraulic parameters and pressure difference Zagreb-Senj (Δp_0) 19 - 21 December 1969.
Tabela 3. Hidraulički parametri i razlika tlaka Zagreb - Senj (Δp_0) za 19 - 21 prosinac 1969.

Day	UTC	N $10^{-2} s^{-1}$	U_B ms^{-1}	ℓ^{-1} m	$\hat{h}$	predicted H_0 m	predicted Δp hPa	Δp_0 hPa
19	12	1.43	12	846	0.94	3900	7.1	7.8
20	00	1.56	13	805	0.99	3800	9.2	9.0
20	12	1.59	12	750	1.07	3650	8.1	9.9
21	00	1.60	10	611	1.30	3360	7.9	11.0
21	12	1.62	11	680	1.18	3500	8.0	9.0

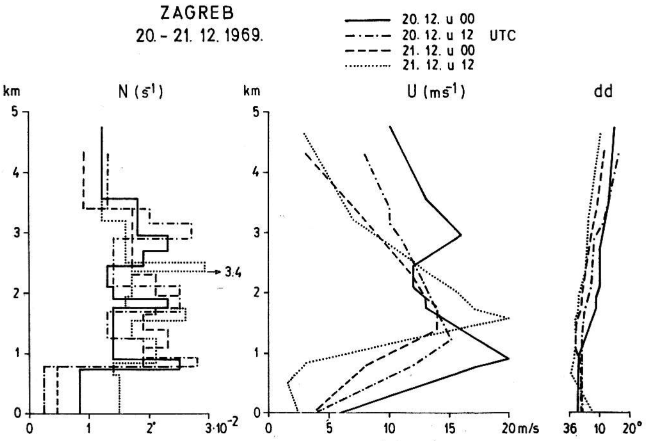

Fig. 6. Vertical profiles of stability (Brunt-Väisälä frequency) in significant layers, and wind speed and direction for 20 - 21 December 1969.
Sl. 6. Vertikalni profil stabilnosti (Brunt-Väisäläeva frekvencija) za značajne slojeve, i brzina i smjer vjetra za situaciju 20 - 21 prosinac 1969.

bora layer, N is recalculated as a mean value through this layer ($\Delta\Theta$ is taken from the top to the bottom of this layer instead of a weighted average in the layered structure shown in Fig. 6). The predicted Δp in Table 3 are generally good, but again the maximum Δp is underestimated as in Table 2. This confirms our previous remark that the **predicted Δp can not react immediately on the upstream flow changes and the 12-hourly period is obviously too long to follow them.**

It is interesting to notice in Fig. 6 that at the level close to 500 m there are very little changes of wind speed (close to $U = 12$ m s^{-1}) and this is the level where inversion forms at the last observation time. This inversion is lowering during the next day (not shown here) with a weakening of the upstream wind speed ($\hat{h}$ is therefore largely increased) and the bora in Senj decays.

c) 1 - 15 January 1971.

This is an interesting case, but we will discuss it only briefly here. On 1 January Table 2 shows the extreme difference between theoretical and observed Δp. This is a consequence of an unsteady state at the beginning of this case with the wind maximum over 25 m s^{-1} at 1000 m altitude, which is sharply decreasing to 5 m s^{-1} at 2000 m, indicating even a more pronounced maximum from those shown in Fig. 6 inside the bora layer. However, if we take some mean-time state, as we did for the space mean in the vertical profiles, the results are very good. For the mean values at 1 - 2 January at 00 UTC $N = 0{,}0166$, $U = 10$ m s^{-1}, and this leads to Δp = 7,6 hPa, for these days (as seen in Fig. 2). For the period 3 - 8 January the main source of error is a relatively low H_e with weak wind and strong stability, which lasts until H_e extends to the stratosphere as already discussed in 4.1 for 9 January. The last days in this case study, although are rather steady in $\hat{p}$ and Δp (Fig. 2) do not appear in Tables 1 and 2 due to large $\hat{h}$ but they would have a very small Δp prediction due to a low H_e and weak upstream wind speed.

We can therefore summarize that the hydrostatic stability being on the average 0,0192 s^{-1} requires $U > 15$ m s^{-1} in order to satisfy $\hat{h} \leq 1{,}0$, but such a high speed usually leads to a high drag state which may overestimate the pressure difference. It is seen that a high pressure drag often appears only briefly at the bora onset before a steady state is reached, and therefore it could not be explained by the present model, unless we consider the time-mean and discuss qualitatively the physics of the flow for which the model is constructed in any case.

Finally, we have taken rather arbitrarily the height h as 800 m. Increasing this height according to its realistic variability of several hundred meters, would give an increase of Δp for 2 - 3 hPa under the same other conditions.

5. SUMMARY AND CONCLUSION

The analysis of 17 severe bora storms in Senj with 197 observations have confirmed what was expected from earlier synoptic studies (Jurčec, 1989) that in most of these cases there are large sea level pressure changes first associated with the cyclonic activity following a cold air outbreak, with the pressure fall, and later on a rapid pressure rise due to the cold air supply and intensifying thermal anticyclone. The mesoscale pressure gradient in terms of pressure difference Zagreb-Senj indicates less variability, but there are cases when a large pressure difference occurs for less than 12 hours. Mean pressure difference Zagreb-Senj for all 197 observations is 6.4 hPa, and the absolute maximum is 14.6 hPa on 3 December 1983, considering data only at 00 and 12 UTC during the bora periods.

It is shown that the cases with relatively small pressure variations, such as in 1968 and 1971 in Fig. 2, do not guarantee the successful theoretical results of pressure drag. There are four basic parameters which mainly dictate the success of the application of theory: the empirical bora layer height, the wind and stability which should be constant inside this bora layer, and the mountain height, h, which is taken as 800 m but obviously (from ℓ^{-1} in Table 2) should be less in order not to violate the model criterion $h\,N/U \leq 1.0$.

In particular, it is suggested that the bora layer should not be defined either in terms of wind direction or stability profile separately. Introduction of joint effect from both of these parameters, particularly in a new definition of "hydrostatic bora layer" can be well guided by hydraulic theory.

The predicted H_0 are at altitudes of about 3500 - 4500 m which is very acceptable from the viewpoint of empirical bora studies. The final bora layer depth could be probably best obtained by some iterative procedure in which N and U would be taken from the first guess of theoretical H_0 and further corrected by the new values of H_0.

On the other hand deep layer with a uniform NE flow is in accordance with the atmospheric structure modeling (Fig. 1) since it may extend above the bora layer, particularly at the bora onset. The illustrated examples have shown that unless the upper flow weakens or the low - level inversion strenghtens, leading to a decoupling of upper and lower troposphere, high pressure drag and severe bora state turn to be a very brief process.

Simultaneity seems to be a large problem if the flow largely depart from the steady state, and 12-hours is too large time resolution in the study of severe bora cases. Therefore some mean values of measured Δp Zagreb-Senj are better compared with the prediction which is also based on the mean state in wind speed and stability profiles.

This study has shown that even in the selection of "steady state" cases with very persistent bora flow (Table 1) for the selected height h = 800 m, there are not more than 15 percent of the total number of observations considered which satisfy the model's constraints for nondimensional effective height $\hat{h} \leq 1{,}0$, and from which only about 10 percent (or 20 observations) offer very good results.

Introduction of "hydrostatic bora layer" (Table 2) removes a complex stability structure, particularly in the lowest troposphere, and makes the stability closer to a constant as required by the model, but such a stability is very large, results in even higher value of $\hat{h}$ and on the average overestimates the pressure gradient. For $\hat{h} < 1{,}5$ about the same percentage as above can be successfully studied by the considered model.

It must be, however, reemphasized that our analysis considers **only severe bora** cases defined by mean hourly speed exceeding 17 m/s, and does not concern most of the bora cases which do not reach this speed. According to Bajić (1989) and Benković (1990) only about **5% of strong bora** cases (with the mean hourly wind speed above 10 m/s) exceed the speed of 17 m/s. Thus, the theory seems more applicable to cases of relatively "weaker" bora. This is understandable since a steady state for which the model is valid, is usually reached in postfrontal situations when severe bora is not such a frequent event even in the northern Adriatic area, except in Senj due to 3-D channeling effects which should be considered separately in the future bora studies.

Acknowledgement: This research is based on the project study of "The Adriatic Bora" supported by the US-Yugoslav Joint Fund for Scientific and Technological Cooperation in cooperation with the NSF under Grant JF 735 during 1987 - 1988.

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KRATKI SADRŽAJ

Analiza 17 situacija s olujnom burom u Senju, prikazanih sa 197 termina motrenja, potvrdila je očekivane rezultate na osnovu sinoptičkih analiza (Jurčec, 1989) da je u svim tim slučajevima, unatoč kontinuirane bure, stanje atmosfere u odnosu na prizemni tlak zraka uglavnom nestacionarno. Promjene tlaka prvo nastaju uslijed ciklonalne aktivnosti povezane s prodorom hladnog zraka uz pad tlaka, a nakon toga dolazi do porasta tlaka uslijed priliva hladnog zraka i intenzifikacije termalne anticiklone. Horizontalni gradijent tlaka preko planine, prikazan razlikom tlaka Zagreb - Senj, pokazuje manju varijabilnost, ali ima slučajeva gdje se velika razlika tlaka pojavljuje u kratkom vremenskom razdoblju manjem od 12 sati. Srednja razlika tlaka Zagreb - Senj za svih 197 motrenja je 6.4 hPa, a apsolutni maksimum je 14.6 hPa i pojavljuje se 3. prosinca 1983. za promatrane periode bure u terminima 00 i 12 UTC kada je na raspolaganju bila radiosondaža Zagreb - Maksimir.

Rezultati primjene Smithove (1985) interne hidrauličke teorije pokazali su da se teorija može uspješno primijeniti za izračunavanje planinskog otpora tlaka. S obzirom na to da se uobičajenom definicijom sloja bure, koja se odnosi samo na promatranje smjera vjetra iz NE-kvadranta, često dobiva sloj kroz cijelu troposferu, a ponekad i donji dio stratosfere, to je velika prednost teorije jer omogućava određivanje visine sloja bure H_0 kao funkcije vjetra i stabilnosti u neporemećenom sloju navjetrine. Jedan dio strujnice ili izentrope na H_0 se prelaskom preko planine cijepa i spušta prema zavjetrini pa na taj način nastaje gradijent temperature koji se hidrostatski odražava u prizemnom gradijentu tlaka zraka preko planine, odnosno u planinskom otporu tlaka. Prema tome, iz nagiba izentropa u navjetrini i zavjetrini $H_0 - H_1$, uz poznatu (konstantnu) brzinu vjetra okomito na prepreku i statičku stabilnost izraženu Brunt-Väisäläevom frekvencijom N, relacija (3) ili (3') pruža mogućnost određivanja planinskog otpora D, i gradijenta tlaka kao omjera D/h. Visina prepreke, h, je u svim računima iznosila 800 m, ali se za daljnji rad preporuča detaljnije proučavanje ovog parametra, naročito u situacijama blokiranja hladnog zraka u navjetrini prepreke. To je jedan od problema koji se može proučavati prikazanom dvodimenzionalnom teorijom, dok se od ostalih problema prednost daje ne-hidrostatskoj stabilnosti za određivanje visine sloja bure.

Rezultati teoretskih vrijednosti H_0 pokazuju razumne visine uglavnom između 3500 i 4500 m, što je u skladu s empiričkim određivanjem sloja bure pri jakim inverzijama. Međutim, duboki sloj NE vjetra u navjetrini, iako nije prikladan za definiciju sloja bure, u skladu je s modelom kontinuirane stratifikacije i daje mogućnost toku određenih karakteristika da izabere neku strujnicu ili izentropu na visini H_0 da bude vrh sloja bure, prema modelu na sl. 1. Duboki jednoliki sloj NE vjetra pojavljuje se većinom na početku i na kraju bure i pokazuje da se olujni vjetar hidrauličkog tipa i planinski otpor tlaka mogu održati samo ako brzina vjetra na visini oslabi ili se pojača stabilnost u donjoj troposferi, što dovodi do odvajanja gornje i donje troposfere i uspostavljanja stacionarnog hidrauličkog toka koji opisuje model. U protivnom slučaju tip jednolikog strujanja pri prodoru hladnog zraka uzrokuje samo kratkotrajnu buru.

Prema tome, u radu se pokazuje da čak pri izboru "stacionarnih" slučajeva s vrlo perzistentnom burom, uz visinu planine od 800 m, ima svega 15 % slučajeva od ukupnog broja promatranih terminskih motrenja koji zadovoljavaju uvjete modela da je bezdimenzionalna efektivna visina $\hat{h} \leq 1{,}0$, a od tog broja svega 10 % (ili 20 termina) pružaju vrlo dobre rezultate.

Uvođenje "hidrostatskog sloja bure" uklanja kompleksnu strukturu stabilnosti, naročito u najnižim slojevima troposfere i omogućava približavanje stabilnosti konstanti kako zahtijeva model. Međutim, takva stabilnost je vrlo visoka i uzrokuje još više vrijednosti h. Tako se za graničnu vrijednost $\hat{h} \leq 1{,}5$ dobiva isti procenat kao gore, no za svih 197 opažanja olujne bure u Senju, tj. 15 % slučajeva bitno ne narušava kriterij modela, a 10% daje vrlo dobre rezultate.

Međutim, treba ponovo naglasiti da se naša analiza odnosi samo na slučajeve olujne bure definirane srednjom satnom brzinom vjetra većom od 17 m/s. Prema statističkim analizama (Bajić, 1989; Benković, 1990) samo 5% jakih bura (sa srednjom satnom brzinom preko 10 m/s) prelazi 17 m/s, pa je teorija bolja za slučajeve bura koje nisu olujnih jačina. To je i razumljivo jer se stacionarna stanja, za koje je model predviđen, javljaju u postfrontalnim situacijama kada olujna bura nije tako česta pojava niti u sjevernom Jadranu, osim u Senju uslijed trodimenzionalnih kanalnih efekata koje bi u budućim istraživanjima trebalo posebno razmatrati.