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SPATIAL BORA VARIATIONS IN RELATION TO COLD AIR OUTBREAK AND SURFACE PRESSURE GRADIENT

Prostorna varijabilnost pojave olujne bure u odnosu na prodore hladnog zraka i prizemni gradijent tlaka

ALICA BAJIĆ
Hydrometeorological Institute of Croatia, Zagreb
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Abstract: Bora wind on the northern Adriatic is associated with an upstream cold air outbreak although the most pronounced outbreaks are not always connected with the strongest bora storms.

During the cold season between 1973 - 1982 in Zagreb only 3 strong cold air outbreaks were associated with severe bora in the northern Adriatic. In these cases bora onset is almost simultaneous along the entire northern Adriatic coast, it lasts 1 - 2 days and its strength is nearly equal at all considered meteorological stations.

The cut-off processes and blocking circulation pattern connected with the less pronounced long lasting cold air outbreak resulted with the longest bora duration.

In 12 considered severe bora situations a drop of temperature due to cold air outbreaks is followed by the characteristic mesoscale pressure field with low pressure area along the coast and islands and higher pressure in the upstream bora region.

The estimated correlation coefficient between the cross mountain sea level pressure difference Δp and mean hourly bora velocity V_s show the stohastic significancy in all 12 severe bora cases. The relationship between Δp and V_s is stronger using Senj data than data measured at Omišalj and Pula what is a consequence of Senj's specific location in relation to the mountain barrier. In 3 most pronounced cold air outbreak situations the constants in the correlation expression obtained using Senj data are almost the same. Thay enable us to estimate the mean hourly bora wind speed in Senj for predicted Zagreb - Senj pressure differences in similar weather situations.

K e y w o r d s: severe bora wind, the northern Adriatic, surface pressure difference

Sažetak: Pojava bure na sjevernom Jadranu posljedica je prodora hladnog zraka u navjetrinu. Međutim, najizraženiji prodori hladnog zraka nisu uvijek praćeni najjačom burom. U hladno doba godine u razdoblju 1973 - 1982 u Zagrebu su zabilježena samo 3 vrlo izrazita prodora hladnog zraka praćena olujnom burom na sjevernom Jadranu. U tim je slučajevima pojava bure bila istovremena duž čitavog sjevernog Jadrana, trajala je 1 - 2 dana i njena jačina je bila gotovo jednaka na svim promatranim meteorološkim stanicama.

Cut - off procesi i cirkulacija blokirajućeg tipa praćena s manje izrazitim, ali dugotrajnim prodorima hladnog zraka rezultirali su olujnom burom najvećeg trajanja.

U 12 promatranih situacija s olujnom burom pad temperature uslijed prodora hladnog zraka bio je praćen s karakterističnim poljem tlaka u mezorazmjerima s područjem niskog tlaka duž obale i otoka, te visokim tlakom u navjetrini Dinarida.

Proračun koeficijenata korelacije između razlike tlaka preko planinske prepreke (Δp) i srednje satne brzine bure (V_s) pokazao je da postoji stohastička zavisnost između te dvije varijable u svih 12 promatranih situacija. Odnos između Δp i V_s je izrazitiji u slučaju korišćenja podataka za Senj nego u slučaju Omišlja ili Pule, što je posljedica specifičnog položaja Senja u odnosu na planinsku prepreku.

U 3 situacije s najizrazitijim prodorom hladnog zraka konstante u izrazu za linearnu korelaciju dobivene pomoću senjskih podataka gotovo su identične. To nam omogućava da odredimo srednju satnu brzinu vjetra u Senju za svaku prognoziranu vrijednost razlike tlaka Zagreb - Senj u sličnim vremenskim situacijama.

K l j u č n e r i j e č i: olujna bura, sjeverni Jadran, prizemna razlika tlaka

1. INTRODUCTION

In the previous issue of this journal (Bajić, 1989) the statistical analysis of wind field in the northern Adriatic indicated that the location with the greatest frequency of severe bora wind is Senj. At the other considered locations in the northern Adriatic with hourly measured wind data (Omišalj and Pula) severe bora is not so frequent. Besides the considerably smaller relative frequencies of strong bora occurrence in Omišalj and Pula, the bora duration there was not as long as in Senj. The statement that the long bora duration is its basic characteristic are shown to be valid for bora in the cold season particularly in Senj. That does not concern the frontal bora which is very brief in all seasons. The analysed bora occurrences were based on different periods of hourly measured wind data at three locations. Because of that it was not possible to compare all details concerning the characteristics of strong and severe bora. Wind data from climatological observations will give us additional information about bora wind characteristics.

The purpose of this paper is to present the results of detailed analysis of time and space variations in severe bora occurences in the northern Adriatic particularly in relation to mesoscale sea level pressure difference across the mountain barrier. Special emphasis will be placed on three situations with the most pronounced cold air outbreak in the upstream bora region (29 - 31 March 1977, 1 - 2 January 1979, 10 - 12 November 1979).

Namely, bora onset is always associated with a cold air outbreak either following a deep tropospheric front or some period after a front passage when the cold air arrives from the low level blocking on the northern side of the Alps representing therefore orographic deflecting air around the Alps (Bajić, 1987; Jurčec, 1988; Jurčec 1989a,b).

The strongest cold air outbreak in the upstream bora region does not necessarily generate the strongest bora in the northern Adriatic. From 21 cases of very cold air outbreaks during the cold season between 1973 - 1982 in Zagreb (Bajić, 1984) only 3 cases (mentioned above) were associated with the severe bora in the northern Adriatic.

2. THE SPACIAL DISTRIBUTION OF BORA OCCURRENCE ON THE NORTHERN ADRIATIC

The analysis which follows will be done on the examples of 12 situations characterized with severe bora in Senj and strong bora in the greater part of the northern Adriatic coast.

The presentation of selected situations contains a review of bora onset, its strength and duration at several meteorological stations on the northern Adriatic coast. The location of considered stations are marked in Figure 1. All available wind data from climatological observations (7, 14 and 21 local time) are used. Wind is estimated in beaufort and therefore bora classification is based on this scale, such as: weak bora (< 6 B), strong bora (6 and 7 B) and severe bora (> 7 B). Bora is defined as a wind with a N - E direction. Daily courses of bora occurrences at 12 meteorological stations are presented in Figure 2. These daily courses confirm the fact that Senj's bora is specific considering its long duration and high velocities. The

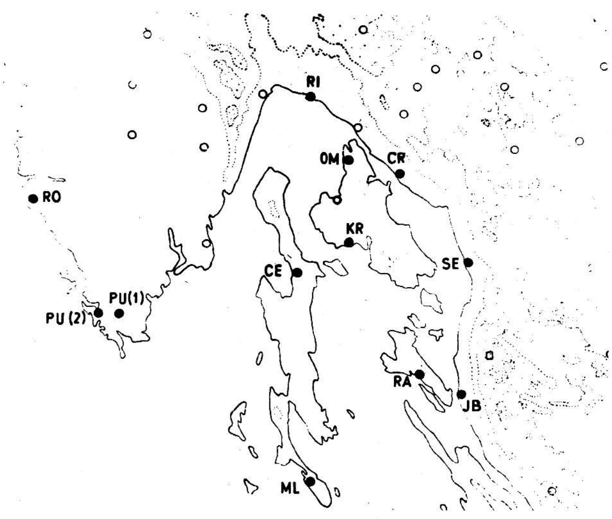


Fig.1. The northern Adriatic area with considered meteorological stations.
Sl. 1. Područje sjevernog Jadrana s položajem meteoroloških stanica.

differences between the bora in Senj and on other locations are minimal in situations with pronounced cold air outbreak behind the front passed over the upstream bora regions (March 1977, January and November 1979). In these situations bora onset is almost simultaneous along the entire northern Adriatic coast, it lasts 1-2 days and its strength is nearly equal at all considered stations. The sudden bora onset occurs as a consequence of cold air outbreak behind the surface front characterized by a large amplitude and a short wavelength wave known to be dynamically unstable (Jurčec, 1989). The similar characteristics of bora onset were shown in some ALPEX - SOP frontal cases (Jurčec, 1988).

Further synoptic development into cut-off processes over the Mediterranean and the prevailing high pressure pattern over the European continent mark other bora features. Since these cases are quasi-stationary and allow the cold air supply over central Europe with a shallow but strong anticyclone at the surface layer, this causes long lasting temperature inversions and the longest bora condition (January 1963, December 1967, December 1968). The stable layer is particularly pronounced in cases with prefrontal warm advection on the advanced side of the upper trough, and in postfrontal cases with slow upper level motion and a strong subsidence associated with anticyclone in central Europe. The stable layer weakens when the supply of cold air in the low layer cases and the upstream bora layer becomes very thin allowing bora occurrence only across the lowest mountains and passes. This is the reason for the greatest bora duration in Senj which is located beneath the very pronounced Vratnik Pass.

From Figure 2. the dependence of bora characteristics on a particular locality could also be seen. The meteorological station at Rovinj (RO) shows the N-E wind less frequent than the other stations and bora strength is never > 7 B. The Rovinj location is on the western coast of Istra far from the mountain barrier and on the lee side of Učka mountain.

Besides Senj, another location with frequent strong and severe bora is Jablanac (JB). This meteorological station is located near a mountain pass, too. Seven of considered

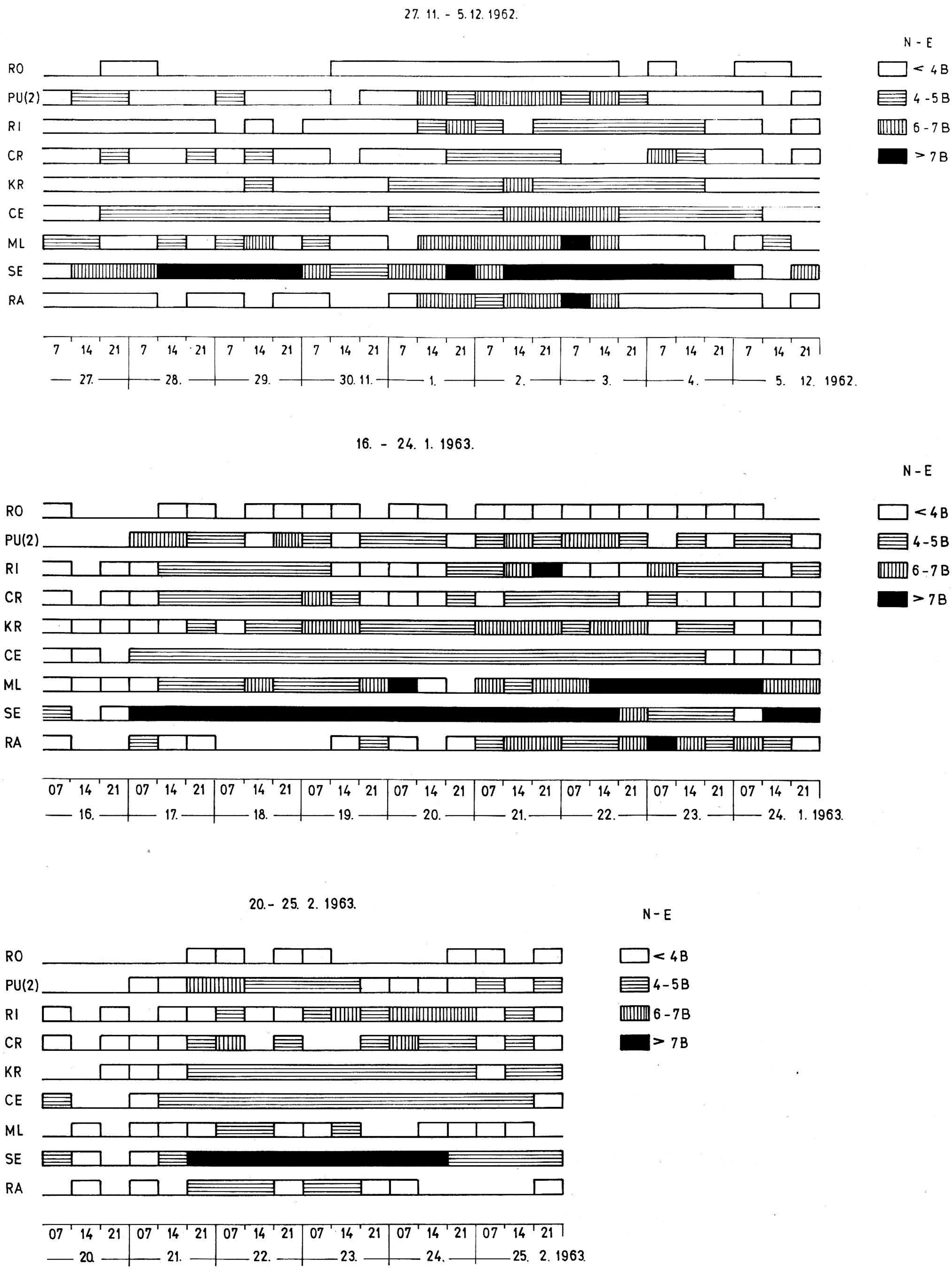
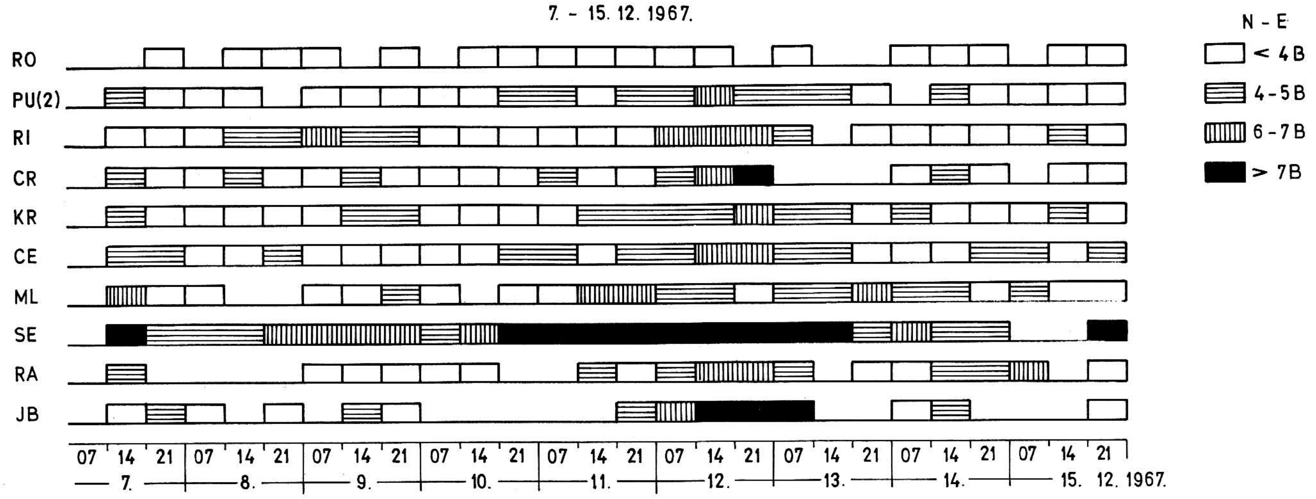
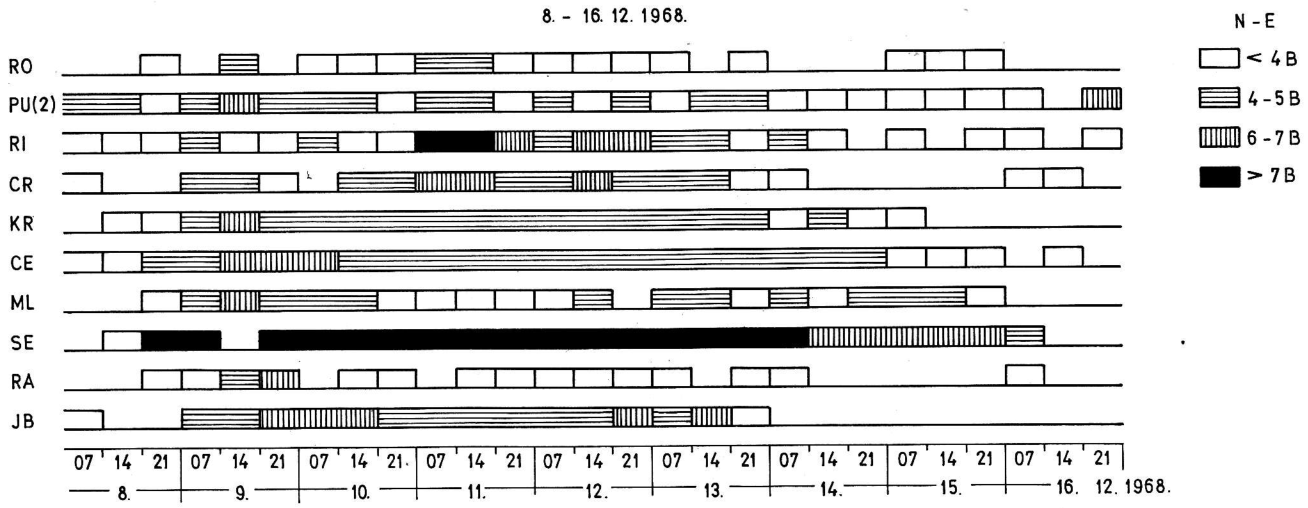


Fig. 2. The daily courses of bora occurrences on the northern Adriatic (from climatological observations).
Sl. 2. Dnevni hodovi bure na sjevernom Jadranu (na osnovi klimatoloških podataka).





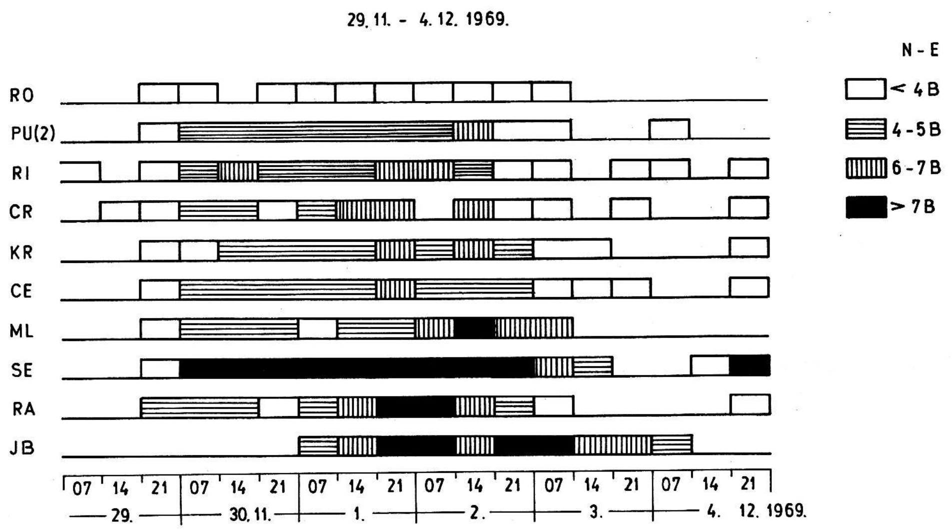
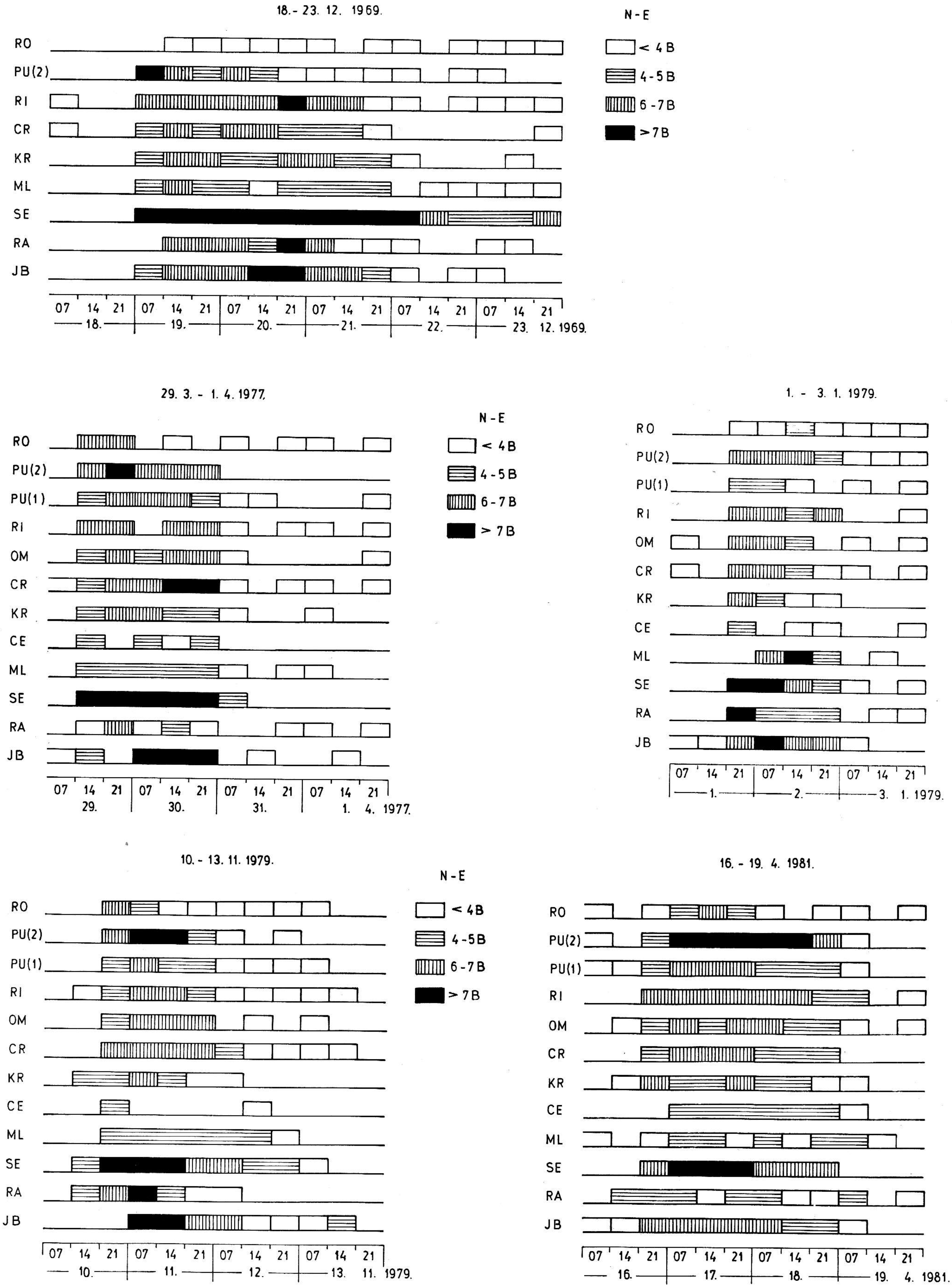


Fig. 2. Continuation
Sl. 2. Nastavak



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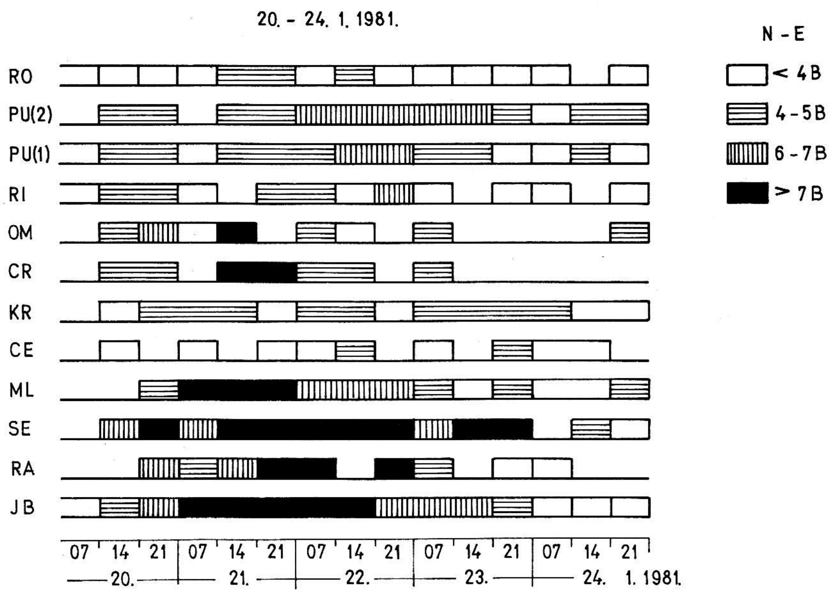

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bora storms were presented by Jurčec (1989a,b) in more detail. Here we shall pay more attention to hourly measured surface data in 3 bora cases which follow the strong postfrontal cold air outbreak (29 - 31 March 1977, 1-2 January 1979, 10-12 November 1979).

3. DAILY COURSES OF MEAN HOURLY WIND SPEED

The courses of mean hourly wind speed in periods with N-E wind direction on three stations on the Adriatic coast (Senj, Pula and Omišalj) and one in the upstream bora region (Zagreb) are presented in Figure 3. The common characteristic in all situations and at all coastal stations is a sudden increase of wind speed at the bora onset i.e. when the wind changes its direction to the N-E. In the first 4-5 hours mean hourly speed may increase even by 16 m/s. The sudden bora onset with an increase of mean hourly velocity for 15 m/s in 2 hours accompanied by an increase of maxima wind gusts for 24 m/s is observed in the most pronounced cold air outbreak situation on 1 January 1979. As could be seen in Figure 3. the wind speed reaches its maximum very soon after bora onset and then decreases slowly.

The wind in the downstream bora region turn to the N-E direction in considered situations 6 - 8 hours latter than in Zagreb. However, daily courses of mean hourly wind speed are very simillar in all considered locations.

4. TEMPERATURE AND PRESSURE CHANGES AND ASSOCIATED BORA

Bora onset in the three considered postfrontal cases is a consequence of a shallow front with very strong cold air outbreak. On Figure 4. the daily courses of air temperature in Zagreb and Senj show the intensity of these cold air outbreaks. With the change of wind direction in Zagreb temperature rapidly decreasing (19°C/7 hours on 1 January 1979) and a few hours later the same occurs in Senj. Sudden changes in temperature are accompanied with the specific see level pressure courses (Figure 5).

In Figures 4 and 5 we can isolate 1-2 January 1979 as a situation with the greatest variations in presented meteorological elements. A basic difference in the development of this synoptic situation and the other two is faster movement of the upper level trough to the east causing the change of tropospheric winds to the northerly direction (Jurčec, 1989a).

5. BORA WIND SPEED IN RELATION TO MESOSCALE SEA LEVEL PRESSURE DIFFERENCES

During the bora occurences along the northern Adriatic coast the characteristic sea level pressure field is observed. In the Gulf of Kvarner there is a low pressure area in comparison with the higher pressure in the upstream region.

The quantitative measure of relationship between the bora wind velocity and sea level pressure differences across the mountain barrier could be obtained by computing the coefficent of correlation between those two variables. In its simplest form r assumes that the most probable value of mean hourly wind speed V_s *(y)* corresponding to any given value of sea level pressure difference Δp *(x)* is determined by the expression $y = ax + b$ where a and b are constants which depend on the units in which V_s and Δp are expressed as well as on the relationship between them.

Koračin and Poje (1982) estimated the coefficient of correlation between the air pressure difference means at Ogulin - Omišalj and the ten - minute wind speed mean at Hamaz near Omišalj in 6 situations with strong bora. They found that the ten minute mean wind speed statisticaly depends upon the sea level pressure difference. In order to show the spatial variability of such a dependence and its existance in a greater number of severe bora situations we will compute the correlation coefficients between the bora

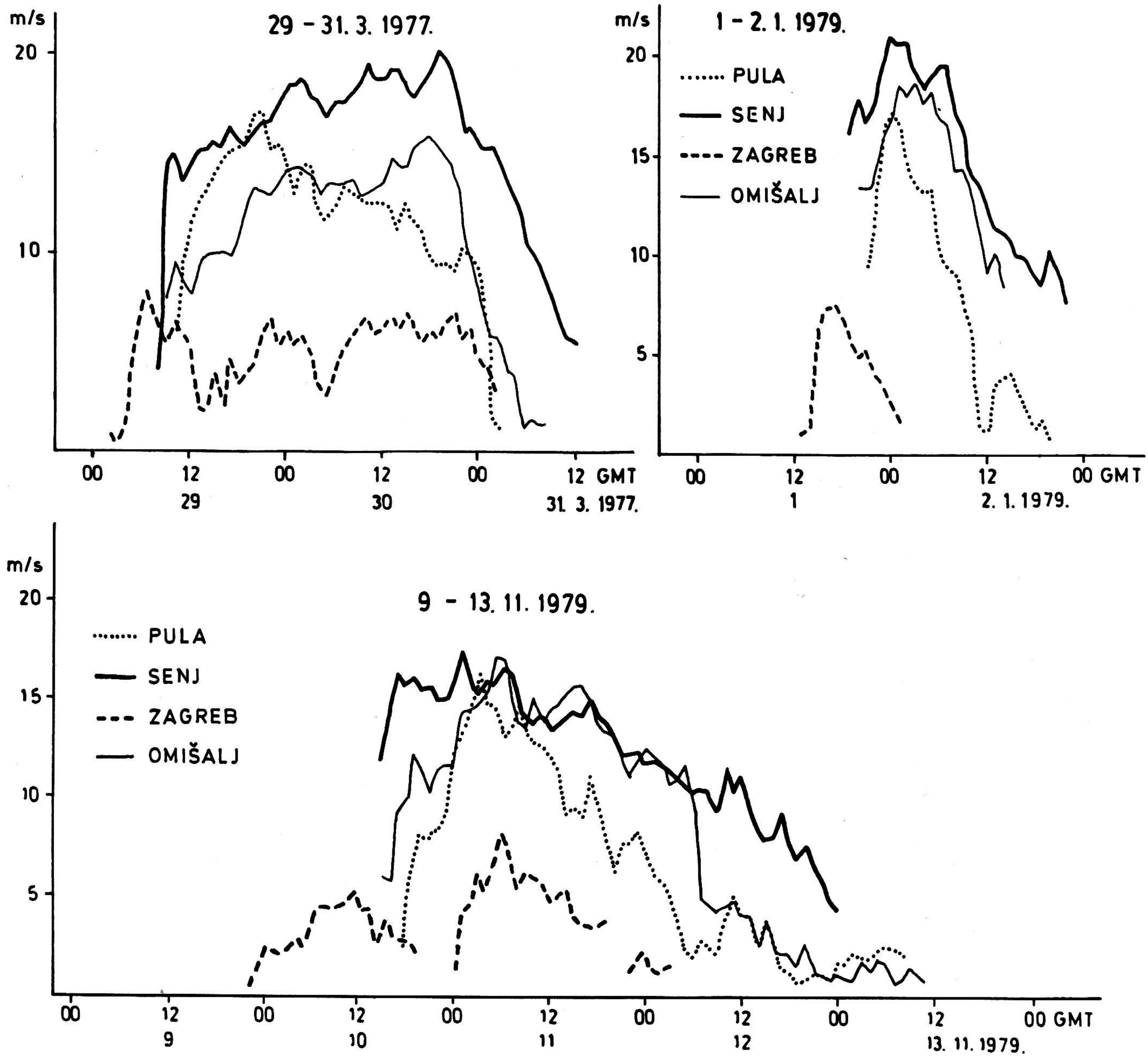


Fig. 3. The daily courses of mean hourly wind velocity (N - E direction).
Sl. 3. Dnevni hodovi srednje satne brzine vjetra (N - E smjera).

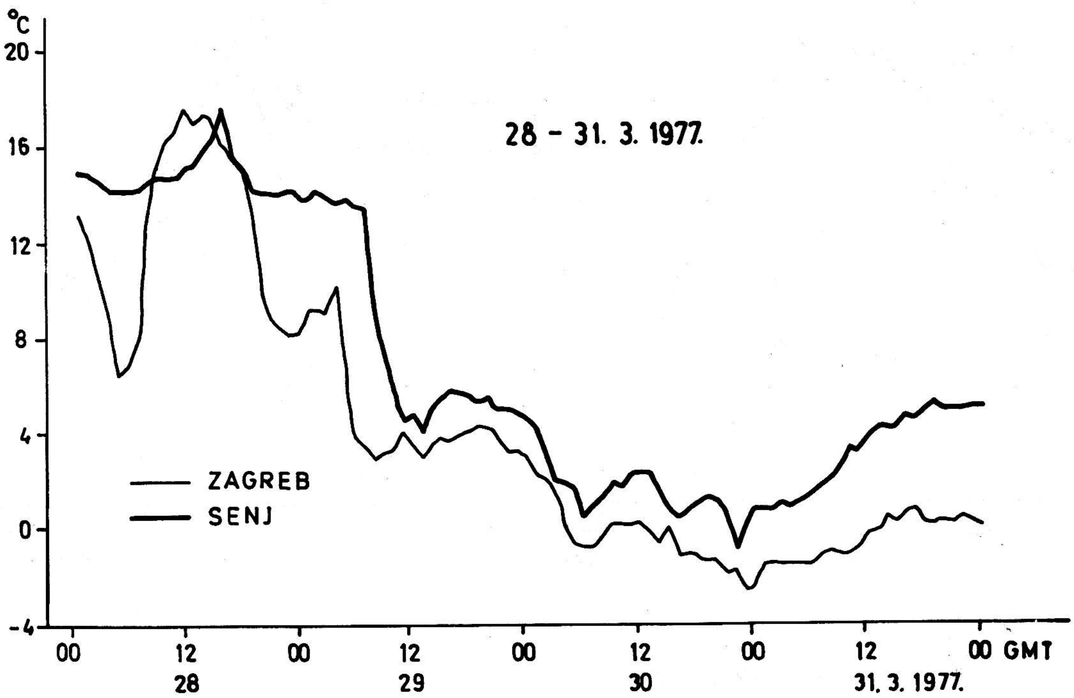
wind speed and cross mountain sea level pressure difference measured at 8 terms daily (every 3 hours) during the bora periods. Ten - minute wind speed data usually are not available and therefore we will use mean hourly wind speed. The computation will be done using Senj–s wind speed data (the only station with available hourly measured wind data in all considered cases) and sea level pressure data for Zagreb and Senj in 12 situations with severe bora.

Obtained correlation coefficients *r* and constants in correlation expression *a* and *b* are given in Table 1. All *r* coefficients are shown to be statistically significant on the $\alpha = 0,05$ significance level. It is interesting to notice almost the same values of *a* and *b* constants in 3 situations with the most pronounced cold air outbreaks (March 1977, January and November 1979).

Although the number of cases are two small for general conclusion it seems that knowing *a* and *b* constants in V_s - Δp regression expression and having predicted sea level pressure field we could predict the mean hourly wind speed in Senj in situations with sudden and strong cold air outbreaks in the upstream bora region. In order to show once again the spatial variability of bora characteristics we estimate the relationship between V_s and Δp for Omišalj and Pula in 5 situations with available hourly measured wind speed data (Table 2 and 3). Although the *r* coefficients obtained for Omišalj and Pula are smaller than those presented in Table 1 a stohastic dependence between V_s and Δp still exists.

The values of *a* and *b* constants given in Tables 2 and 3 show no regularity in linear regression expression in similar weather situations.

It seems, according to the presented results, that the time variations in mesoscale sea level pressure differences are best reflected in the mean hourly wind speed variations in



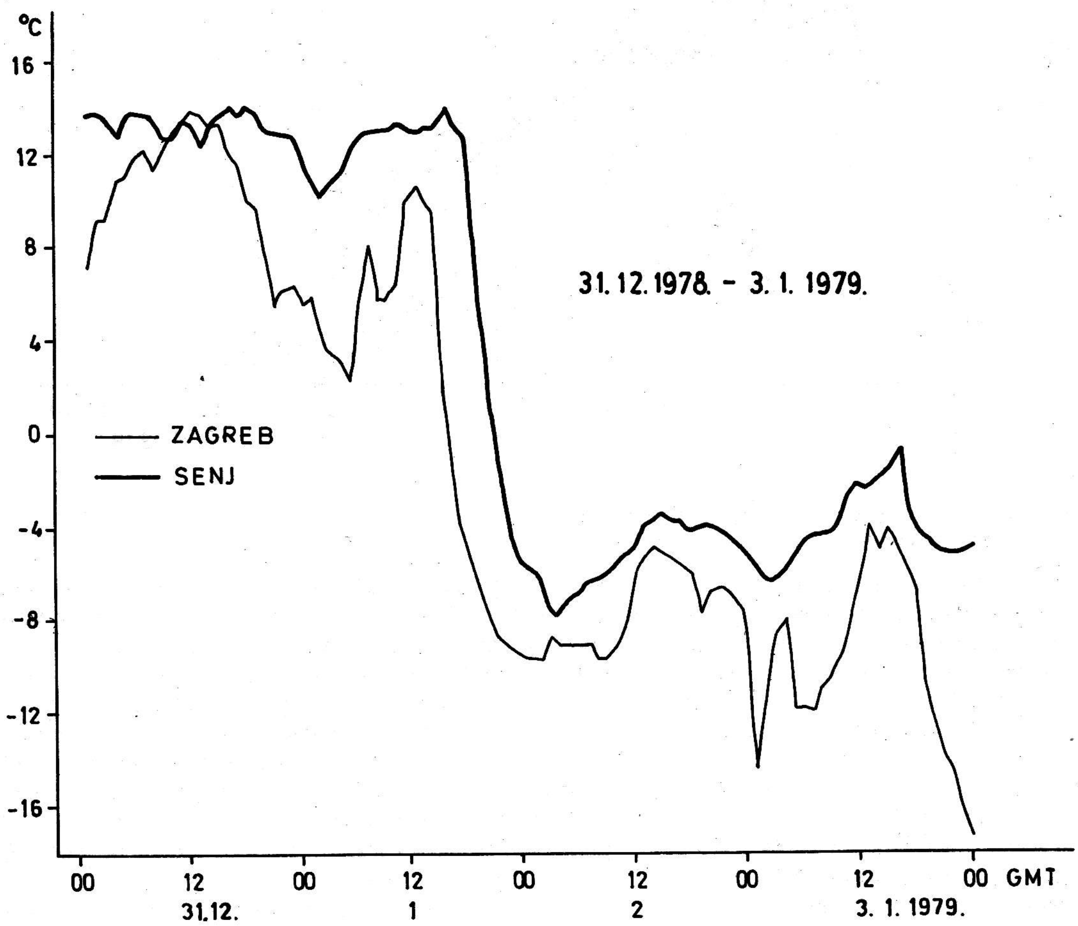


Fig. 4. The daily courses of surface temperature in Zagreb and Senj in situations with severe bora on the northern Adriatic.
Sl. 4. Dnevni hodovi temperature zraka u Zagrebu i Senju u situacijama s olujnom burom na sjevernom Jadranu.

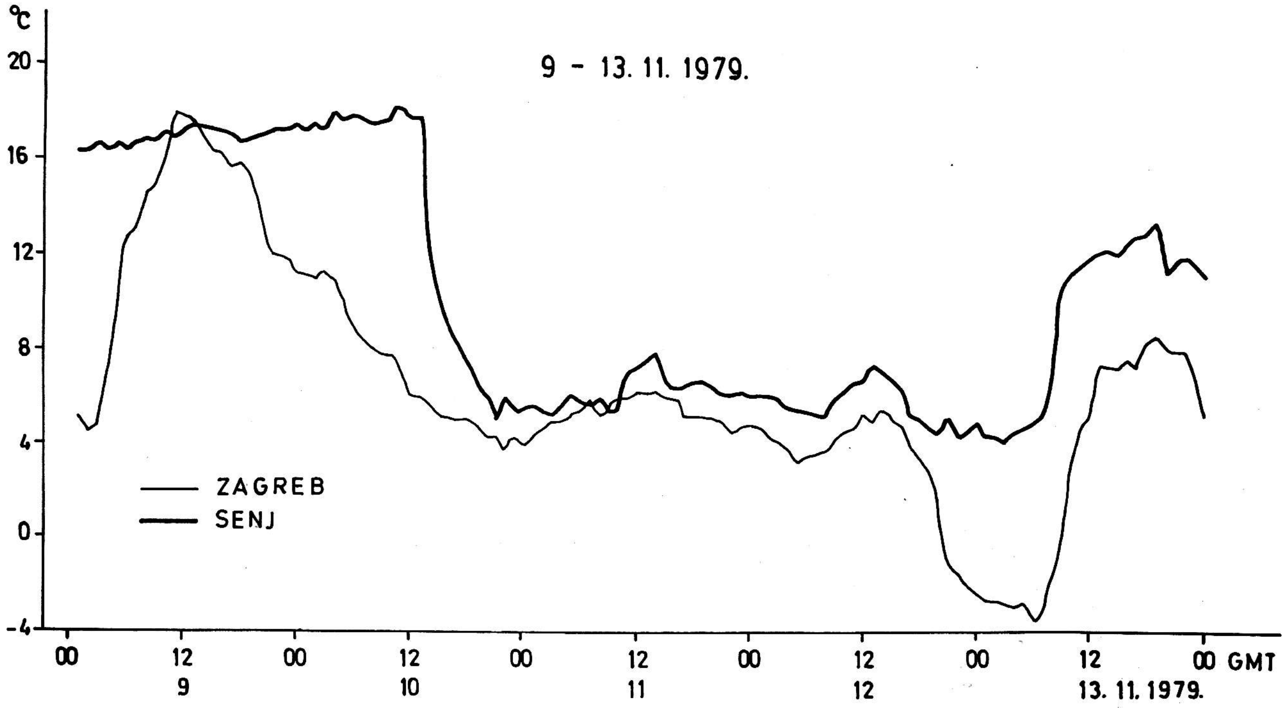


Fig. 4. Continuation
Sl. 4. Nastavak

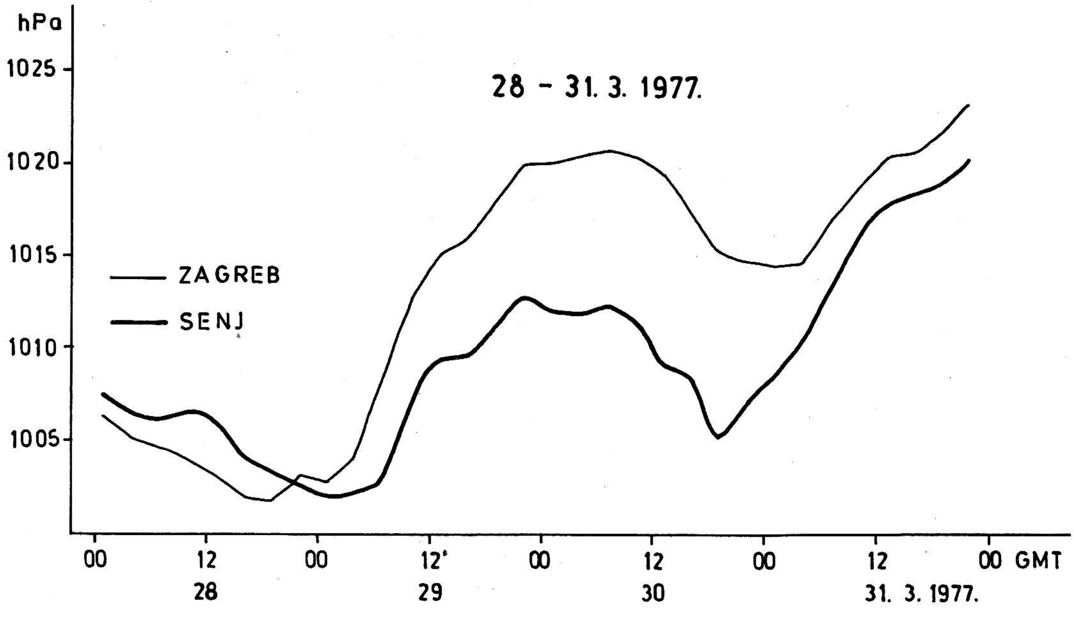


Fig. 5. The daily courses of sea level pressure in Zagreb and Senj in situations with severe bora on the northern Adriatic.
Sl. 5. Dnevni hodovi tlaka zraka reduciranog na morsku razinu u Zagrebu i Senju u situacijama s olujnom burom na sjevernom Jadranu.

Senj due to its characteristic location in relation to mountain barrier.

6. CONCLUSION

The presented analysis of severe bora wind on the northern Adriatic confirms the statement that the Senj bora is specific in respect to its duration and high speed.

The longest bora duration is a consequence of cut-off processes and blocking circulation pattern with the persistent anticyclone over central Europe in the cold surface boundary layer.

In postfrontal cases with a very pronounced cold air outbreak bora occurs almost simultaneusly in broader area but with larger variations in speed. The temperature drop is associated with a characteristic pressure variations. Consequently strong bora event is always connected with characteristic mesoscale pressure field. In the Gulf of

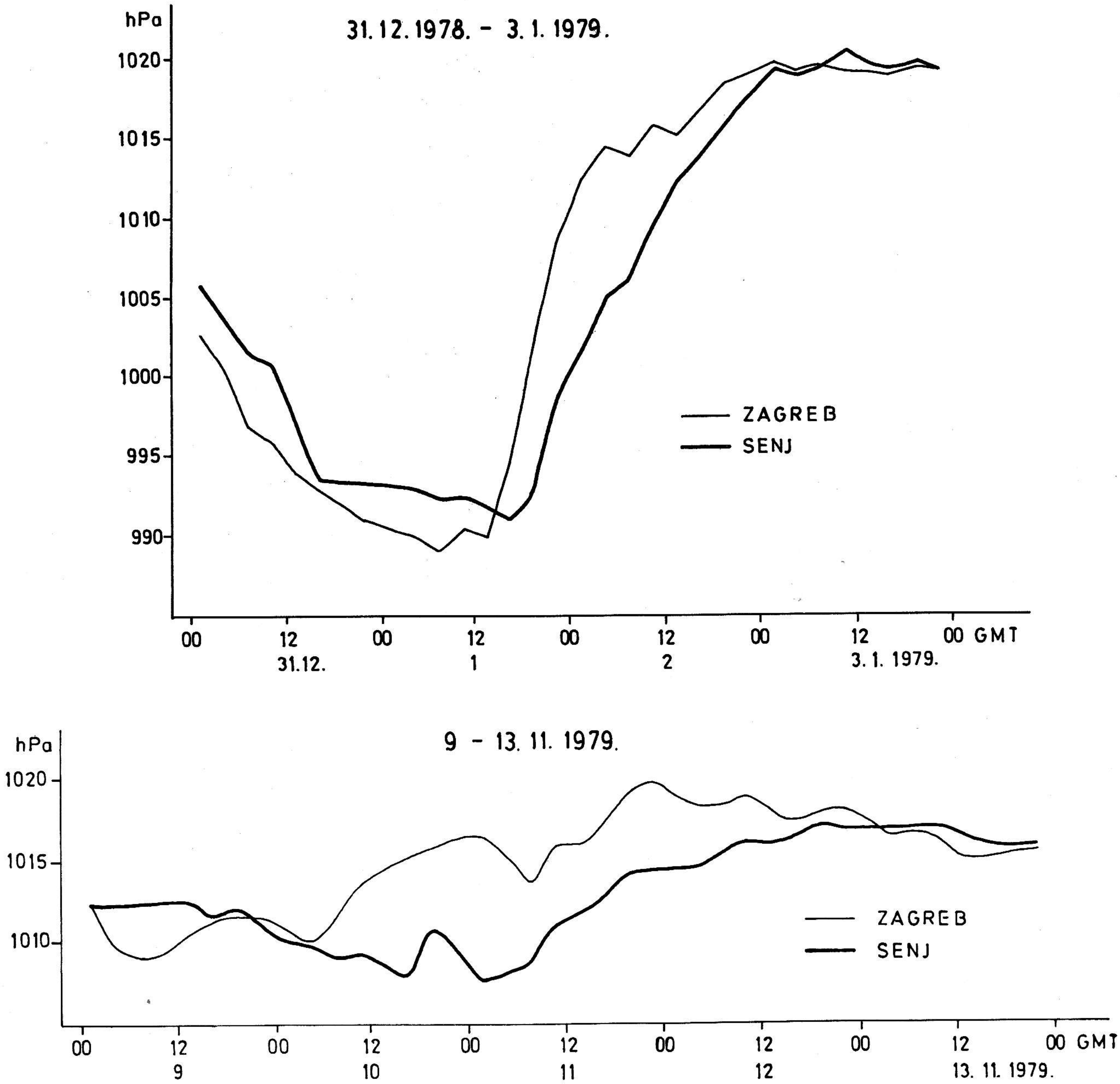


Fig. 5. Continuation
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Kvarner there is a low pressure area in comparison with the higher pressure area in the upstream region.

The estimation of degree of relationship between pressure differences Zagreb - Senj and mean hourly wind speed in Senj show the statisticaly significant correlation between those two variables in 12 considered severe bora situations. In the strongest 3 cold air outbreak cases the constants in correlation expression are almost the same. They enable us to predict the mean hourly wind speed in Senj for any predicted Zagreb - Senj pressure difference in similar weather situations.

The same estimation using Omišalj and Pula wind data show a lower degree of relationship between the upstream - downstream sea level pressure difference and mean hourly wind speed. The reason for this is probably the location of Pula and Omišalj stations at some distance from the mountain barrier. These results confirm, once again, the fact that the Senj bora is specific in respect to other localities.

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Table 1. Correlation coefficients *(r)* between cross mountain sea level pressure difference *(Δp)* and mean hourly wind speed *(V_s)* in Senj in severe bora cases (*a* and *b* are constants in linear correlation expression).

Tabela 1. Koeficijent korelacije *(r)* između razlike tlaka zraka preko planinske prepreke *(Δp)* i srednje satne brzine vjetra u Senju *(V_s)* u situacijama s olujnom burom (*a* i *b* su konstante u izrazu za linearnu korelaciju).

Situation	Sample size	r	a	b
27.11 - 04.12.1962	60	0.81	5.60	1.41
17 - 23. 01. 1963.	51	0.79	-0.49	2.02
21 - 25. 02. 1963.	38	0.91	2.10	1.95
07 - 14. 12. 1967.	57	0.91	4.64	1.59
08 - 16. 12. 1968.	60	0.77	4.36	1.69
28.11-03.12.1969.	30	0.87	2.70	1.95
18 - 22. 12. 1969.	29	0.67	1.17	2.09
29.03 - 01.04.1977.	18	0.92	6.86	1.27
01 - 03. 01. 1979.	10	0.93	6.68	1.21
10 - 12. 11. 1979.	19	0.88	6.76	1.26
20 - 24. 01. 1981.	22	0.71	2.94	1.54
16 - 19. 04. 1981.	19	0.91	6.55	1.14

Table 2. Correlation coefficients *(r)* between cross mountain sea level pressure difference *(Δp)* and mean hourly wind speed *(V_s)* in Omišalj in severe bora cases (*a* and *b* are constants in linear correlation expression).

Tabela 2. Koeficijent korelacije *(r)* između razlike tlaka zraka preko planinske prepreke *(Δp)* i srednje satne brzine vjetra u Omišlju *(V_s)* u situacijama s olujnom burom (*a* i *b* su konstante u izrazu za linearnu korelaciju).

Situation	Sample size	r	a	b
29 - 31. 03. 1977.	15	0.76	5.05	0.95
01 - 02. 01. 1979.	7	0.78	8.36	0.85
10 - 11. 11. 1979.	12	0.66	9.49	0.73
20 - 21. 01. 1981.	8	0.65	-13.30	4.39
16 - 19. 04. 1981.	19	0.52	9.48	0.27

Table 3. Correlation coefficients *(r)* between cross mountain sea level pressure difference *(Δp)* and mean hourly wind speed *(V_s)* in Pula in severe bora cases (*a* and *b* are constants in linear correlation expression).

Tabela 3. Koeficijenti korelacije *(r)* između razlike tlaka zraka preko planinske prepreke *(Δp)* i srednje satne brzine vjetra u Puli *(V_s)* u situacijama s olujnom burom (*a* i *b* su kosntante u izrazu za linearnu korelaciju).

Situation	Sample size	r	a	b
29 - 31. 03. 1977.	13	0.66	19.02	-0.76
01 - 02. 01. 1979.	6	0.93	- 3.41	1.74
10 - 11. 11. 1979.	12	0.60	3.15	1.24
20 - 23. 01. 1981.	24	0.47	6.17	0.37
16 - 18. 04. 1981.	14	0.76	6.36	0.78

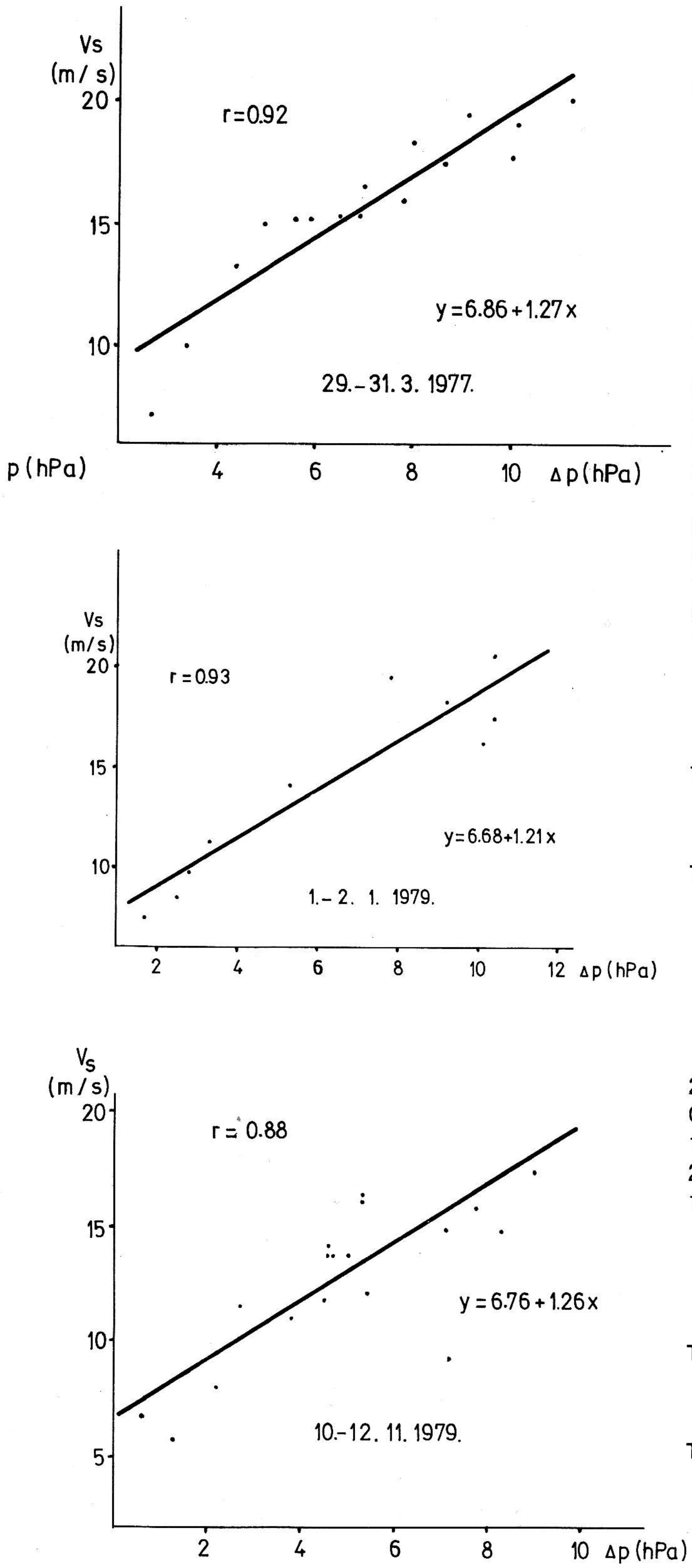

Fig. 6. The correlation between the mean hourly wind speed in Senj (V_s) and Zagreb - Senj pressure differences (Δp).

Sl. 6. Odnos između srednje satne brzine bure u Senju (V_s) i razlike tlaka Zagreb - Senj (Δp).

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KRATKI SADRŽAJ:

Analiza prostornih i vremenskih varijacija pojave bure na sjevernom Jadranu na osnovi 12 vremenskih situacija karakteriziranih olujnom burom u Senju potvrdila je specifičnost senjske lokacije.

Za vrijeme dugotrajne olujne bure koja je posljedica otcjepljenja ciklone u Sredozemlju i razvoja anticiklone nad srednjom Evropom (blokirajući tip cirkulacije) brzina vjetra u Senju veoma malo varira. Kvazistacionarnost ovakve vremenske situacije omogućava dugotrajno pritjecanje hladnog zraka u navjetrinu planinske prepreke i preko najnižih prijevoja, te pojavu olujne i dugotrajne bure uglavnom samo u Senju.

U postfrontalnim situacijama s vrlo izrazitim i naglim prodorom hladnog zraka podjednako intenzivna i kratkotrajna bura zabilježena je gotovo istovremeno na širem području sjevernog Jadrana. Tri takva slučaja olujne bure analizirana su detaljnije. Pad temperature uzrokovan prodorom vrlo hladnog zraka (19°C/ 7 sati 1 siječnja 1979) praćen je karakterističnim varijacijama tlaka zraka, te postojanjem razlike tlaka između područja niskog tlaka nad Kvarnerskim zaljevom i znatno višeg tlaka u navjetrini Dinarida.

Određivanje stupnja ovisnosti srednje satne brzine bure *(V_s)* o razlici tlaka preko planinske prepreke *(Δp)* pokazalo je da postoji stohastička zavisnost između ove dvije varijable u svih 12 promatranih situacija.

U tri situacije s najizrazitijim prodorom hladnog zraka u navjetrinu Dinarida pokazano je da su konstante u izrazu za korelaciju između Δp i srednje satne brzine vjetra u Senju gotovo identične, iako dnevni hodovi reduciranog tlaka zraka u navjetrini (Zagreb) i zavjetrini (Senj) planinske prepreke, te njihova razlika Δp, nisu slični. To daje mogućnost da se u sličnim vremenskim situacijama na osnovi poznatog Δp procijene brzine bure u Senju.

Slični proračun učinjen koristeći podatke Omišlja i Pule pokazao je manji stupanj zavisnosti promatrane dvije varijable. Razlog tome je vjerojatno položaj ove dvije stanice na većoj udaljenosti od planinske prepreke. Ovi rezultati još jednom potvrđuju specifičnost senjske bure u odnosu na buru na ostalim lokacijama duž sjeverne obale Jadrana.