GEOFIZIKA VOL. 12 1995

Original scientific paper
UDC 551.555.4

The Adriatic bora: special case studies

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Received 13 November 1995, in final form 2 May 1996

Two cases of the most severe bora episodes along the Adriatic coast of Croatia are investigated. In the first case of 29 January 1994 the absolute maximum gust of 48.5 m/s was recorded in Split.

The second case is related to the longer-lasting bora of 13–17 March 1962, when it was possible to investigate the vertical atmospheric by means of downstream sounding in Split and two upstream soundings in Zagreb and Beograd.

Although in both cases the bora onset is caused by a frontal passage, the maximal local speeds occur afterwards and coincide with a pronounced short period pressure perturbation.

Both cases were characterized by the temporal occurrence of the well marked superadiabatic layers in the low troposphere.

The vertical structure in the March case shows the temperature inversion in Split data that is strongest during the maximum bora speed, and an unstable layer below inversion, in agreement with the turbulent »dead« region defined in the internal hydraulic theory.

Bura na Jadranu: posebni slučajevi

Proučavana su dva slučaja izrazite olujne bure na Jadranu. U prvom slučaju od 29. siječnja 1994. registriran je u Splitu apsolutni maksimalni udar vjetra od 48.5 m/s.

U drugom slučaju dugotrajnije bure od 13.–17. ožujka 1962. bilo je moguće pratiti vertikalnu strukturu atmosfere pomoću radiosondaže u Splitu u zavjetrini planine, i dvije radiosondaže u navjetrini u Zagrebu i Beogradu.

Premda je u oba slučaja nastup bure bio uzrokovan prolazom fronte, lokalna maksimalna brzina vjetra se pojavljuje kasnije i koincidira s izrazitom kratkotrajnom perturbacijom tlaka.

Oba slučaja karakterizira povremena pojava izrazitih superadijabatskih slojeva u donjoj troposferi.

Vertikalna struktura atmosfere u drugom slučaju pokazuje u Splitskoj sondaži temperaturnu inverziju, koja je najintenzivnija za vrijeme najjače bure, i nestabilni sloj ispod inverzije, što je u skladu s turbulentnim »mrtvim« područjem definiranim u internoj hidrauličkoj teoriji.

1. Introduction

The bora (bura in Croatian) is a well-known downslope wind in the Adriatic coast and many similar phenomena around the world have been referred to as »bora-like winds«. Popularly bora was considered a fall wind, *i.e.* a wind that accelerates due to its coldness and greater density as it moves downslope.

Theoretically downslope winds were studied through the mountain waves that appear when the air flows over a mountain. They can transport energy to great heights. Laprise and Peltier (1989) discovered the »local convective« and »deep resonant« modes in a numerical simulation of mountain waves. The local mode grows from the gravitational potential energy associated with the superadiabatic region of the mountain wave and is temporally episodic. The deep mode extracts its energy from the kinetic energy of the mean flow and is shown to be responsible for a rapid acceleration of the low-level flow in the lee of the mountain. However, for sufficiently high mountains, streamlines are forced to overturn locally. Such »breaking« mountain waves are followed by bifurcation that results in a dramatic intensification of downslope windstorms.

Peltier and Clark (1979) were first to demonstrate the important role of a wave-breaking region characterized by strong mixing and a local reversal of the cross-mountain wind. Using numerical simulations they have suggested that the energy in the upward propagating wave is trapped below this »self-induced critical layer« producing a substantial increase in the wave amplitude. However, numerical results are more difficult to interpret than those obtained analytically.

The research flight missions during the Alpine field experiment (ALPEX) provided the first aerial observations of bora structure and together with theory have led to new understanding of the bora phenomenon. An essential result obtained directly from these observations is the shallow layer acceleration that begins upstream of the ridge crest. This acceleration is generated by the descending part of the bora layer capped by an inversion, since the downsloping isentropes influence the pressure gradient hydrostatically and control the bora dynamics. Since this acceleration begins upstream it contradicts the model of the fall wind with a downslope acceleration. Thus, data from the ALPEX field measurements support neither the fall wind nor of the vertically propagating mountain waves as the mechanism responsible for the bora.

Smith (1985) promoted an internal hydraulic mechanism for the bora with the mountains partially controlling the flow upstream. He obtained analytical solutions for the flow beneath a breaking wave assuming that the air in the overturned region has been mixed and neutrally stratified. Such a »dead region« between the split streamlines or isentropes contains the turbulent region, a layer that decouples the upper, less disturbed air, from the active low-layer below the descending isentropes.

Durran (1986) proposed that the wave breaking mechanism presented by theories of Clark and Peltier and Smith will not become active unless a rather large amplitude wave has already been produced by other physical processes. He examined the role played by hydraulics and vertically propagating internal waves on the development of large-amplitude waves employing a numerical model. The results emphasize the role of an elevated inversion for the occurrence of downslope winds, in particular the dominating influence of the pressure gradient produced by the displacement of the inversion with respect to other contributions to the total pressure perturbation along the lee slope. Therefore the flow was constrained to be supercritical as predicted by the hydraulic theory.

In our case studies we are particularly interested in what could be the »other physical processes« and the »other contributions to the total pressure perturbation« responsible for large amplitude wave and dramatic increase of surface wind speed in Split.

The results of numerical simulations of the 15 April 1982 ALPEX bora case (Klemp and Durran, 1987) have suggested that the factor that contributed most directly to the bora development was the wave overturning region that formed beneath the inversion layer. In this particular case the low-level response that was decoupled from the inversion and the internal stratification – not the inversion itself – was primarily responsible for the genesis of high bora speeds in Senj. It was shown that the overturning will be likely to dominate the dynamics in a case of weak flow since the effective mountain height Nh/U (where N is the Brunt-Vaisala frequency, h the mountain height and U is the flow speed) is large. Thus, the wave amplitude is sufficiently large for producing the wave breaking, and at the same time the vertical wavelength $2\pi U/N$ is small, increasing the chance that the wave breaking height would lie below the inversion. Jurčec and Glasnović (1991) argued that these results are valid only for the special characteristics of the local bora in Senj in such cases, and not for the bora flow across the higher mountains along the Adriatic coast. Nevertheless the inversion layer is believed to play an essential role for a more persistent bora even along the Dalmatian coast as discussed in this paper.

Although a complete understanding of bora requires the knowledge of airflow splitting *i.e.* a solution to the 3-D mountain induced flow field, some insight can be gained from the 2-D hydraulic theory and well-established principles of fluid mechanics as shown in many successful applications of this theory to the bora cases in the northern Adriatic.

Recently several studies of southern Adriatic bora were undertaken (Vučetić, 1993; Jurčec and Visković, 1994; Ivančan-Picek and Tutiš, 1995) emphasizing large differences between the bora structure and mechanism in the northern and the southern Adriatic. From the statistical survey for the period 1987–1993 (Brzović and Benković, 1994) it appears that during this period bora was even stronger in the southern than in the northern Adriatic.

Our first case study deals with the recent extraordinary strong bora in Split in January 1994, having the highest gust of 48.5 m/s since the beginning of wind recording. The largest problem in obtaining more conclusive results in bora behaviour and environmental state of the atmosphere is that no soundings exist on the southern Adriatic coast to represent the atmospheric structure of bora in the lee side of the mountain. For this study, we have therefore selected a severe bora case in March 1962 during an exceptional period when the radiosoundings in Split were available.

It is the aim of this study to present the bora structure during these two special bora episodes that will aid the understanding of various scale processes associated with the bora events in the Adriatic sea.

2. Case study of 28–30 January 1994

2.1. Daily evolution of wind and pressure at observing stations

Fig. 1 illustrates daily evolution of wind from 28 to 30 January 1994 in Split, Lastovo and Šibenik, and the pressure evolution in Split and Lastovo during the same period. From these figures it is clear that the extremely

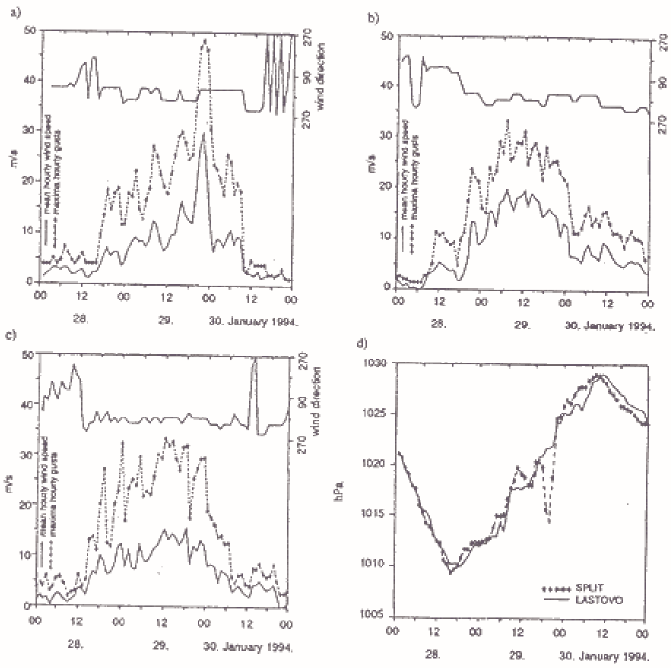


Figure 1. Daily courses of mean hourly wind speed, maximal hourly gusts and wind direction in Split (a), Lastovo (b) and Šibenik (c), and air pressure in Split and Lastovo (d) during the period 28–30 January 1994.

strong wind gusts of 48.5 m/s close to midnight of 29/30 January in Split were a local phenomenon related to the pronounced pressure perturbation. According to customary criteria that the mean hourly wind speed $v > 10.8$ m/s indicates the strong wind, and $v > 17.2$ m/s severe wind, it is seen from Fig. 1 that in spite of very strong gusts in Šibenik the bora did not reach severe state according to this classification. Data in Senj (not shown here) indicate that the bora there was even weaker. In Lastovo severe bora started earlier than in Split, but during Split's maximal speed it was at there already in a decaying stage. The maximum hourly wind speed of 30.1 m/s represents the absolute maximum not only in Split but along the entire Adriatic coast since 1957. The earlier absolute maximum of 29.2 m/s was recorded also in Split on 15 March 1962. This case will be considered in the next chapter.

2.2. Synoptic situation

The synoptic scale features in the considered case are illustrated in Fig. 2. It is seen that the bora onset coincides with the frontal passage in the after-

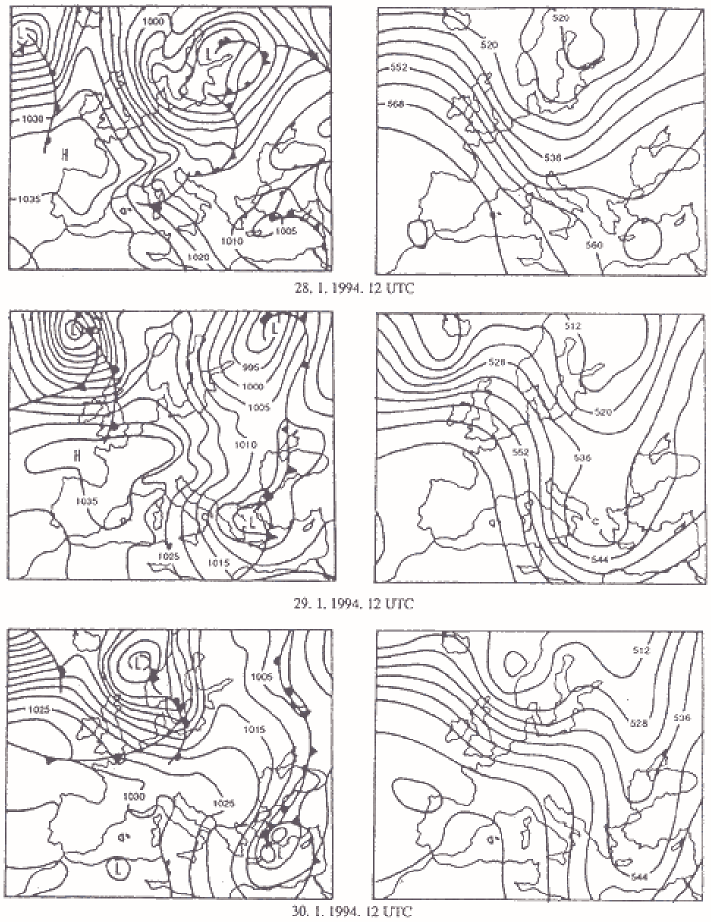


Figure 2. Synoptic charts 28, 29, and 30 January 1994, 12 UTC. Surface (left) and 500 hPa geopotential (right).

noon of 28 January when the station's pressure minimum (Fig. 1d) was observed. The pressure perturbation and maximum gust in Split therefore occurred during an intensifying ridge following the movement of a mesoscale cyclone and the associated frontal system further to the east of the Adriatic. Thus, this figure illustrates the fact that the bora in Split at that time was of a clear, anticyclonic type according to the classification presented by Jurčec and Visković (1994), whereas the earlier severe bora in Lastovo was of a dark, cyclonic type caused by the passage of the mesoscale cyclone in the southern Adriatic. The synoptic charts indicate that the large scale structures – the fast moving deep cyclones in the Atlantic and Northern Europe, and the large pressure changes – are therefore a clear sign of a pronounced isalobaric field and an ageostrophic flow associated with the horizontal accelerations. These are the processes that could, under special circumstances, transfer the energy to the mesoscale, and cause local bora with temporally dramatic increase of the wind speed and gusts.

2.3. Nonhydrostatic motions and atmospheric energy

Although the sounding of Zagreb may not be representative for the vertical atmospheric structure analysis in Split, the temporal variations of meteorological variables may give some idea of possible influences of the larger scale processes on the mesoscale atmospheric structure interacting with the special local phenomena.

Jurčec and Brzović (1995) presented various vertical profiles of wind and temperature and their derived parameters for this case, with the conclusion that the nonhydrostatic motions and strong vertical accelerations in the low troposphere could be the basic cause for some observed local phenomena under such an extreme condition. The dynamics of such processes is particularly governed by the available atmospheric energy and its transformation among various energy forms.

It seems particularly convenient for this study to present these processes by means of one dimesionless energy parameter, $\hat{E}$, derived by Glasnović (1993) (see also Glasnović, 1995) and applied to some special cases by Glasnović et al. (1994) in the form:

$$\hat{E} = 1 + \kappa \frac{\partial \ln p}{\partial \ln \Theta} = \frac{\gamma}{\gamma - \Gamma_d} \tag{1}$$

where $\kappa = R/c_p$, R is gas constant for dry air, c_p is specific heat at constant pressure p, and Θ is the potential temperature.

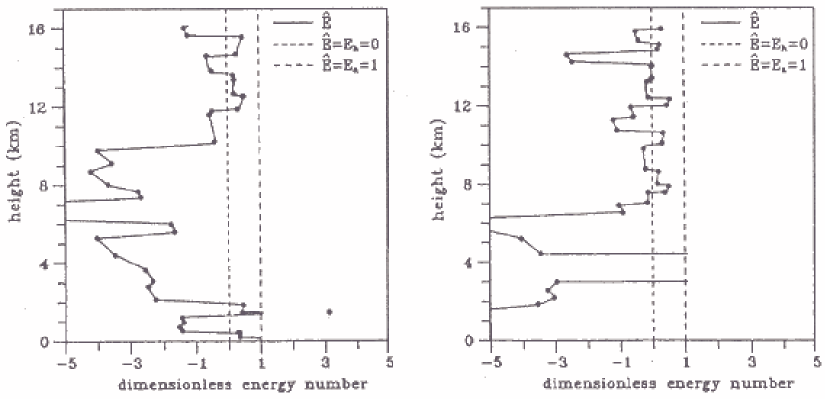
This parameter is expressed with respect to the temperature lapse rate, γ, while its inverse variation as a function of $\hat{E}$ describes stability:

$$\gamma(\hat{E}) = \frac{\Gamma_d\,\hat{E}}{\hat{E} - 1} \tag{2}$$

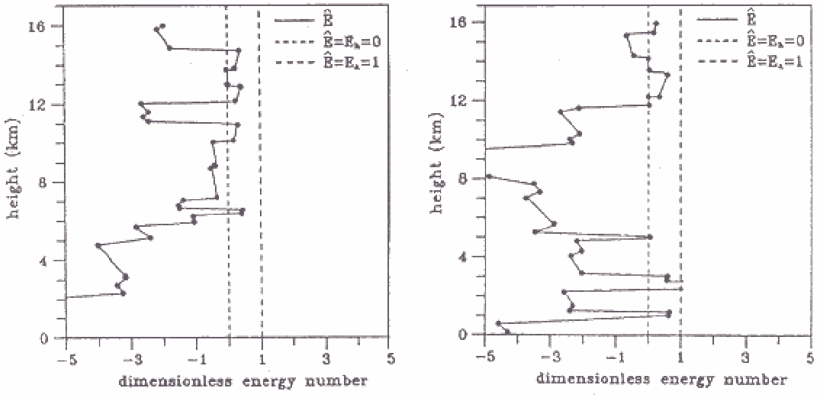
where $\Gamma_d = g/c_p$ is the dry adiabatic lapse rate.

Fig. 3 shows the vertical profiles of $\hat{E}$ in the considered case of January 1994 in Zagreb. It is seen that $\hat{E}$ values are close to zero (*i.e.* close to stable hydrostatic equilibrium) in the stratosphere, while in the troposphere this case exhibits large variations. The most pronounced instability is found on 29 January, 00 UTC, approximately at the onset of the strong bora, which is characterized by a superadiabatic layer between some 3 and 5 km altitude. Unfortunately there was no sounding on 30 January 00 UTC, close to the time of maximum wind speed in Split.

The sounding in Split was not available for this case, but we expect that such a low tropospheric state is representative for larger area.



Zagreb 00 UTC 28 January 1994 **Zagreb 00 UTC 29 January 1994**



Zagreb 12 UTC 29 January 1994 **Zagreb 12 UTC 30 January 1994**

Figure 3. Vertical profiles of dimensionless energy number $\hat{E}$ in Zagreb. ($\hat{E} = E_h = 0$ corresponds to isothermal stratification, while $\hat{E} = E_a = 1$ is asymptotic value which can not occur in nature).

This analysis may point to some process similar to temporally episodic local convective mode in the numerical simulation of Laprise and Peltier (1989), in which waves grow from the gravitational potential energy associated with the superadiabatic layer. Unfortunately the scarcity of sounding data in time and in space does not allow us to make any firm conclusion about the direct connection between these superadiabatic layers and the bora acceleration which must await numerical simulation of such bora case.

3. Case study 13–17 March 1962

3.1. The basic characteristics at observing stations

There was a short period (1959–1963) when the soundings in Split were available for the study of vertical atmospheric structures. During this period there were six severe bora storms recorded in Split. According to the analysis by Vučetić (1993) for the case of March 1962, the maximum hourly speed of 29.2 m/s in Split was an extreme value measured along the coast during the period 1957–1993. The highest hourly speed in Senj for the same period was 28.9 m/s recorded twice, in 1967 and 1969. This was the longest lasting severe bora event in Split, with a maximum gust of 42.2 m/s, and the only case during the considered 5-years period when severe bora also occurred in Dubrovnik.

In Fig. 4a the mean hourly wind speeds are presented for Split, Senj and Dubrovnik. Sudden bora onset is noticed at all these localities, caused by the frontal passage. This is illustrated in Fig. 4b, c for Split, by a sudden temperature drop and an increase of relative humidity. The pronounced pressure fall did not follow the temperature drop. Thus, although the bora onset follows the frontal passage, the extreme speed recorded in Split in the evening of 15 March is clearly related to the low pressure, and particularly to the large pressure change also accompanied by a sudden decrease in humidity, and consequently to the atmospheric stability undergoing rapid changes.

On the next day bora rapidly weakens at all three stations, particularly in Senj but it still remains strong in Split during the further increase in pressure with continuously low air temperatures.

3.2. The synoptic situation

Surface synoptic development begins with a high pressure in Central Europe and a small scale cyclone in the western Mediterranean. This results in an intensifying pressure gradient and an increasing mountain drag first in the northern Adriatic, where the bora starts on 13 March. The upper-level flow is characterized by a strong NW jet stream directed towards the western Mediterranean. The dynamically unstable deep upper-level trough leads to a cut-off process in the Mediterranean (Jurčec, 1989). A deepening surface

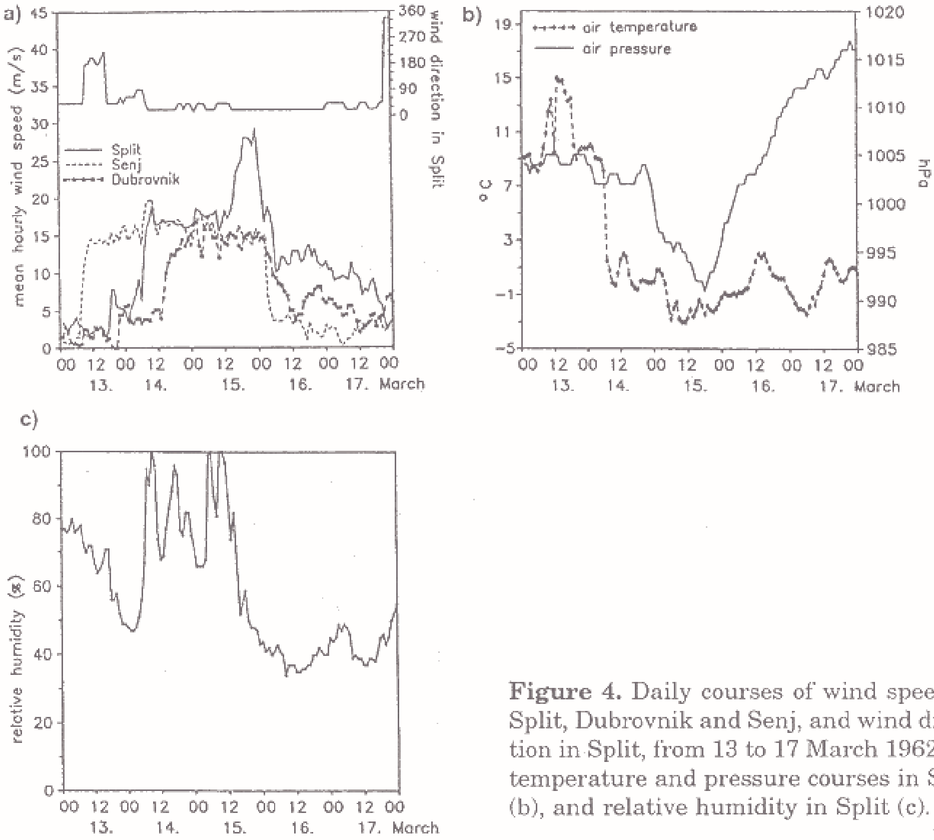


Figure 4. Daily courses of wind speed in Split, Dubrovnik and Senj, and wind direction in Split, from 13 to 17 March 1962 (a), temperature and pressure courses in Split (b), and relative humidity in Split (c).

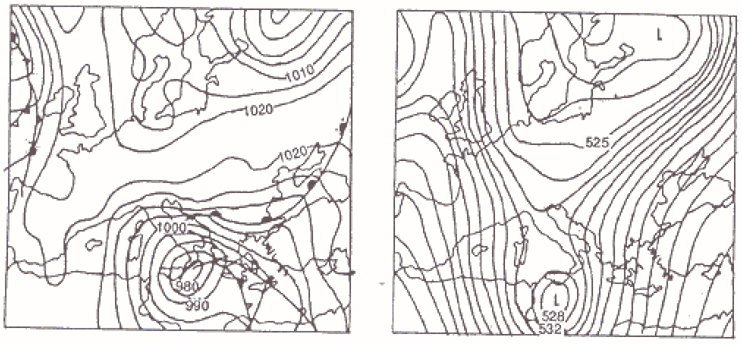
cyclone in the Tyrrhenian sea on 15 March (Fig. 5a) moves to the Balkan region across the Adriatic. On 16 March the upper level cyclonic vortex is situated above the southern Adriatic and on 17 March the surface cyclone moves above the Black Sea. At this time (Fig. 5b) a difluent geostrophic flow appears in the northern Adriatic and the bora rapidly decays in Senj.

Thus, the synoptic analysis shows that the bora onset follows the frontal passage, but the local extreme of the wind speed, such as the observed maximum in Split, is not related to the frontal activity. This maximum speed is associated with the low above the southern Adriatic and the rapid change in pressure and pressure gradient caused by this low and the intensifying high in the western Europe. This leads to the large disturbances in the geostrophic equilibrium as well as to the changes in the vertical atmospheric structure which will be considered in the next section.

3.3. The vertical time cross sections

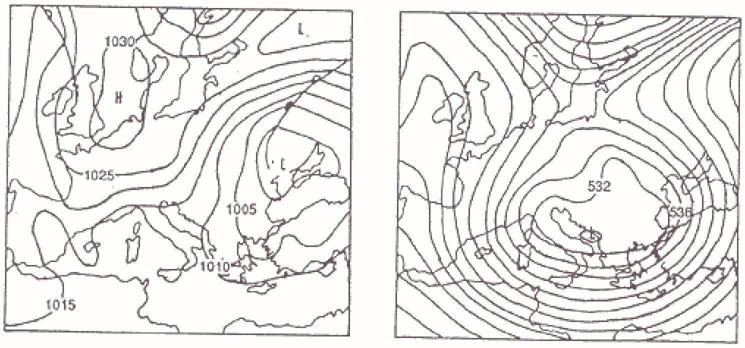
For the presentation of vertical atmospheric structure we have used the products of the diagnostic model named »High Resolution Isentropic Diagnosis (HRID)«, and described in detail by Glasnović et al. (1994).

a)



15. 3. 1962, 00 UTC

b)



17. 3. 1962, 00 UTC

Figure 5. Surface synoptic chart and the 500 hPa geopotential for 15 March 1962, 00 UTC (a), and 17 March 1962, 00 UTC (b).

The vertical cross-section in Zagreb (Fig. 6) indicates the upper-level frontal zone on 14 March recognized by the downsloping isentropes and a pronounced vertical wind shear associated with the SW jet stream on the front side of a deep tropospheric trough. The frontal zone extends down to 4 km altitude where a very strong inversion is seen capping the bora layer. The E–NE flow intensifies to a low-level jet (LLJ) below the inversion on 16 and 17 March, when the upper tropospheric southerly winds weakened (see also Fig. 9a).

For comparison, 48-hour cross-sections are shown for Beograd (Fig. 7), but starting 12 hours later. The upper tropospheric SW wind maximum is found here too, but contrary to Zagreb's structure, there is another maximum of SE direction, 9 km below the tropopause after 36 hours, on 16 March, 00 UTC, associated with the upper-level vortex seen in Fig. 5. In the lower troposphere the inversion is as strong as in Zagreb, but appears at lower altitude of 2–3 km. A lower inversion in Beograd than in Zagreb indicates a three-dimensional structure in the upstream bora region. The winds below the inversion are weaker than in Zagreb. During the last 12 hours low-level winds turned to NW and the inversion layer split with its lower branch between 1 and 2 km.

The most interesting structure for our analysis is the one above Split (Fig. 8). Unfortunately, the data are available only up to 10 km where the SW

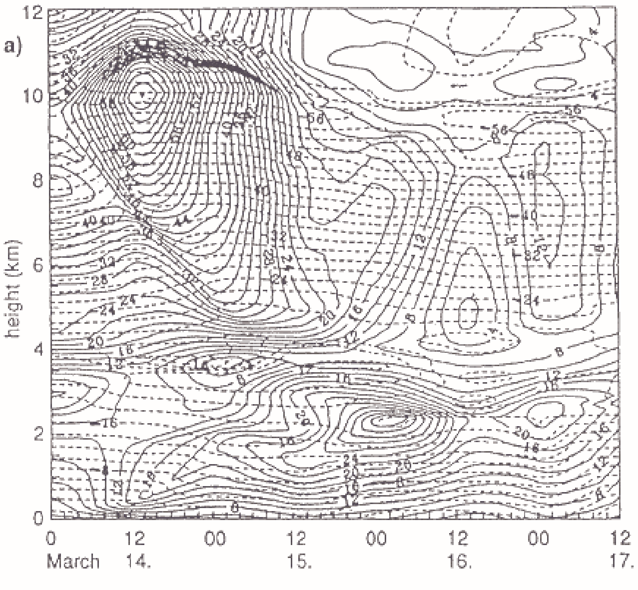


Figure 6. Vertical time cross-sections in Zagreb from 14 March, 00 UTC to 17 March, 12 UTC, 1962; isotachs (m/s, solid lines) and isotherms (°C, dashed lines) (a); isentropes (K, dashed lines) and wind arrows from 14 to 16 March 00 UTC 1962 (b).

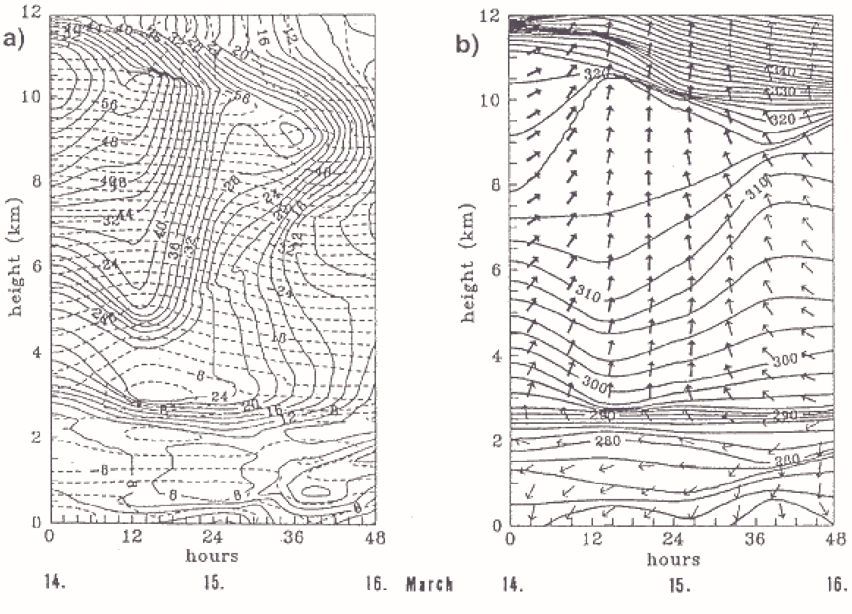


Figure 7. Vertical time cross-section in Beograd from 14 March to 16 March, 12 UTC, 1962, isotachs (m/s, solid lines) and isotherms (°C, dashed lines) (a); isentropes (K, dashed lines) and wind arrows (b).

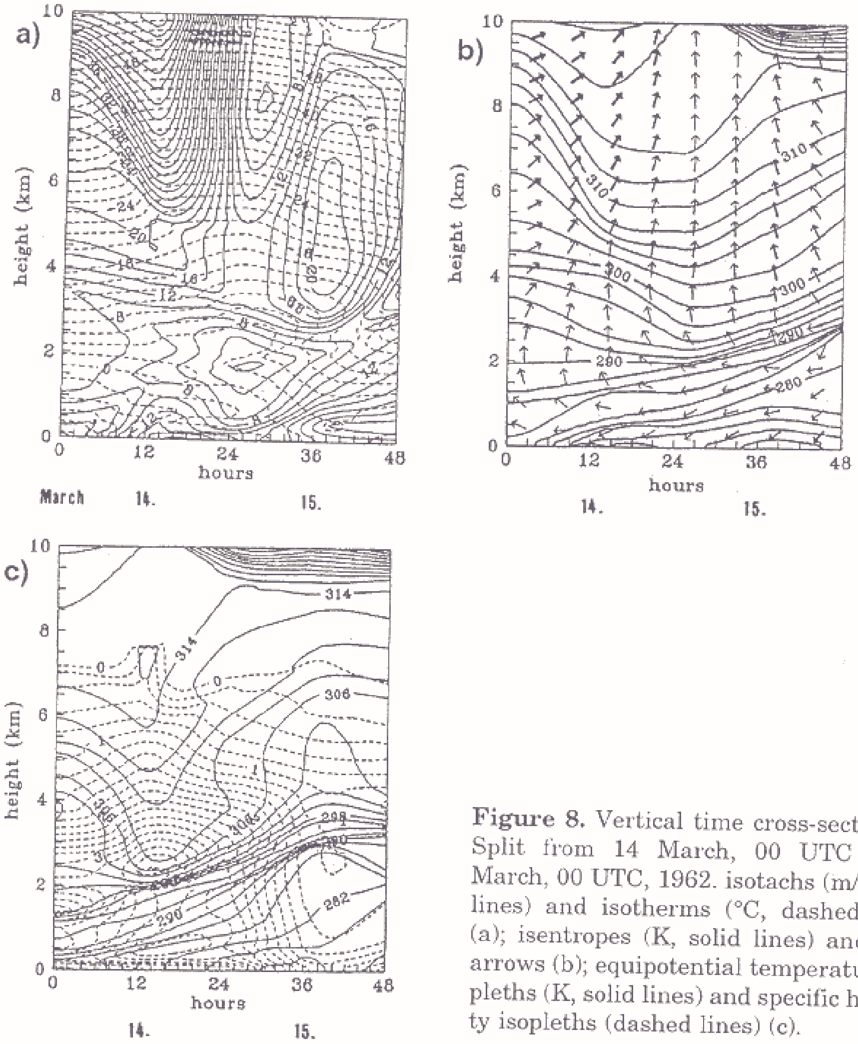


Figure 8. Vertical time cross-sections in Split from 14 March, 00 UTC to 16 March, 00 UTC, 1962. isotachs (m/s, solid lines) and isotherms (°C, dashed lines) (a); isentropes (K, solid lines) and wind arrows (b); equipotential temperature isopleths (K, solid lines) and specific humidity isopleths (dashed lines) (c).

maximal wind appears during the first day of analysis, on 14 March. The upper level frontal zone, well-marked by the vertical wind shear and downsloping isentropes, extends down to the lower troposphere. The upper-level winds sharply weakened next day, and turned to the S–SE direction in agreement with the displacement of the upper level vortex to the southern Adriatic.

The basic feature on 15 March when the bora intensified in Split for the last 12 hours, is the strengthening of the lifting inversion between 2 and 3 km altitude marked by the wind reversal. At the same time the stability decreases below the inversion recognized by the vertical widening of the isentropes. This could be identified as a »dead region« of high turbulence in the internal hydraulic theory by Smith (1985) as observed by the research aircrafts in the ALPEX bora cases.

Fig. 8c emphasizes the role of humidity in these processes. The inversion layer in terms of equipotential temperature isopleths, forms earlier, is stronger, and stresses even more the unstable layer following a rapid decrease of humidity below the inversion. This is in agreement with results of numerical experiments by Buzzi and Alberoni (1992) who concluded that humid processes appear to be an essential ingredient for the short-term forecasting of synoptic and subsynoptic fields.

This analysis clearly shows that neither Zagreb's nor Beograd's data are sufficiently representative for important features of the vertical atmospheric structure over the bora flow.

3.4. Vertical wind profiles and profiles of dimensionless energy number

Fig. 9 shows the consecutive vertical wind profiles in Zagreb, Split and Beograd for the three days.

Zagreb's profile marks the LLJ inside the bora layer at the time of the most severe bora in Split. LLJ was observed in other cases of bora storms,

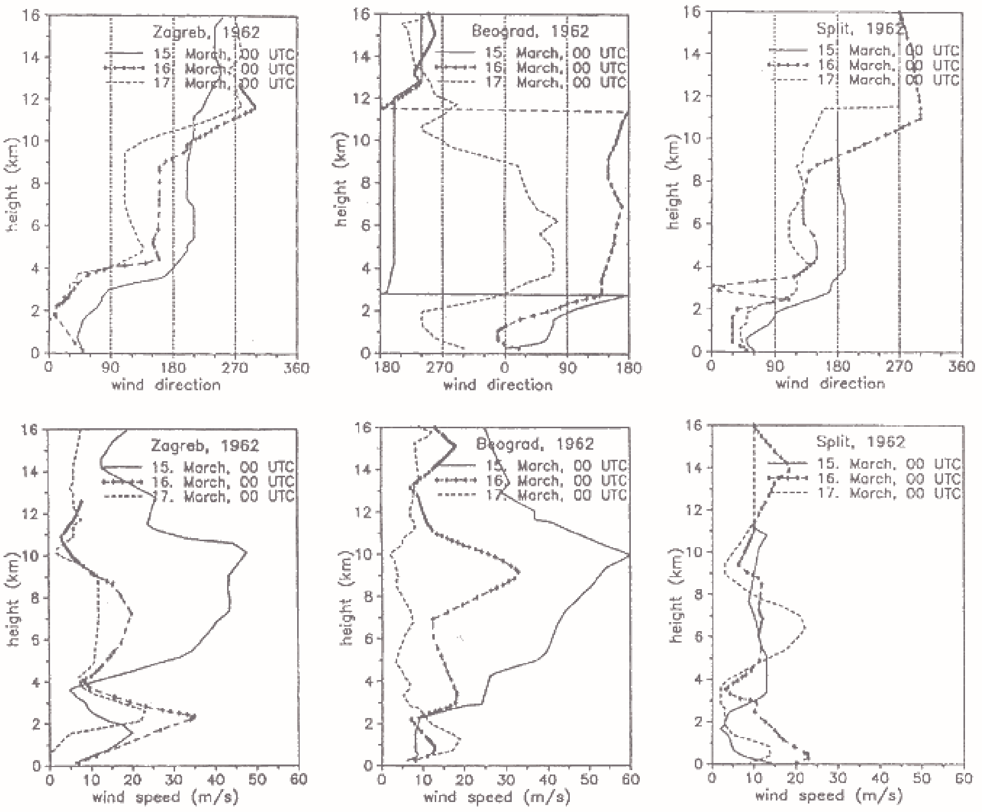


Figure 9. Vertical wind profiles for 15, 16 and 17 March 1962, 00 UTC in Zagreb, Beograd and Split.

particularly during the ALPEX SOP with soundings every three hours, when it was shown that this feature is not very persistent (Jurčec, 1984, 1991).

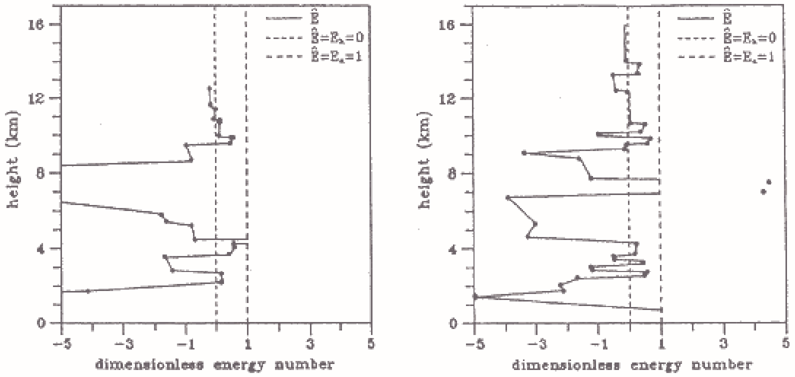
Split's sounding indicates rapid oscillations of the wind direction between ESE and N, below the inversion and close to the time of the maximum bora speed on 16 March, 00 UTC, which has been recognized in the cross-section analysis as the turbulent »dead« region. The wind maxima above the ground on 15 and 16 March are less than the surface maximal velocity in Fig. 4, but it must be emphasized that the used elaboration of soundings data undergo smoothing in order to eliminate possible measurement and telecomunication errors as well as to make them representative for a broader area. Poje (1988) presented this problem particularly in the case of bora when the usual procedure of tripple smoothing of wind data may lead to a notable degree of distortion in respect to the actual condition.

The soundings of Beograd indicate weakening of the upper level wind maxima and increasing of the low level wind on the last day. The essential feature is the wind change to westerly direction at low-level, since such a flow with NE current in Zagreb, indicates the horizontal divergence in the upstream region of the Dalmatian bora. This is an important fact since it supports the 3-D theoretical approach of Smith (1988, 1989) in which the linear theory is used to predict the flow type associated with the occurrence of stagnation points and their relation to severe downslope winds.

On the basis of the above analysis we speculate that, at least in the final stage of prolonged Dalmatian bora, steeply sloping isentropic surfaces would lead to the onset of stagnation points at the ground level and wave breaking aloft would never occur. However, the surface splitting flow in the upstream region of Bosnian mountains could not lead to the flow around the mountain. Instead, the cold air would flow through the mountain passes, which would strongly influence the bora strength at particular localities. Such a locality is also Split, where the bora speed is largely influenced by the Klis passage (Visković, 1991) similarly as the Vratnik pass under certain conditions influences the bora in Senj.

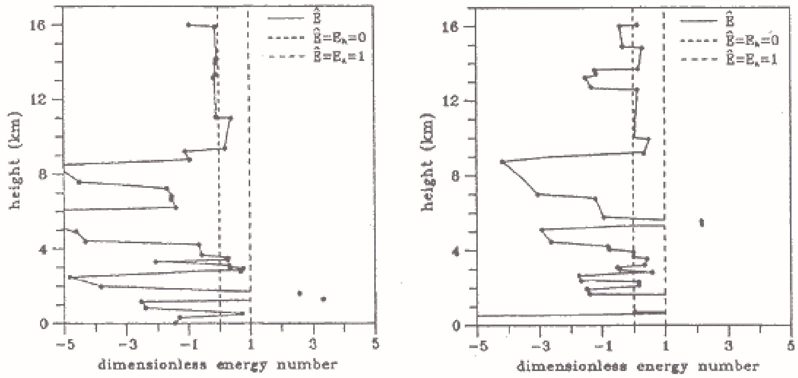
Since the theory could not be directly applied to the particular bora case, in order to arrive at the final conclusion a numerical simulation by a fine mesh model would be required, which would have to include the splitting flow in the upstream bora region of the Pannonian plain, and the channeling effects of mountain passes such as Vratnik and Klis.

Finally, Fig. 10 shows the plot of nondimensional energy number $\hat{E}$ for both Zagreb and Split at 00 and 12 UTC on 16 March 1962 close to the time of maximum bora in Split. It proves that the assumption in the previous case (related to Fig. 3) was correct *i.e.* in such situations superadiabatic gradients in the $\hat{E}$–profiles occur in the larger area. We find them both in Zagreb and in Split, although they do not occur in the same layers.



Zagreb 00 UTC 19 March 1962

Zagreb 12 UTC 19 March 1962



Split 00 UTC 16 March 1962

Split 12 UTC 16 March 1962

Figure 10. Vertical profiles of dimensionless energy number $\hat{E}$, in Zagreb and Split. (Legend as on Fig. 3).

4. Conclusions

We investigated the two most severe mid-Adriatic bora storms. On 29 January 1994 the absolute maximum gust of 48.5 m/s and the maximum mean hourly speed of 30.1 m/s in Split exceeded the gust of 42.2 m/s and the hourly speed of 29.2 m/s, which occurred during the bora of 13–17 March 1962, as the maximal for the period 1957–1993.

It is shown that although the bora onset was caused by the frontal passage, the extreme speeds that occurred in both cases later on were associated *with the surface pressure perturbation*. This was particularly pronounced in the January case during the general rising and strenghtening of surface pressure gradients.

The analysis of Glasnović's (1993) stability function $\hat{E}$ indicated *superadiabatic layers in the low troposphere* in both cases. Such layers, associated with gravitational energy were recognized in the numerical experiments by Laprise and Peltier (1989) for a local growth of mountain waves, and may be responsible for a rapid acceleration of the upstream flow and its dramatic influence on the bora speed and gust. Thus, the mountains partially control the flow upstream which does not support the pure fall wind hypothesis as the mechanism of the bora.

The March case was an extraordinary event in respect to severe bora research, since the radiosounding data for vertical atmospheric structure analysis were available in Split, in addition to Zagreb's and Beograd's soundings in the upstream bora region. This analysis emphasizes *the existence of temperature inversion* capping the bora layer in Split as well as in the upstream area. This inversion was the highest in Zagreb.

Inside the bora layer in Zagreb the *low-level jet* appeared with the maximum speed over 30 m/s, which was frequently observed in the ALPEX bora cases in the northern Adriatic.

Downstream, during the strongest bora in Split on 16 March, *the unstable region below the inversion* indicated turbulence with rapid oscillation of the wind direction. This is in agreement with the »dead region« in Smith's hydraulic theory, in which such a turbulent layer helps to decouple the descending layer from the less disturbed flow aloft. This does not support the theory of vertically propagating waves as the mechanism of the bora.

However, it is not clear whether the rapid change of density across the inversion is primarily responsible for the generation of high surface wind speeds or is it the internal stratification with overturning beneath the inversion, as in the experiment of Klemp and Durran (1987) for Senj's bora. The low-level upstream flow is weak satisfying *the condition for breaking waves* at low heights, and the channeling effects are present in the case of Split's as well as of Senj's bora.

The larger scale upstream condition for Dalmatian bora is different and more complex than in the case of the north Adriatic bora where it is well defined based on the Zagreb's sounding. Our analysis of low-tropospheric wind direction in Beograd on 16 and 17 March indicates changes to westerly wind in comparison with NE wind in Zagreb. This is taken as a sign of *low-level divergence in the upstream region* of Dalmatian bora which would support the 3-D theoretical approach by Smith (1988). This theory predicts the occurrence of stagnation points and their relation to severe downslope winds. Our analysis of low-level divergence and steeply sloping isentropic surfaces, caused by the cold air outbreak, would lead to the onset of *stagnation points and the splitting flow* at the ground-level and wave breaking aloft would never occur. However, the cold air that flows through the mountain passes strongly influences bora strength at particular localities.

We have therefore suggested that the problem of bora understanding and forecasting is the problem of understanding various scale processes and their interactions. Since the orography and mountain passes play an important role in the local bora intensity, it is considered that more conclusive results of bora distribution along the Adriatic coast and the causes of extreme bora velocity and gusts cannot be predicted without recourse to numerical simulations employing a fine mesh model with very realistic topography, and a high level of sophistication for moist, turbulent and non-hydrostatic processes.

Acknowledgment – We wish to thank our colleague Dražen Glasnović for making HRID products available for this study and for the useful discussion of this problem. Special thanks are due to Jean-Francois Geleyn of Meteo-France, Toulouse, for reading the manuscript and to Krešo Pandžić and an annonimous reviwer for their remarks and suggestions on how to improve the paper. This research was supported by the USA-Croatia Joint Fund for Scientific and Technical Cooperation in cooperation with the NSF under Grant JF 990-0.

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