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BORA ON THE ADRIATIC COAST DURING ALPEX SOP ON 27 TO 30 APRIL 1982

Bura na Jadranu u toku ALPEX-SOP 27. do 30. 4. 1982.

VLASTA TUTIŠ
Hydrometeorological Institute of Croatia, Zagreb
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Abstract: The periodically blowing bora wind on the Yugoslav Adriatic coast at the end of the ALPEX SOP (27-30 April) was analysed. The first case on 27 April was a consequence of the frontal passage, the second one on 28 and 29 April, of the cold north outbreak and the third case on 30 April was triggered by the Genoa lee cyclogenesis. General characteristics of the surface pressure field were the relatively weak gradients which resulted in generally weak bora, while the periods of locally stronger bora were rather brief. The cold stable airmass from inland poured over the mountainous barrier in the direction of the strongest gradients causing the relative humidity and temperature decrease and local pressure increase in the lee. The most pronounced bora was close to the lowest mountain passes and where the channelling effects were the strongest. The upper level wind usually had two maxima: the main in the upper trposphere due to macroscale motions and the secondary in the lowest few kilometres due to the surface accelerating mesoscale flow, defined as the bora layer. Assuming that bora has a certain similarity with the supercritical flows described by the hydraulic theory, the parameters of the real flow and those predicted by the theory are compared. It was concluded that a distinction should be made between the cases with the sharply defined bora layer (by strong inversion or flow reversal - like on 27 and 30 April) and continuously stratified cases (as on 28/29 April) where the upstream bora layer usually cannot be immediately determined.

Key words: ALPEX SOP, bora, hydraulic theory, mesoanalysis

Sažetak: U ovom je radu analizirana bura koja je povremeno puhala duž Jadranske obale na samom kraju ALPEX SOP perioda (27. do 30. aprila). Možemo razlikovati tri slučaja: prvi, 27. 04, koji je posljedica prolaza fronte, drugi, 28. i 29. 04, koji je posljedica hladnog sjevernog prodora i treći, 30. 04, koji je uzrokovan đenovskom ciklogenezom. Opća karakteristika prizemnog polja tlaka bili su slabi gradijenti, zbog čega je i bura bila slaba, a periodi s jakom burom bili su vrlo kratkotrajni. Za pojavu bure značajno je prelijevanje hladnog stabilnog zraka u smjeru najjačih gradijenata preko planinske prepreke, što dovodi do pada temperature i relativne vlage te istovremenog porasta tlaka u zavjetrini. Najjača bura zabilježena je uz planinske prijevoje, kao i na onim područjima gdje je efekt kanaliziranja najjači. Visinski vjetar obično ima dva maksimuma - glavni u višoj troposferi (makroskalna gibanja) i sekundarni u nižoj troposferi (zbog prizemnog akcelerirajućeg sloja zraka koji definira sloj bure). Pod pretpostavkom da je bura atmosferski mezoskalni proces, koji ima određene sličnosti sa superkritičnim strujanjem, koje opisuje hidraulička teorija, uspoređeni su parametri stvarnog toka s teoretski prognoziranim vrijednostima. Na temelju te analize slučajeve bure s jasno raspoznatljivim slojem bure u navjetrini (27. 04. i 30. 04) možemo odvojiti od slučaja 28/29. 04. kada je određivanje sloja bure otežano zbog kontinuirane stratifikacije atmosfere.

Ključne riječi: ALPEX SOP, bura, hidraulička teorija, mezoanaliza

1. INTRODUCTION

Bora is usually a strong, gusty and cold katabatic wind which blows on the Yugoslav coast from the northeast quadrant. It is generated when cold stable air flows from inland over a relatively low orographic barrier into the Adriatic basin. In spite of adiabatic heating during leeward descend, the newcoming air is still colder than the already present air-mass.

Although bora appears along the whole coast, it is most frequent and strongest on the northern Adriatic in the Velebit Channel, immediately at the foot of the steep Velebit mountain chain, and generally near mountain passes (especially the area of Ajdovščina, Senj, Šibenik and Split).

The most frequent bora periods last two to three days, but can be even longer than five days. The local sea-shore circulation can strongly affect bora: during the day bora slows down, while during the night it picks up.

The effect of bora on the climate of the narrow coastal area is strong enough to give it a more continental character during the winter.

More about theoretical, observational and statistical studies can be found in Makjanić (1978), Jurčec (1981), Lukšić (1975) and Yoshino (1976).

At the end of the ALPEX SOP, during the period of four days (from 27 - 30 April), bora wind was periodically blowing on the greater part of the Yugoslav coast (Fig. 1). Since the synoptic situation was rather complex, it was very difficult to select even a short period when the bora had a unique synoptic source on the entire coast. Maximum windspeed, 24. 8 m/s, was observed in Šibenik on the 29th.

During this period there were no research flights. Also, no bora analysis for this case have been made until now.

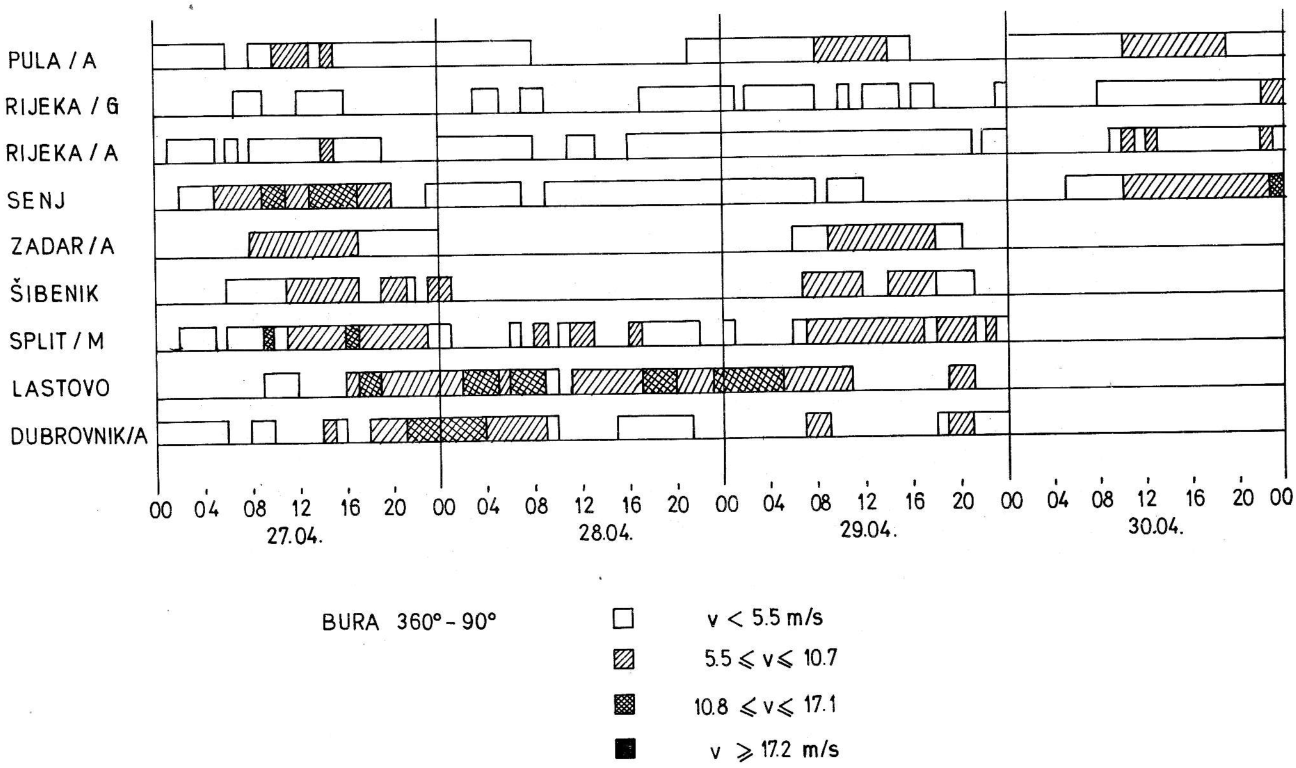
2. SYNOPTIC DEVELOPMENT

The bora period at the end of April was particulary interesting because of the exchange of several synoptic situations, each one responsible for bora generation along the Yugoslav coast: the frontal passage, the cold north outbreak and the Alpine lee cyclogenesis. Such variability was the reason for a rather weak bora with brief strong periods (if any).

Beginning on 26. April, a northerly flow over western Croatia was established due to the presence of a surface high pressure over the Atlantic Ocean west of Ireland, combined with a broad surface low pressure over northern and eastern Europe and the Mediterranean. The cold front, coming from the northwest passed over Croatia on the 26th and 27th, so during the next two days a surface ridge of the Atlantic anticyclone influenced the weather (Figs. 2, 4 and 5).

Fig. 1. Time distribution of bora along the coast, according to main synoptic stations, from 27th to 30th April 1982. Due to strong orographic adjustment, bora is here considered as wind blowing from the northeast quadrant (azymuth 360° to 90°).

Sl. 1. Razdoblje s burom prema podacima glavnih sinoptičkih stanica, od 27. do 30. 04. 1982. Zbog izraženih orografskih efekata, pod burom podrazumijavamo vjetar koji puše iz sjeveroistočnog kvadranta (azimut 360° do 90°)



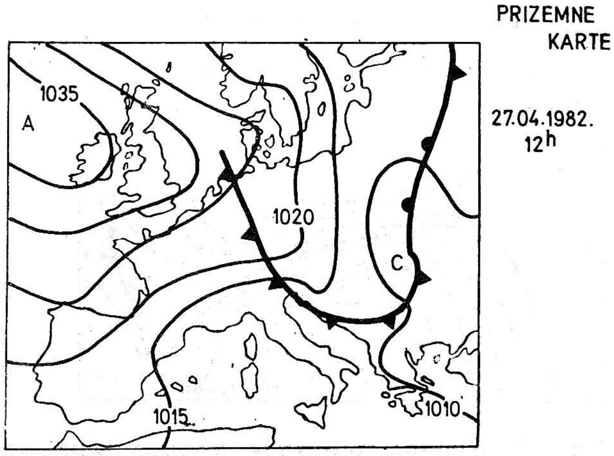


Fig. 2. Surface analysis on 27th April at 12 UTC

Sl. 2. Prizemna analiza, 27. 04. 1982. u 12 UTC

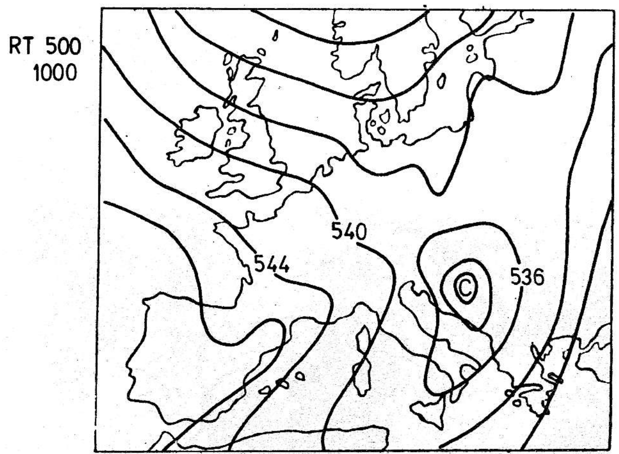


Fig. 4. RT 500/1000, on 29th April at 00 UTC

Sl. 4. RT 500/1000, 29. 04. 1982. u 00 UTC

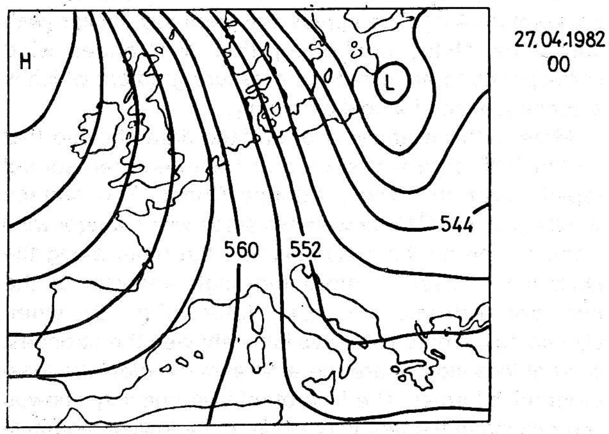


Fig. 3. AT 500 hPa, on 27th April at 00 UTC

Sl. 3. AT 500 hPa, 27. 04. u 00 UTC

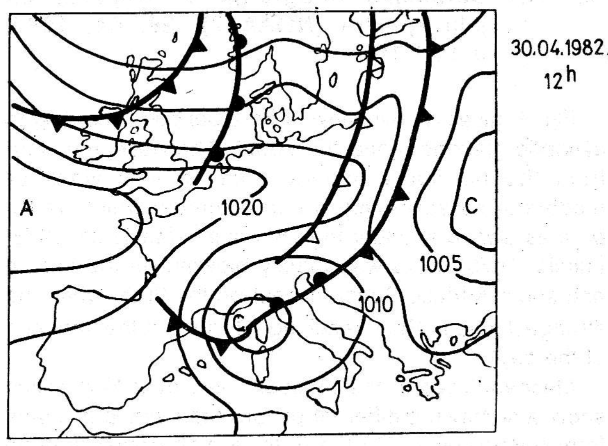


Fig. 5. Surface analysis on 30th April at 12 UTC

Sl. 5. Prizemna analiza, 30. 04. 1982. u 12 UTC

At the same time, an upper air ridge over the northeastern Atlantic Ocean and western Europe combined with a cut-off low pressure area over the eastern Balkans (from the surface up to the 300 hPa level) resulting in a northerly flow over the western part of the Balkans, extending to the lower stratosphere (Fig. 3).

On the 28th a cold airmass which arrived in the Balkans from northern Europe began to pour over the Dinaric Alps to the Adriatic Sea and Mediterranean basin causing the strongest bora along the Dalmatian Coast on the 29th.

Also, on the 28th and 29th resonant lee vaves can be recognised on visual satellite photographs by characteristic cloud bands. Lee waves were better developed on the 28th when they extended over the most part of Slovenia, Croatia and west Bosnia (Fig. 6). The estimated wavelength is between 6 and 12 km. Leewaves indicate the stable stratification of the atmosphere and the tendency for horizontal energy transport.

As the cold north outbreak supply was exausting, another cold front, arriving from the northwest, triggered (on April 30th) the Genoa lee cyclogenesis (Buzzi, 1984), which could therefore stop bora along the middle and south Adriatic coast, but initiate it again at the northern Adriatic (Fig. 5).

Analysing the synoptic scale of motion over the Balkan Peninsula and the Adriatic Sea, the general characteristic of the surface pressure field was that there were relatively weak gradients which resulted in generally weak bora, while the periods of locally stronger bora were rather brief.

3. SURFACE DATA ANALYSIS

Bora is a basically mesoscale atmospheric process; for its closer investigation, we present surface mesoanalyses of meteorological elements.

The period between 27 - 30 April is rather different than other thoroughly investigated bora periods during ALPEX SOP. Due to macroscale analysis, there were three distinct synoptic situations which caused bora.

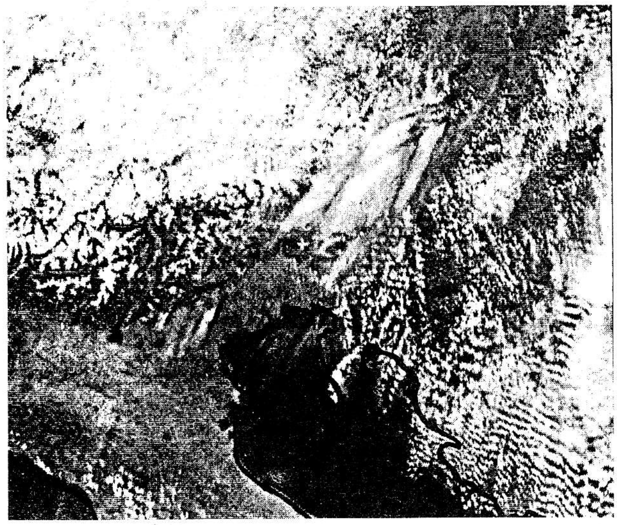


Fig. 6. **Visual satellite photograph (NOAA 7), on 28th April at 13 UTC**

Sl. 6. **Satelitska fotografija u vidljivom dijelu spektra (NOAA 7), 28. 04. 1982. u 13 UTC**

Fig. 1. gives an overview of bora periods according to synoptic stations along the coast. The observed wind from the northeast quadrant was mostly weak or moderate, so according to some authors which define bora as a wind stronger than 5.5 m s^{-1} (Makjanić, 1978; Lukšić, 1975), bora was mainly blowing on the middle and south Adriatic Coast, except on the 30th (when the strongest was in Senj, reaching 18 m s^{-1} at the very end of the day).

Mesoanalyses of the pressure field over Yugoslavia show a somewhat different picture than synoptic charts from paragraph 2. On the 27th, a high pressure ridge was penetrating from the NW, following cold fronts, while a very weak low, together with an occluding front was moving from the south Adriatic to the SE. The strongest pressure gradients were first over Gorski Kotar and Lika, where the mountain barrier is the most narrow (Fig. 9). During the 27th the gradients were rising also over the Dinaric Alps in Bosnia, Hercegovina and Montenegro, due to a pressure rise in the rear of the secondary cold front, simultaneously a deepening of the mesoscale low over the southern Adriatic, where cyclogenetic processes persisted. The inland high pressure zone is furtherly maintained by a cold air outbreak from the north, which filled the lower part of the atmosphere over the Balkans with cold stable air. This new cold air mass began to pour over the Dinaric Alps in the direction of the strongest gradients. On the 30th there was still a residual shallow layer of cold air in the southwestern part of the Pannonian valley, while the new cold front from the NW reached the Alps. The weak low southerly of the Alps indicates a beginning cyclogenetic process in the Mediterranean and therefore pressure gradients over the most narrow part of the Dinaric Alps became stronger again.

The mesoanalyses of the pressure field show a very high correlation between enhanced gradients and bora strenght, as can be also seen in Fig. 8, where the pressure differences across the mountain barrier between Ogulin (Zagreb) and Senj are compared with the mean hourly values of wind velocity in Senj (projection on azymuth 45°). The curves are generally similar (with little time shift), confirming that a stronger wind corresponds to an increased pressure gradient which is a consequence of a cold air supply.

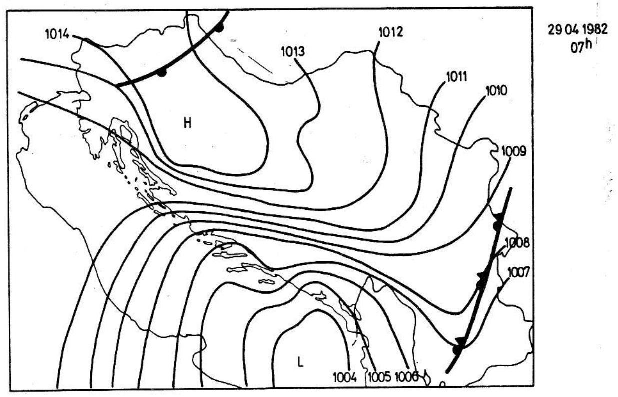


Fig. 7. **Surface pressure mesoanalysis on 29th April at 06 UTC**

Sl. 7. **Mezoanaliza prizemnog polja tlaka, 29. 04. u 06 UTC**

More detailed analysis of surface data showed that on the 27th bora first started at Senj and then spread rapidly over the whole Adriatic Coast. The surface windfield at 12 UTC showed two areas with stronger wind - one on the northern Adriatic and the other along the Dalmatian Coast. A more thorough analysis of the northern Adriatic an hour later (Fig. 9) when climatological data were available showed the strongest wind at localities where the airstream overflew the least orographic barrier. The field of relative humidity showed two minima in the lee, very close to the lowest mountain passes where the downward motion of the airstream was obviously the most pronounced. Over Istria, the wind was generally slowed down and changed direction due to orographic forcing, confirming thus the statistical result (Makjanic, 1978) that this area is not as strongly affected by bora as is the area immediatelly to the lee.

On 28 April bora first started in Senj at 09 h local time (08 UTC), and advanced very slowly into Kvarner Bay and Istria. In Senj (Fig. 11), Rijeka (airport) and Rijeka (town) it started with gusts, but other stations registered gradual intensifying of wind valocity. Observed wind shows fluctuations in direction and also in speed.

As windspeed is relatively small, there is rather large orographic influence on the airflow, probably the main reason for direction fluctuations. The other interesting feature of this case is the periodical existence of calm areas from Kraljevica to Crikvenica (from own experience during other similar situations probably extended to Novi Vinodolski), near Jablanac and Cres.

On the 28th at 20 UTC bora was observed on most of the northern Adriatic Coast. The present airmass was relatively dry and the weather clear. Accumulated cold air in the inland was blocked, and caused an increase in the pressure gradient over Gorski Kotar. The streamline field was obviously controlled by orography: from prevailing northeast upstream to the north or even northwest in the lee, including divergence over Istria

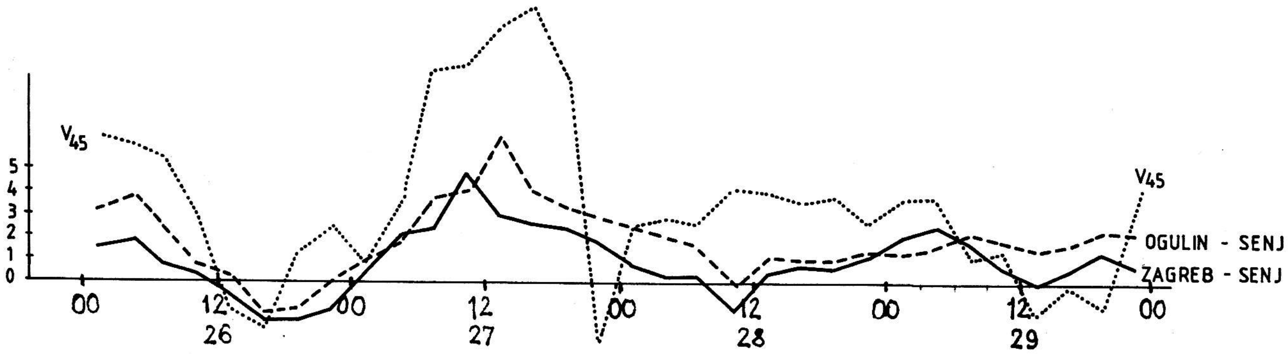


Fig. 8. Pressure differences (Δ p) between Zagreb and Senj and Ogulin and Senj, compared with mean hourly values of velocity in Senj (projection on azumuth 45°)

Sl. 8. Razlika tlaka (Δ p) između stanica Zagreb - Senj i Ogulin - Senj u usporedbi sa srednjim satnim vrijednostima brzine vjetra u Senju (45°)

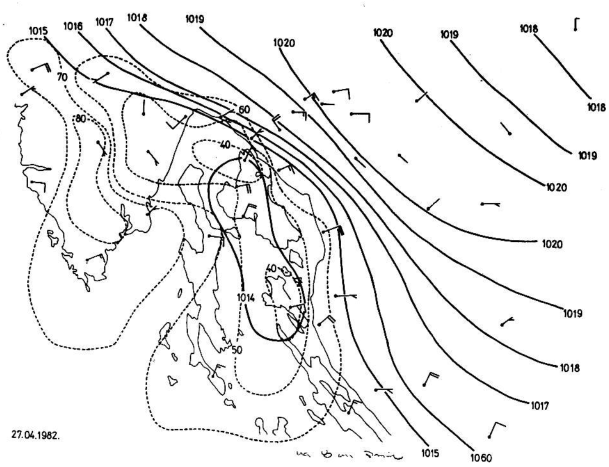


Fig. 9. Mesoanalysis for the northern Adriatic on 27th April at 13 UTC

Sl. 9. Mezoanaliza za područje sjevernog Jadrana, 27. 04. u 13 UTC

(the airflow splits over Rijeka (town) and Opatija into two parts - one continues down to the south over the Kvarner Bay and the other goes southward around Čičarija mountain, causing the bora on the western coast of Istria). At the same time, the relative humidity field had again two minima, one south of Rijeka (town) and the other in the Velebit Channell between Senj and Rab, which correspond to maximum windspeed areas, as on the 27th.

On 29 April at 06 UTC (Fig. 10) the greatest pressure gradient was on the coastal belt. The weather was cloudy with local rain and, above 600 m, snow. The streamline field was still controlled by orography and similar to the previous analysis, except over western Istria where wind had changed or stopped.

Extending the analysis to the whole coastal belt, we may state that the strongest wind is observed at stations where the topographic channeling effects are strongest (Šibenik, Split), while strong northerly wind on the open sea was also partly due to enhanced pressure gradients connected with the Adriatic mesocyclone.

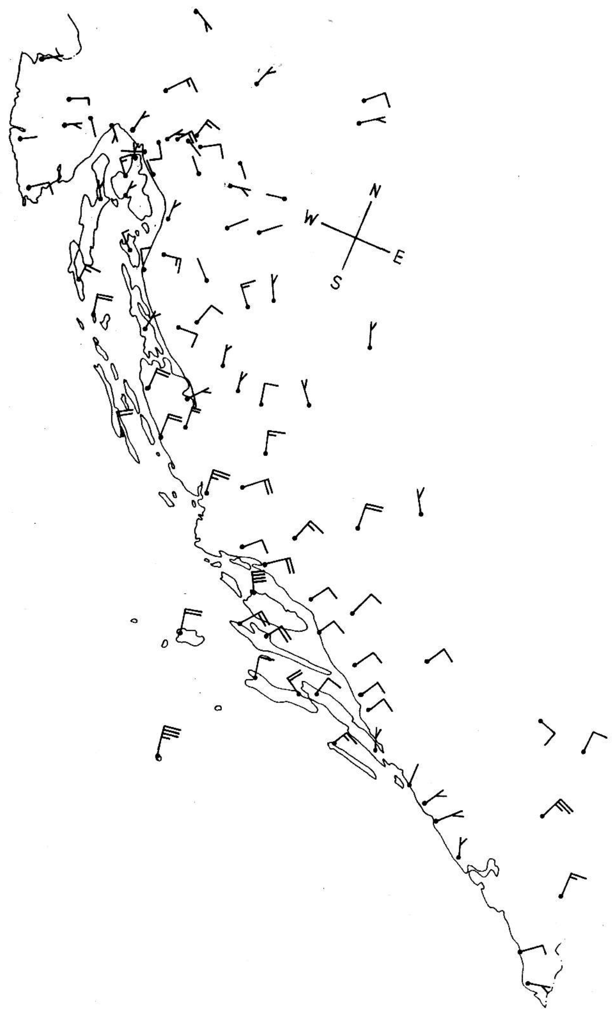


Fig. 10. Surface wind observation at the Adriatic Coast on 29 April at 06 UTC

Sl. 10. Prizemno polje vjetra duž jadranske obale, 29. 04. u 06 UTC

The bora on the northern Adriatic on the 30th, when following the Genoa cyclogenesis, is accompanied by easterly and southerly winds over the middle and

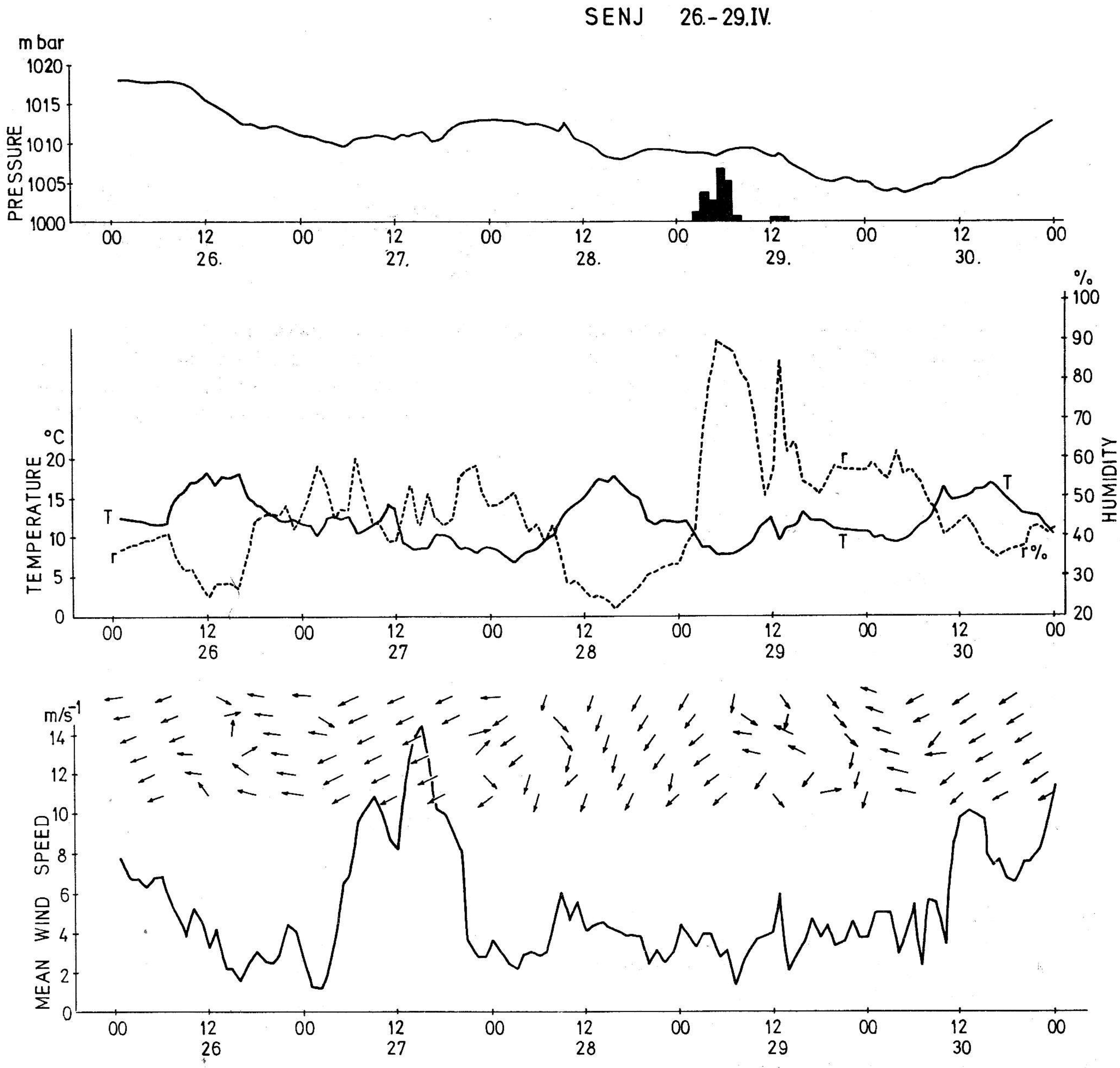


Fig. 11. **Time section of hourly values of pressure (hPa), temperature (°C), relative humidity (%), and mean wind for Senj**

Sl. 11. **Srednje satne vrijednosti tlaka (hPa), temperature (°C), relativne vlage (%) i vjetra u Senju**

southern Adriatic. The strongest bora gusts (reaching 18 m s^{-1}) were observed at Senj during the night of the 30th/31st when the deepening of the Genoa cyclone was the most pronounced atmospheric process nearby.

Comparing hourly values of meteorological elements for the two characteristic bora stations - Senj and Split (Figs 11 and 12) for the whole period from the 26th to the 30th, we may notice that bora was accompanied by a relative humidity decrease, followed by a local pressure increase and it also strongly influenced the temperature during the day. These features are common to all bora observations, indicating an inflow of a cold airmass to the Adriatic basin.

4. UPPER LEVEL DATA ANALYSIS

From 26 - 30 April there were soundings in Zagreb, Pula and Zadar, mostly every six hours but on the 29th and 30th every three hours. Regarding soundings from Zadar, only wind upper level data (up to 4 km) are included in this analysis, but they are not completely comparable with data from Zagreb and Pula (because they are smoothed half-minute values).

The bora cases on the 27th and on the 28th to the 29th were basically similar because there was northerly flow troughtout the whole troposphere.

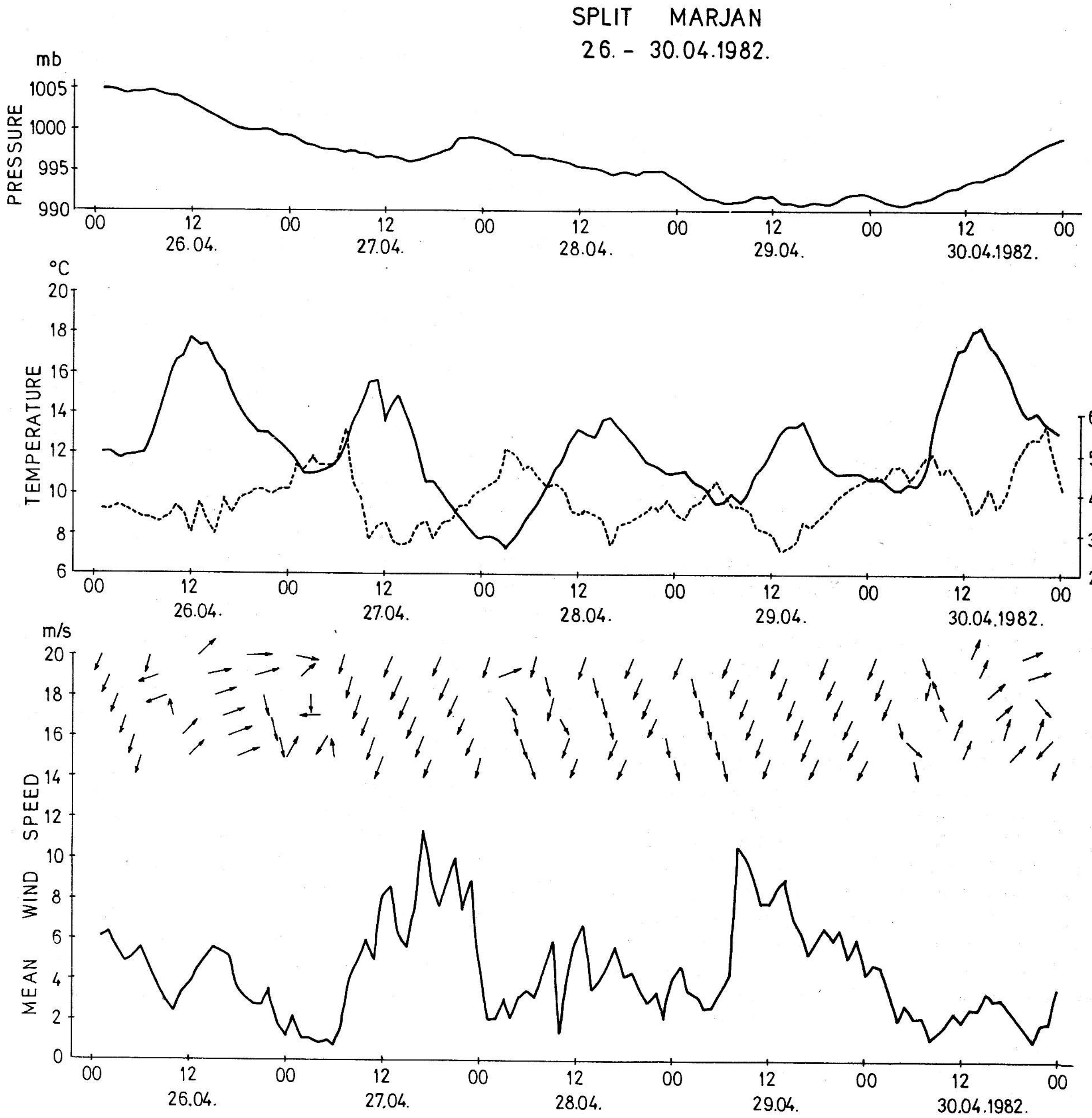


Fig. 12. Same as Fig. 23, but for Split

Sl. 12. Isto kao sl. 23, ali za Split

For our orientation, the airparticle takes about three hours to come from Zagreb to Pula (assuming that the average speed over Zagreb at 3 km height is 17 m s^{-1}).

The bora case on the 30th is characterised by wind reversal in the lower atmosphere, thus defining nicely the surface bora layer.

In Fig. 13 the vertical time cross-section for the pseudopotential temperature at Zagreb is shown. The main perturbation of isentropes at the beginning of the period is connected with the cold front. For the rest of the period, other smaller perturbations (clearly visible above 3 km height) are connected with the cold north outbreak, which can be divided into the finer mesoscale portions, not detectable in hourly surface data. The vertical gradients of pseudopotential temperature are rather small, especially in the lowest 3 or 4 km, indicating that the same airmass occupies the greater part of the troposphere. Present inversions are mostly due to weak inhomogenities in vertical stratification or to descending motions (excluding diurnal variations).

Vertical wind distribution over Zagreb, Pula and Zadar are shown in Figs 14, 15 and 16.

On the 27th (Fig. 14) the wind varied generally very little in direction. At 12 UTC there was a jet stream over Zagreb above 7 km height, but in the following six hours the wind decreased, since the frontal zone was going away. At the same time the wind over Pula was weaker than over Zagreb. Comparing the two vertical distributions of velocity over Pula, there is a significant velocity increase in the lowest 4 km. In the lowest 3 km thick layer over Zadar, the wind-direction was turning from north (12 UT) to northeast and east (18 UTC), explained by the influence of the simultaneous frontal movement over that region and displacement of the strongest surface pressure gradients.

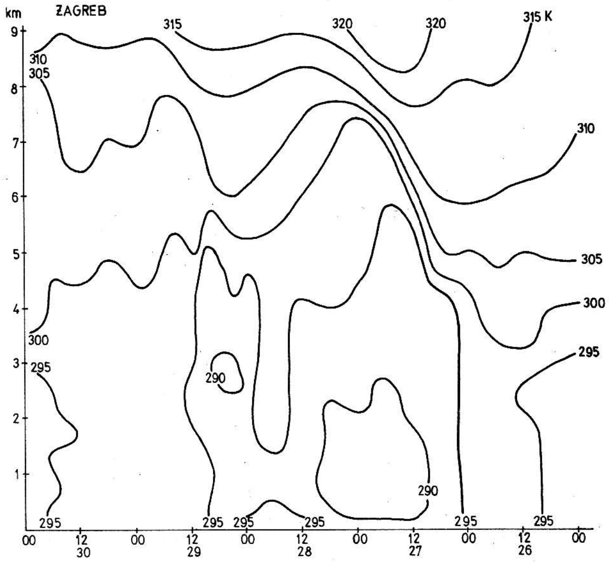


Fig. 13. Vertical time cross-section in pseudopotential temperature over Zagreb

Sl. 13. Vertikalni vremenski presjek pseudopotencijalne temperature u Zagrebu

On the 28th the wind over Zagreb (average azymuth above 1 km is about 25°) also generally increases with height. In the higher trposphere there is a jet-stream (v > 30 m s^{-1}), intensifying during the 28th and weakening during the 29th together with a gradual descent of its axis from 9 to 7 km. Since the first part of the cold air supply was exhausted, there was a windspeed decrease in the lowest 5 km on the 28th during the afternoon and evening. A new portion of the cold air which reached Zagreb during the night again increased windspeed in the lower troposphere (up to 5 km), (Fig 15).

In Pula bora started on the 28th at 20 UTC and the maximum windspeed was observed on the 29th at 13 UTC: the most interesting upper level data are those from 29 April. The wind over Pula gradually turns from the average azymuth 25°to 360°, increasing with height (the jet stream is about 8 km). During the bora, the vertical wind profile changes very little in time. The maximum surface windspeed (on the 29th at 12 h) coincided with increasing velocity in the lowest, 2 km thick layer, and diminishing humidity mixing ratio. In Zadar bora started on the 29th at 05 UTC and strongest gusts along the Dalmatian Coast were observed between 09 and 12 UTC. Vertical distributions of wind speed over Zadar (Fig. 15) also show characteristic local maximum in the lowest (1 km thick) layer during the bora.

Concerning humidity the air upstream is rather moist below and dry above 3 km height. Downstream, there is a moist layer between 2.5 and 3.5 km and a relatively dry surface layer up to 2.5 km during the bora. The cold air advection (above 3 km) during the night caused slight inhomogenity in vertical stratification which induced condensation around the boundary separating the lower, already blocked air (from previous mesoscale outbreak) and the higher, incoming portion of cold air. Therefore, the weather became cloudy, locally with fallout.

The bora situation on the northern Adriatic Coast on April 28th and 29th is basically similar to the bora situation on the 25th of March.

On the 30th, the upper wind situation was quite different (Fig. 16). At both stations there was southerly and westerly flow above 3 km height, but the strongest wind shear layer was over Pula, from 1.3 to 3 km height. The velocity was generally less than before, showing the two maxima, one in the higher atmosphere (connected with the macroscale geostrophic motion), and the other below 1 km height (connected with a possible hydraulic-like flow in the surface bora layer).

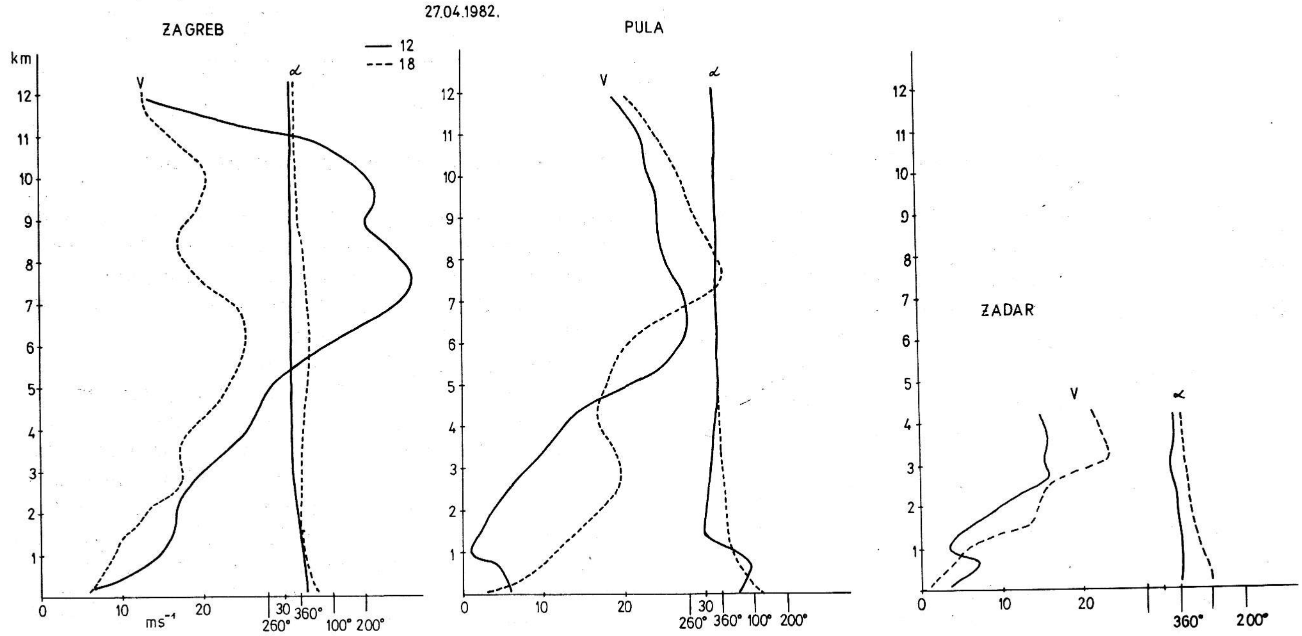


Fig. 14. Vertical wind profiles over Zagreb, Pula and Zadar on the 27th at 12 and 18 UTC

Sl. 14. Vertikalni profil vjetra za Zagreb, Pulu i Zadar 27. 04. u 12 i 18 UTC

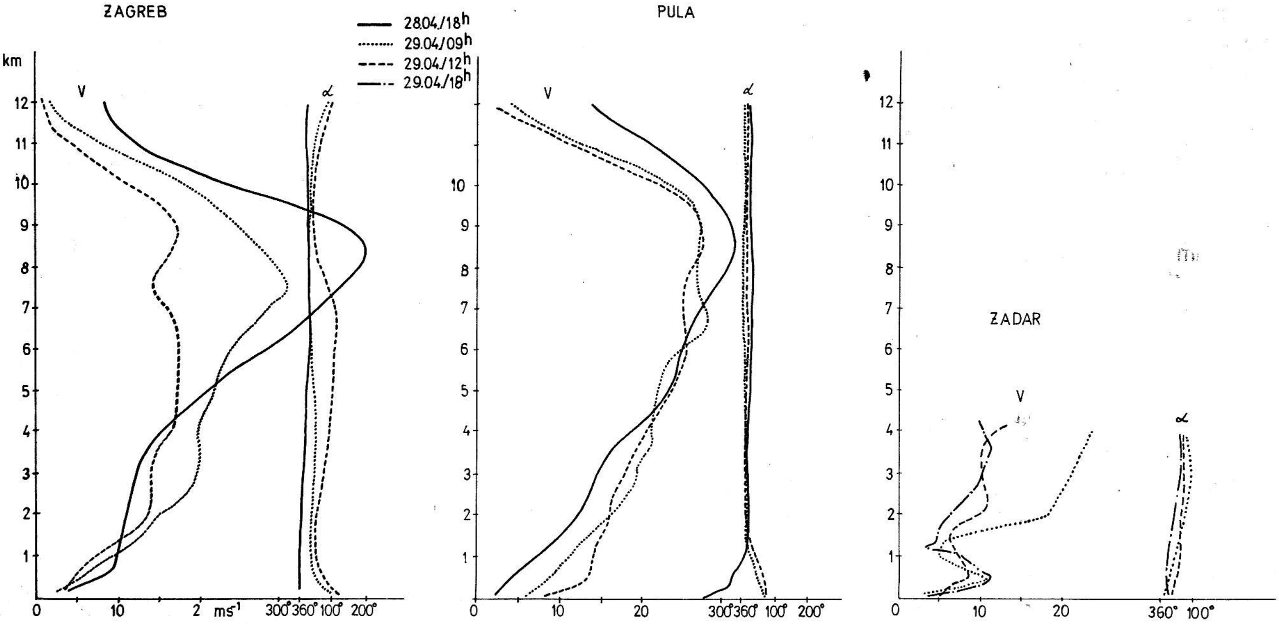


Fig. 15. **Vertical wind profiles over Zagreb, Pula and Zadar on the 28th at 18 UTC and the 29th at 09 and 12 UTC**

Sl. 15. **Vertikalni profili vjetra za Zagreb, Pulu i Zadar 28. 04. u 18 UTC i 29. 04. u 09 i 12 UTC**

5. APPLICATION OF HYDRAULIC THEORY

Numerical simulations and observational results suggest that there are striking similarities between strong downslope winds and supercritical flows. The bora is an atmospheric phenomen where the hydraulic theory is most likely applicable. Previous analyses of the bora cases indicate at least two major upstream flow types. The first group includes all cases when there is a strong inversion layer above the cold, nearly neutrally stratified, low level air which could behave like the discontinuity in density at a layer interface as described by hydraulic theory (including shallow water equations). A certain relationship must exist between the parameters of the flow (Long 1954):

$$\frac{h}{H} = 1 + \frac{1}{2} F_o^2 - \frac{3}{2} F_o^{2/3}$$

(Symbols are the same as in Smith, 1985, 1987; see also Vučetić in this Volume).

The second important group of bora flows includes all cases when we cannot immidiately determine the bora layer depth because the upstream flow is continuously stratified. Smith (1985) developed an analitical model applicable on such a continuously stratified airflow (continued by the paper Smith and Sun, 1987) by solving the hydrostatic Long's equation for flow beneath the breaking layer.

Wave breaking is a process whereby a wave becomes unstable to instabilities of a scale smaller than the wave itself. The overturning layer is well mixed so that the density in that region is constant. Clark and Peltier (1977) were the first to discover the importance of the wave breaking amplification mechanism in many downslope windstorms. It is assumed that the breaking region trape the wave energy within the underlaying flow. Recent numerical simulations (Klemp and Durran 1987) showed that the wave breaking is likely to dominate the dynamics whenever the cross mountain flow is weak and when the overturning level is beneath a strong inversion layer. Solutions to Long's equations for the atmosphere with constant mean wind and stability (no critical layer) indicate that wave breaking will occur at a $0.75L_z$ height when hN/U exceeds 0.85 (L_z is a vertical wavelength). Thus if the mountain is sufficiently high and the elevation of the mean flow critical layer exceeds $0.75L_z$

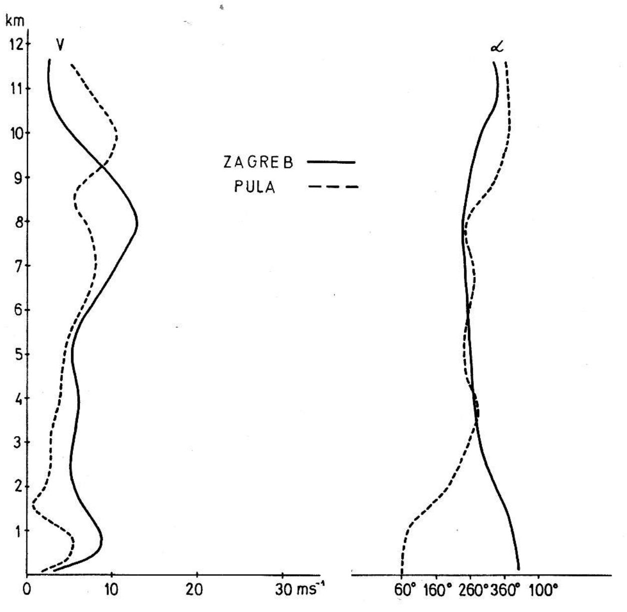


Fig. 16. **Vertical wind profiles over Zagreb and Pula on 30th at 21 UTC**

Sl. 16. **Vertikalni profili vjetra za Zagreb, Pulu i Zadar 30. 04. u 21 UTC** wavebreaking may still develop beneath that layer, producing a strong response.

Hydraulic theory is applied on the bora cases analysed in the previous sections. Using cross section Zagreb (upstream) - Pula (downstream), which is directed northeast to southwest, it is assumed that the average height of the mountainous region is 800 m and that the final terrain height h drops 200 m bellow its upstream value. In the case where the final terrain height is the same as upstream, the predicted values in the lee are higher for a few hundred meters (those results are not listed here because they show less agreement with the observation). For the purpose of application of hydraulic theory it is also assumed that the flow is stationary, althought this is not a case for the analysed situations. The only case with the neutral layer capped by an inversion was on 27 April at 12 UTC, while all other cases have nearly constant stratification. It's interesting to mention the rise of the stability from upstream to downstream in all cases. This change in the stability is obviously dominated by the stronger vertical gradients of the potential tempeature in the lee caused by the hydraulic-like flow.

The parameters of the bora flow are shown in Tabs 1,2 and 3 and the comparison of upstream conditions with the predictions of hydraulic theory is shown in Fig. 17.

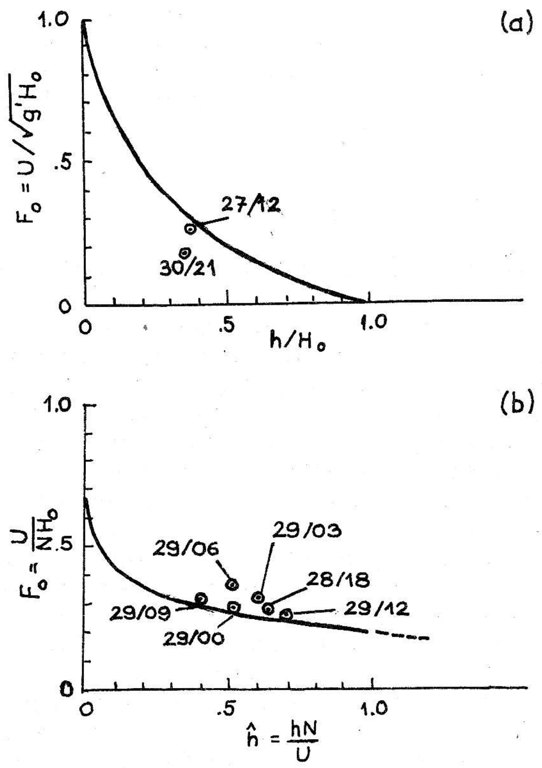


Fig. 17. Comparison of upstream conditions with the prediction of the hydraulic theory under critical conditions:
a) layered case
b) continuously stratified case

Sl. 17. Usporedba parametara toka u navjetrini s prognoziranim teoretskim vrijednostima uz kritične uvjete:
a) slojevit slučaj
b) kontinuirano stratificiran slučaj

The bora on the northern Adriatic on 27 April was caused by the frontal passage. The atmospheric structure immidiately after the frontal passage (according to sounding data) was very similar to the theoretical structure assumed by Long's hydraulic theory.Therefore, it was reasonably to expect a good agreement in Fig. 17a.

The last case, on 30 April, when the bora on the northern Adriatic was triggered by the Genoa lee cyclogenesis, is rather similar to the formerly mentioned post-frontal case. Although the atmposphere is continuously stratified, the flow reversal (at 2,3 km height) sharply defines the surface bora layer. It is very interesting that if we apply the theory for the layered and for the continuous flow type on all situations, those two cases act very similar. In both cases there is well defined H_o with $z_o < H_o$ (but the overturnig most likely do not happen because of $h > 1$) and the upstream Froude numbers are less than for other situations. In both cases, the prediction of the bora layer height in the lee, using method for the continuous type, completely fails, giving unreasonably low values. However, the points which represent those two cases in Fig. 17 b would be plotted further on the right, though very close to the curve. The predicted surface windspeed on 27th (54 m s^{-1}) is nearly twice the observed maximum gust at Senj (23 m s^{-1}) but on 30th, because of small U_o (3.5 m s^{-1}), the predicted surface windspeed (17.5 m s^{-1}) is very close to average hourly values at Senj.

The bora on 28 and 29 April gradually spread over the whole Adriatic coast. It was caused by the pronounced cold north outbreak, so the same airmass occupied the whole troposphere. The Long's layered hydraulic theory is no more applicable, but, instead, Smith's hydraulic theory for the continuously stratified flow offers some reasonably good predictions. The accelerating bora layer in this situation is mostly succesfully a priori determined using vertical distribution of the Scorer parameter (including wind shear term) although there are situations where nothing indicates bora layer depth.

As shown in Table 2. the predicted upstream bora layer height H_o^* is very close to the value of H_o a priori determined. This fact is used in those situations where nothing a priori indicates H_o. Comparing H_o with wind surface data from Senj (mean hourly values) it seems that the wind speed is inversely proportional to H_o in the same time. However, the surface windspeed in Split is proportional to the upstream bora layer depth. As shown by synoptic and mesoanalyses, the cold north outbreak was the strongest over the middle part of the Dinaric Alps where the airflow had to pass wider orographic barrier. The critical parameters for the wavebreaking (Table 2) suggest that overturning is most likely not responsible for generation of the analysed bora because z_o is always greater then H_o. The bora layer height in the lee is calculated according to Smith (1985). The results are very similar to the values determined from soundings at Pula (Table 3), except on 29 April at 12 UTC where we have obvious disagreement. The reason for this disagreement is probably that Pula's sounding is not any more representative for the outbreak since it is near the bora ending time at Pula and the main process is southeasterly over the middle Adriatic coast.

Tab. 2. Parameters of the bora flow - continued case:

Tab. 1. Parametri bure - slojevit slučaj:

Time	H_o (km)	$\bar{\theta}$ (K)	$\Delta\theta$ (K)	U (m/s)	Fr_o	$\frac{h}{H_o}$	U_{SENJ}(m/s)
A27/12	3.0	2.83	7	10	0.37	0.27	11.5
A30/21	2.3	2.85	4	3.5	0.16	0.35	8.2

Tab. 2. Parameters of the bora flow - continued case:

Tab. 2. Parametri bure - kontinuirani slučaj:

Time	H_o (km)	$\bar{U}_o$ (m/s)	$\bar{N}$ x10^3 (s^{-1})	$\bar{l}\cdot 10^4$ (m^{-1})	Fr_o	$\hat{h}$	$\hat{\delta}^*$	H_o^* (km)	Z_c (km)	U_{SENJ} (m/s)	U_{SPLIT} (m/s)
A28/18	4.5	12	9.2	7.7	0.29	0.62	- 0.92	5.0	6.1	3.8	4.2
A29/00	-	15	9.6	6.4	0.30	0.51	- 0.81	5.5	7.4	3.8	4.2
A29/03	4.0	18	13.5	7.5	0.33	0.60	- 0.90	5.1	6.3	3.9	3.2
A29/06	4.0	17	10.7	6.3	0.39	0.50	- 0.80	5.6	7.5	1.4	3.2
A29/09	6.0	18	9.5	5.3	0.31	0.42	- 0.72	6.2	8.9	2.7	9.8
A29/12	-	10	8.8	8.8	0.28	0.70	- 0.99	4.6	5.3	5.9	7.8
A30/21	2.3	3.5	7.7	22.0	0.19	1.79	- 1.99	2.9	5.3	8.2	-

Tab. 3 Parameters of the bora flow in the lee (terrain height in the lee = - 200 m) z (R_i < 2) = bottom and top of the layer where the Richardson numbers is less than 2

Tab. 3. Parametri bure u zavjetrini (visina terena = - 200 m): z (R_i < 2) = donja i gornja visina sloja gdje je Richardsonov broj manji od 2

Time	H_1 (km)	H_1^* (km)	Z(R_i < 2) (km)	$\bar{l}\cdot 10^4$ (m^{-1})
A28/18	1.5	1.6	1-3	23.0
A29/00	2.0	2.0	0.5-1.5	10.0
A29/03	2.5	2.7	1.5-3	18.0
A29/06	2.0	2.2	-	11.0
A29/09	2.5	2.5	0.5-2	5.4
A29/12	3.5	1.5	0.5-1 3.0-3.5	6.0
A30/21	1.7	0.2	1.5-2	73.0

The Richardson number (less than 2) is used to locate the position of the turbulent "dead" region in the lee, which cannot be determined more precisely from the vertical time cross-section in the potential temperature. Mean values of H_o (4.5 km), U (15 m s^{-1}) and $\hat{h}_z$ (-0.14) are used to find an average vertical displacement of the critical streamline and a predicted value of the surface windspeed. The prediction (42m s^{-1}) is less than twice the maximum gust observed at Šibenik on 29th (25 m s^{-1}).

A certain similarity between the parameters of the analysed bora flows (27-30 April) and those predicted by the theory indicates that the atmospheric processes during bora generation most likely include dynamical mechanism proposed by the hydraulic theory.

6. CONCLUSION

During a period of four days (27-30 April 1982) the bora was periodically blowing on the greater part of the Yugoslav Coast as a consquence of the cold front (passing from the NW to the SE), then the cold north outbreak and, finally, the Genoa cyclogenesis.

More detailed analysis of the surface data showed the strongest wind at the localities where the airstream overflow the lowest orographic barrier and where the channeling effects are most pronounced. As wind is relatively weak, there exists rather large orographic influence on the airflow, being probably the main reason for the direction fluctuations. The bora was accompanied by the relative humidity decrease, followed by local pressure increase and it also strongly influenced the temperature during a day, features which are common to all bora observations indicating an inflow of a cold airmass to the Adriatic basin.

The upper level wind usually had two maximums. The main jet stream was above the bora layer in the higher troposphere (due to the macroscale geostrophic motion) and the secondary maximum was usually in the bora layer (due to the surface accelerating mesoscale flow).

The bora cases on 27th and on 28th to 29th were basically similar because there was northerly flow through the whole troposphere. The bora case on 30th is characterised by the flow reversal in the lower troposphere, defining thus nicely the surface bora layer.

However, a different similarity rises after the application of hydraulic theory and examination of the predicted parameters. Now, the cases on 27 and 30 April 1982 become very similar because sharply defined upstream surface bora layer (3 km and 2.3 km) describe rather low accelerating airstream, passing over the lowest and the most narrow part of the Dinaric Alps. The Long's theory for the layered flow type gives rather good prediction for those two situations.

The Smith's theory for the continuously stratified flow gives better prediction for the bora situation on 28th and 29th. The average value of the upstream bora layer height is 4.5 km, the mean wind speed in the layer is stronger than on 27th and 30th, so the main part of the cold airmass now from inland flows over the wider orographic barrier to the middle Adriatic.

Although it seems that hydraulic theory offers some satisfactory suggestions on the dynamical mechanism of the bora, there are still a lot of details which should be included in some general bora theory. For example, three-dimensional effects (more realistic presentation of the orography), surface friction and quick movement or exchange of synoptic features (unsteadiness) strongly affect the real bora flow, as it is documented with the analysed bora period from 27 to 30 April.

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KRATAK SADRŽAJ

U toku posljednja četiri dana ALPEX SOP perioda, od 27. do 30. 04. 1982. bura je povremeno puhala duž većeg dijela jadranske obale, i to neposredno nakon prolaza hladne fronte sa sjeverozapada (27. 04), u toku prodora hladnog zraka sa sjevera (28/29. 04), te za vrijeme stvaranja i produbljavanja alpske zavjetrinske ciklone (30. 04). S obzirom na sinoptičku i mezoanalizu slijedi da je bura 27. 04. u osnovi slična onoj 28/29. 04, budući da postoji sjeverno strujanje kroz čitavu troposferu zbog sličnih makrovremenskih uvjeta. Bura koja je puhala 30. 04. samo na sjevernom Jadranu razlikuje se po tome što se u nižoj troposferi mijenja smjer strujanja, čime je jasno određen prizemni sloj bure.

Za provjeru hidrauličke teorije na analiziranim slučajevima bure promatrali smo presjek Zagreb - Pula, uz pretpostavku da je prosječna visina planinskog područja 800 m i da je visina terena u zavjetrini niža za 200 m od one u navjetrini te da je strujanje stacionarno. Interesantno je spomenuti porast statičke stabilnosti od navjetrine prema zavjetrini, što je očito uzrokovano jačanjem vertikalnih gradijenata potencijalne temperature pri hidrauličkom strujanju.

Iz analize pojedinih parametara računatih na temelju podataka sondaža, kao poseban slučaj sada izdvajamo termin od 27. 04. u 12 UTC budući da možemo uočiti približno neutralan prizemni sloj koji je pokriven inverzijom, što odgovara polaznim pretpostavkama za Longovu hidrauličku teoriju. Iako u svim ostalim slučajevima atmosfera ima skoro konstantnu stratifikaciju, zadnji slučaj bure, 30. 04. je također specifičan (promjena smjera vjetra na oko 2,3 km visine), tako da se određeni parametri strujanja ponašaju vrlo slično buri 27. 04. u 12 UTC. U oba slučaja postoji dobro definiran sloj bure H_o, kritična visina za lom vala z_c je manja od H_o (međutim, do loma vala ipak ne dolazi zbog $h > 1$) i uzvodni Froudeov broj je osjetno manji nego u svim ostalim promatranim terminima. Prognozirana prizemna brzina vjetra 27. 04. (54 m/s) je skoro dvaput veća od izmjerenog maksimalnog udara vjetra u Senju (23 m/s). No 30. 04. prognoza prizemne brzine vjetra (17,5 m/s), zbog male srednje brzine vjetra u sloju bure u navjetrini (samo 3,5 m/s), više odgovara srednjim satnim vrijednostima u Senju.

Za simulaciju bure 28/29. 04. pogodniji je Smithov model za hidrauličko strujanje u konstantno stratificiranoj atmosferi. Prizemni sloj bure je u većini termina sondaže uspješno određen pomoću vertikalne raspodjele Scorerova parametra (uključujući i član smicanja vjetra), a tako određena visina H_o je uvijek vrlo slična prognoziranim vrijednostima H_o^*. Ta činjenica je iskorištena u onim slučajevima kada nije bilo moguće iz podataka sondaže odrediti visinu sloja bure. Kako su najjači gradijenti tlaka pri tlu tada bili nad središnjim dijelom Dinarida, tako je i prizemna brzina bure na obali srednjeg Jadrana proporcionalna s visinom sloja bure u navjetrini. Ni u ovoj situaciji lom vala najvjerojatnije nije uzročnikom pojačanog vjetra budući da su vrijednosti za kritičnu visinu loma vala uvijek veće od visine H_o. Visina sloja bure u zavjetrini računata je prema Smith (1985) i rezultati su vrlo slični vrijednostima određenim prema pulskoj sondaži, osim u jednom slučaju kada ta sondaža najvjerojatnije više nije reprezentativna. Za lokaciju turbulentnog "mrtvog" područja u zavjetrini analiziran je Richardsonov broj (u obzir su uzete sve vrijednosti manje od 2), čime se postiže ipak malo bolja predstava o izgledu strujnog polja nego samo na temelju vertikalnog vremenskog presjeka potencijalne temperature.

Hidraulička teorija, kako se čini, može objasniti neke bitne karakteristike dinamičkog mehanizma bure, no za potpuniju sliku valjalo bi ne zanemarivati trodimenzionalne efekte, prizemno trenje kao i nestacionarnost na makro i mezoskali.