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Mesoscale characteristics of southern Adriatic bora storms

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The bora in Dalmatia is compared to the better known bora in the northern Adriatic. Fifteen severe storms in Split are selected during the period January 1980 to January 1983.

It is shown that in most cases such a severe bora does not last long, but the gusts are above 30 m/s, with the absolute maximum of 45 m/s, and therefore it is comparable with the strength of northern Adriatic bora. The mean surface pressure distribution and AT 500 hPa for these cases emphasize a mesoscale cyclone in the southern Adriatic, which may or may not be seen on large scale (synoptic) charts. Two »bora types« according to local weather characteristics are distinguished. »Dark bora« (cyclonic type) with cloudy sky and precipitation is characterized by deeper surface cyclone and a pronounced upper-level trough from Baltic to the southern Adriatic, in contrast to cloudless (anticyclonic) »clear bora« when mesoscale cyclone is further to the east of Adriatic. The upper level flow in latter case shows a cut-off low with N–NE current above the bora throughout the troposphere. These patterns are in agreement with Defant's (1951) description of cyclonic and anticyclonic bora types, they stress both upstream and downstream influence and emphasize the interaction of large-, meso- and local-scale processes on the Dalmatian bora flow.

The ALPEX bora case of 11–15 March 1982 illustrates local differences in bora occurrence and strength along the Adriatic, and time cross sections exhibit the characteristics of upstream vertical atmospheric structure for bora onset and decay.

Mezoskalne karakteristike bure na južnom Jadranu

Proučavana je bura u Dalmaciji i uspoređena s bolje poznatom burom na sjevernom Jadranu. Odabrano je 15 olujnih bura u Splitu u razdoblju od siječnja 1980. do siječnja 1983. Pokazano je da su u većini slučajeva ove olujne bure kratke, ali su udari preko 30 m/s s apsolutnim maksimumom od 45 m/s, što je usporedivo s jačinom bure na sjevernom Jadranu.

Srednja raspodjela prizemnog tlaka zraka i AT 500 hPa za ove slučajeve ističu mezociklonu u južnom Jadranu. Razlikuju se dva tipa prema lokalnim karakteristikama vremena. »Mračna bura« (ciklonalni tip), s naoblakom i oborinama, ukazuje na dublju prizemnu ciklonu i izraženu dolinu od Baltika do južnog Jadrana, za razliku od (anticiklonalne) »jasne bure« uz vedro vrijeme, pri čemu je mezociklona istočnije od Jadrana. U posljednjem slučaju je na visini odcjepljeni vrtlog a N–NE struja iznad bure zahvaća cijelu troposferu, čime je uz navjetrinu naglašen i utjecaj zavjetrine na tok bure u Dalmaciji, i ističu se međudjelovanja procesa makro-, meso- i lokalnih razmjera.

ALPEX slučaj od 11. do 15. ožujka 1982. ilustrira lokalne razlike u pojavi i intenzitetu bure duž Jadrana, a vremenski vertikalni presjeci ističu karakteristike vertikalne strukture atmosfere u navjetrini pri nastanku i prestanku bure.

1. Introduction

The well known bora wind along the Croatian coast of the Adriatic Sea occurs always in association with a cold air outbreak in the Alpine area. Jurčec (1989) presented some selected cases from the period 1957–1986 when severe bora occurred in the northern Adriatic, particularly in Senj. It is shown that a deep tropospheric through develops mostly into a cut-off low in the Mediterranean and a cut-off high over the middle and western Europe. Such a blocking type circulation prevents the warmer air from the Atlantic to the European continent which is occupied by the cold surface anticyclone. The latter builds up a large pressure gradient across the Alps toward the Mediterranean cyclone, resulting in particularly strong mountain drag along the northern Adriatic coast (Jurčec, 1990, Tutiš and Ivančan-Picek, 1991).

Strong bora in Senj occurs with the reversed upper air flow and pronounced inversion at the top of the bora layer characterized by the cold NE wind. Stronger unidirectional NE current throughout the troposphere usually destroys the inversion and bora ceases (Jurčec, 1989).

Large push in the bora studies was the research following ALPEX special observation period (SOP, March and April 1982) with increased number of radiosoundings at four localities and first research flights in special »bora days«.

Theoretical background for ALPEX bora studies was Smith's (1985) internal hydraulic theory modifying the traditional view of the bora as a »fall wind« or local catabatic wind (Pandžić and Pandžić, 1988) and promoting a hydraulic character to the bora flow (Jurčec and Visković, 1989). This 2-D theory was successfully applied to most of north Adriatic cases, particularly a steady postfrontal bora in Senj (e.g. Jurčec and Glasnović, 1991). The reason for this success is a well defined upstream condition from Zagreb below the warmer southerly flow at the front side of Mediterranean cyclone (Yoshino, 1976).

However, the strongest and most frequent bora in Senj owes its existence to special local characteristics, especially the Vratnik Pass influencing its strength by channeling effects. For this reason bora in Senj is not fully representative for the localities in northern Adriatic with different characteristics.

A detailed study of bora onset characteristics during the ALPEX SOP in Slovenia were presented by Pristov et al. (1989).

The purpose of the paper is to demonstrate in particular the mesoscale influence on the bora in the southern Adriatic. It will be shown that the Dalmatian bora is related to three-dimensional processes in contrast to prevailing two-dimensional bora flow in the northern Adriatic. This paper is the summary of main results achieved by Visković (1992), which contains detailed description on previous bora research, 30-years statistics of bora in Split and the application of hydraulic theory to selected cases.

2. Local bora characteristics in Split

In order to study severe bora characteristics in the southern Adriatic, we have selected 15 cases in Split from January 1980 to January 1983, which include the ALPEX SOP in March 1982 (Visković, 1992). Only those cases are considered in which bora reached severe state at this locality at least for one hour.

These data are shown in Table 1. First and second columns indicate the period and duration from the weak bora onset with the mean hourly speed $v \geq 5.5$ m/s. The third and fourth column contain the maximum mean hourly speed and maximum gust in the particular case. The fifth column presents

Table 1. Selected severe bora cases in Split January 1980 – January 1983.
Maximum mean hourly wind speed, v, and gusts, duration from weak ($v \geq 5.5$ m/s) and severe ($v \geq 17.2$ m/s) bora.
t_1 is time in hours from the bora onset ($v \geq 5.5$ m/s) until strong bora ($v \geq 10.8$ m/s), and t_2 is time in hours from the bora onset until severe storm.

No.	Date	$\bar{v}$	gust	Duration (h)		t_1	t_2
		(m/s)		≥ 5.5 m/s	≥ 17.2 m/s	(h)	(h)
1	2–4 Jan. 1980	20.4	34.0	41	6	3	8
2	7–9 Dec. 1980	17.5	32.1	51	2	4	23
3	22–23 Dec. 1980	17.8	36.0	32	4	6	18
4	7–10 Jan. 1981	20.1	38.0	66	8	2	16
5	15–17 Jan. 1981	20.6	36.5	35	3	4	5
6	20–25 Jan. 1981	20.6	36.0	128	6	10	12
7	26–31 Jan. 1981	17.9	32.0	122	1	2	58
8	5–7 Feb. 1981	18.3	31.1	41	2	10	25
9	18–20 Mar. 1981	20.0	34.0	36	3	6	9
10	2 Dec. 1981	17.2	32.0	8	1	1	3
11	31 Jan.–3 Feb. 1982	20.8	39.4	58	2	1	3
12	2–3 Mar. 1982	18.9	34.7	20	5	1	4
13	11–12 Mar. 1982	18.3	38.4	22	2	0	1
14	13–15 Mar. 1982	18.0	33.0	52	1	4	24
15	31 Jan. 1983	23.8	45.0	7	3	0	1

the bora duration, beginning with weak bora, and the sixth column presents the duration of severe wind state. The last two columns show the time period during which bora became strong and severe. These data show e.g. that the mean hourly speed reached 23.8 m/s during the strongest bora in January 1983 when the gust also shows absolute maximum of 45 m/s. In all cases bora occurs in winter months (December to March). The longest lasting bora was in the last decade of January 1981 when two cases are registered in Table 1 (with 128 and 122 hours) due to small period of interruption. The shortest case of 7 hours was the strongest one in January 1983, it started immediately as severe bora and lasted with this high speed for 3 hours. The similar characteristics had the ALPEX case of 11–12 March 1982, whereas the longest lasting severe bora of 8 hours in October 1981 reached the highest speed 16 hours after the onset. In most cases bora speed increases in a few hours (indicated by t_1 in Table 1), and it is therefore very dangerous for marine traffic.

3. Mean synoptic charts for the considered bora cases

Pandžić (1981) calculated the mean surface pressure distribution and AT 500 hPa for 10 bora cases along the Adriatic coast indicating the cyclone in the southern Italy and the center of anticyclone in the SW Europe. The upper level flow exhibits a trough with the W-geostrophic current over the Adriatic. Pandžić has demonstrated that in case of deeper sea level cyclone in the west Mediterranean with very pronounced upper level trough in this area, the bora occurs only in the northern Adriatic whereas SE warm jugo (scirocco) blows in the southern Adriatic.

Taking all 15 cases from Table 1, and selecting the synoptic charts (available for 12 hourly intervals) closest to the maximum wind speed at Split the mean charts are calculated and shown in Fig. 1. It is seen that the surface mesoscale cyclone is placed in the southern Adriatic, and the upper level flow characterizes a deep trough with the axis from Baltic to the southern Adriatic. Surface pressure ridge occupies SW Europe and extends to the northern Alpine area. In case of north Adriatic bora the cold air was usually blocked in this area undergoing low-level splitting. In case of southern Adriatic bora the upper-level N–NW flow across the Alps gives more chance to the cold air to flow across the Alps resulting in mesoscale cyclogenesis in the northern Adriatic.

The cyclone then moves along the Adriatic to its southern part. Of course, the situation changes from case to case in respect to details of the upper air flow and surface pressure distribution (Visković, 1992).

Two »bora types« are well known, »cyclonic« and »anticyclonic« (Yoshino, 1976) although they are not clearly defined. Petkovšek (personal communication) argued that these two types cannot make sense since bora always occurs in connection with a cyclone in Mediterranean and an anticyclone in the

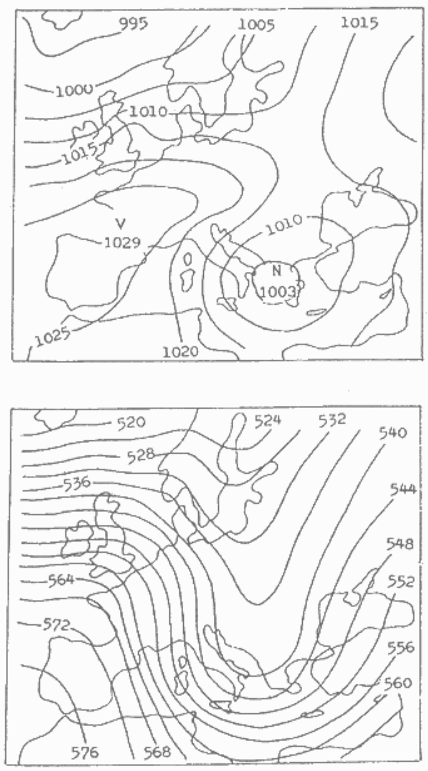

Figure 1. The mean surface pressure distribution (a) and AT 500 hPa (b) for 15 bora cases in Table 1.

middle Europe. This is generally true, except for the Senj's bora which is well known by its longevity caused by the cold air supply from Pannonian Plain (»cold air pool«) when the Mediterranean cyclone need not to be present. Jurčec (1988) introduced the »frontal bora type« since in many cases bora is directly related to the frontal passage, especially in Dalmatia. It is not clear who was the first to distinguish cyclonic from anticyclonic bora, but to our knowledge Defant (1951) defined them in connection with the local winds: »We may distinguish between cyclonic and anticyclonic bora, according to the origin. The cyclonic bora is dependent on the existence of a low pressure area over southern Adriatic, with an especially warm scirocco blowing from the south over the front portion of this low and aloft over bora. Consequently the sky is usually cloudy, and there is precipitation. The bora then blows more steadily and covers the entire Adriatic Sea. For an anticyclonic bora to develop, a strong high pressure area must exist over central Europe with an extension of high pressure over Dalmatia which need not be opposed by a cyclone with closed isobars in the south. In that case the bora exhibits a violent character, but does not extend far out to sea (about 10 nautical miles). The sky remains clear with the exception of a foehn wall over the mountains«. It is interesting to find in this description the bora dependence on low-pressure area over southern Adriatic, which is seen in the mean chart of Fig. 1. Regardless of scientific interest of various »types« and possible bora mechanisms, natives of Dalmatia distinguish »dark bora« with cloudy sky and precipitation, from cloudless »clear bora«. Such a state could naturally be considered only locally and may not last long. 6 hourly synoptic charts were available for this analysis, and we found from data in Table 1 six typical cases of dark bora (No. 1, 5, 9, 10, 13, 14) and four cases of clear bora (No. 4, 7, 8, 11) in Split for construction of relevant mean charts. They are shown in Figs. 2. and 3.

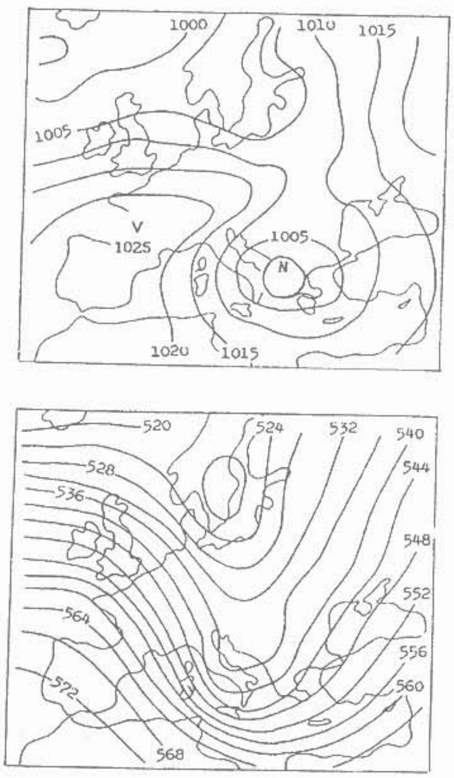

Figure 2. Mean surface synoptic chart and AT 500 hPa for six »dark bora« cases selected from Table 1 (1980: 3 Jan., 01h; 1981: 16 Jan., 07h, 19 Mar., 07h, 2 Dec., 07h; 1982: 12 Mar., 01h, 14 Mar., 13h).

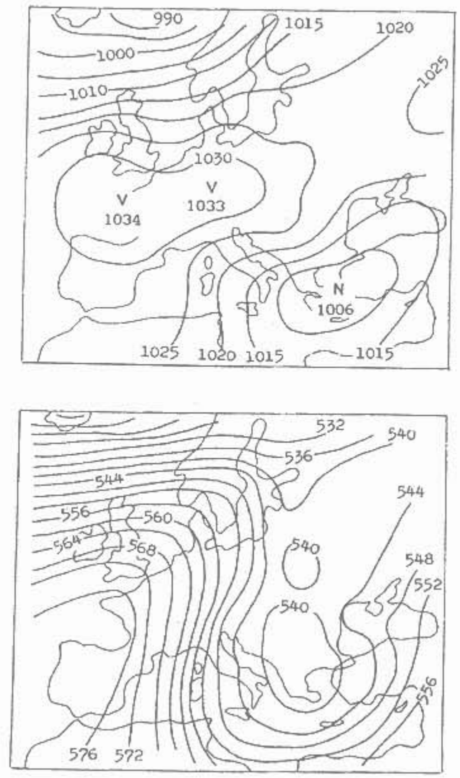

Figure 3. Mean surface synoptic chart and AT 500 hPa for four »clear bora« cases selected from Table 1 (1981: 8 Jan., 07h, 29 Jan., 01h, 6 Feb., 13h; 1982: 1 Feb., 01h).

Dark bora, of cyclonic type, is associated with a cyclone in southern Adriatic. The upper level trough is deeper than in Fig. 1 and its axis is directed toward the middle Italy so that southern Adriatic experiences the SW warmer current aloft and low tropospheric inversion defining the bora layer as mostly observed in cases of north Adriatic bora.

»Clear bora« picture on the other side indicates some anticyclonic or postfrontal state with more intense surface anticyclone over the central Europe and much weaker cyclone further east of Adriatic. Upper level chart displays a cut-off low with N–NE geostrophic current in the middle troposphere. This means that in cases of stationary anticyclonic state the Dalmatian bora could occur in unidirectional NE flow. This was not the case in north

Adriatic, except for a very weak bora with vertically propagating waves as discussed by Smith (1987) for the ALPEX case of 25 March 1982. The above analyses especially stress the influence of mesoscale cyclone on the bora strength and therefore emphasize the downstream as well as upstream effects on bora behaviour in the southern Adriatic.

4. Case study 11–15 March 1982

This ALPEX bora case in Split is registered in Table 1 as two cases (both as dark bora) due to brief interruption when the wind speed in the morning of 13 March dropped below 5.5 m/s. This is illustrated in Fig. 4 with daily courses of maxima gusts where, for comparison, the same courses are shown for Senj and Dubrovnik. Brief maximum in Senj preceded the highest gust in Split, but with much lower speed. Due to brief bora appearance and relatively low speed in the north Adriatic, these days were not registered as the »bora days« during ALPEX SOP. Maxima gusts at all three stations on 11 and 12 March were caused by the frontal passage and formation of shallow mesoscale low in the south Adriatic (Fig. 5). The gusts in the period of 14–15 March, following the second front, were lower but lasted longer under the influence of new mesoscale cyclone and cut-off low at the upper level.

The vertical atmospheric structure from Zagreb's sounding during this period is presented in Figs. 6–8 by the use of diagnostic HRID (High Resolution Isentropic diagnosis) model developed by Glasnović, described in details

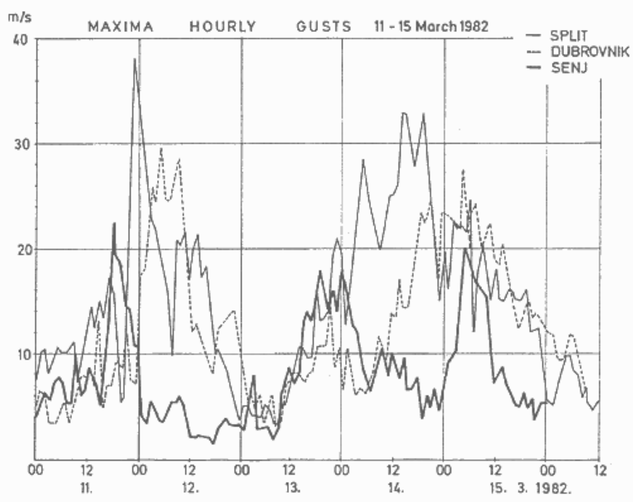

Figure 4. Daily courses of maxima hourly gusts for Split, Senj and Dubrovnik (in m/s) 11–15 March 1982.

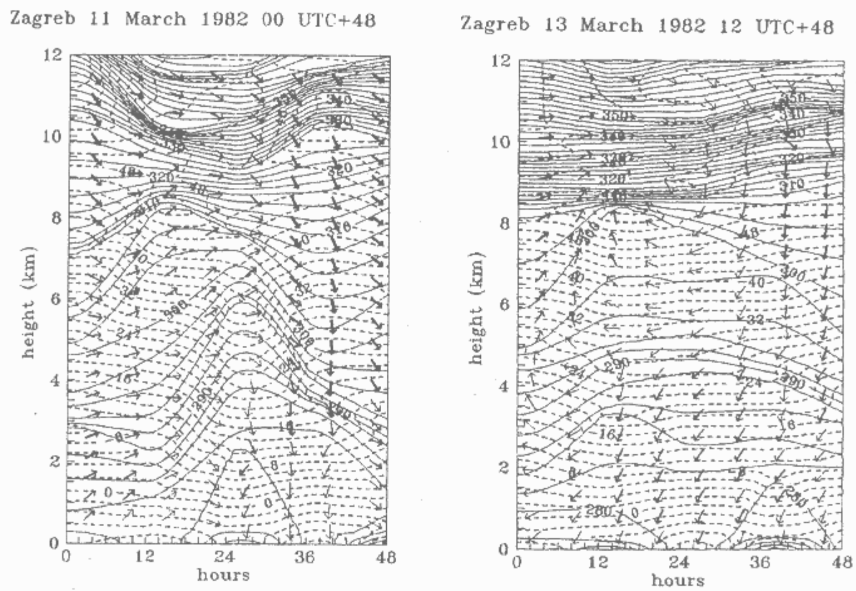

Figure 6. Vertical time cross-sections for 48 hours in Zagreb, 11–13 March 1982, 00 UTC (left) and 13–15 March 1982, 12 UTC (right). Isentropes (solid lines), isotherms (dashed lines) and wind arrows. Thickness of the arrows indicate relative wind speed intensity.

The second cross-section begins on 13 March at the onset of the second bora in all three stations considered in Fig. 4. This front is not so pronounced in temperature field but the low tropospheric winds intensify and sharply change to NE direction. It is a common experience that »the second front« appears in Alpine area in more stable condition than the first one and influences the formation of inversion layer responsible for prolonged bora in the Adriatic.

The reason for this is a postfrontal blocking of cold air in the Alpine upstream (northern) area leading to splitting flow around the mountain. Such a cold and stable air stream around the eastern Alps leads to strong NE bora in the northern Adriatic coast.

An example is the bora at the beginning of ALPEX SOP. The first front crossed the Alps on 2 March 1982 causing a lee cyclogenesis in the Adriatic sea. The mesoscale cyclone moved along the sea and strong bora occurred in Dalmatia (Visković, 1992). Following this front, the cold air blocking appeared on the northward side of Alps and the second front on 4 March was more stable undergoing stronger deformation with the air stream around the eastern Alps. This caused the strongest ALPEX bora on 5–6 March on the northern Adriatic (Jurčec, 1991).

Fig. 7. exhibits the humidity field for the same cross sections in Zagreb. It is seen that the frontal zone 11/12 March is even better presented by equivalent potential temperature distribution and high humidity along these zones. In the second period inversion layer intensifies on 14/15 March above the low tropospheric humid and unstable air. An intensification of Senj's bora on the last day, 15 March, is probably primarily influenced by this inversion, which is typical for strong bora at this locality. Jurčec (1991) analysed 6-hourly wind data in Zadar on 14 March 1982 illustrating the low-level wind maximum of 26 m/s at 1.5 km altitude at the time of strongest bora in Split on this day.

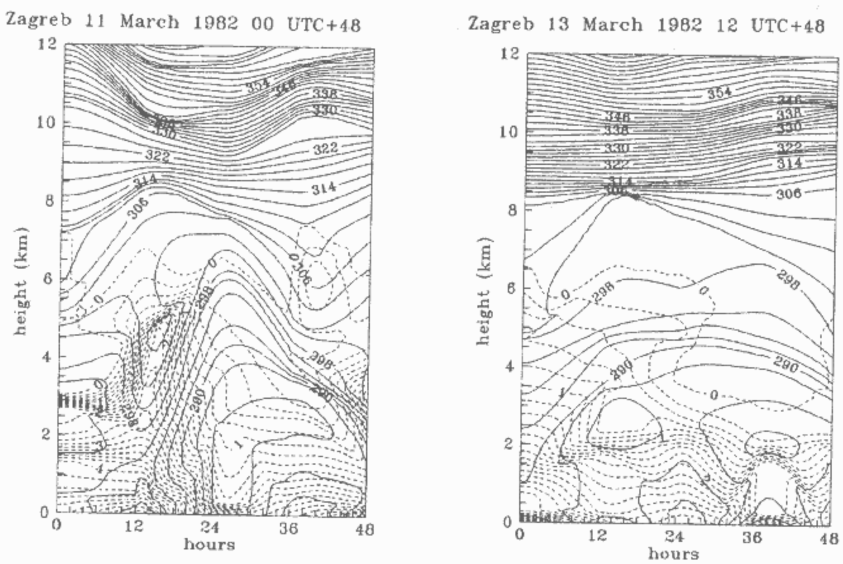

Figure 7. Vertical time cross-sections for 48 hours in Zagreb for the same periods as in Figure 6. Equivalent potential temperature isopleths (solid lines) and specific humidity isopleths (dashed lines).

The changes in vertical structure is illustrated in Fig. 8 by 2+1 D topography of isotachs and isohypses and 12-hourly changes of wind speed profiles in Zagreb (Fig. 9). These vertical distributions emphasize the weakening of the upper tropospheric winds in both periods of the strongest bora, particularly in Senj. The Dalmatian bora is less sensitive to the upper tropospheric wind intensification in Zagreb, and weakens more slowly than the bora in Senj. However, in spite of good presentation of frontal zone, usually reaching the Adriatic Sea from N–NW, Zagreb's sounding can not offer reliable presentation of upstream conditions, and particularly, of downstream vertical struc-

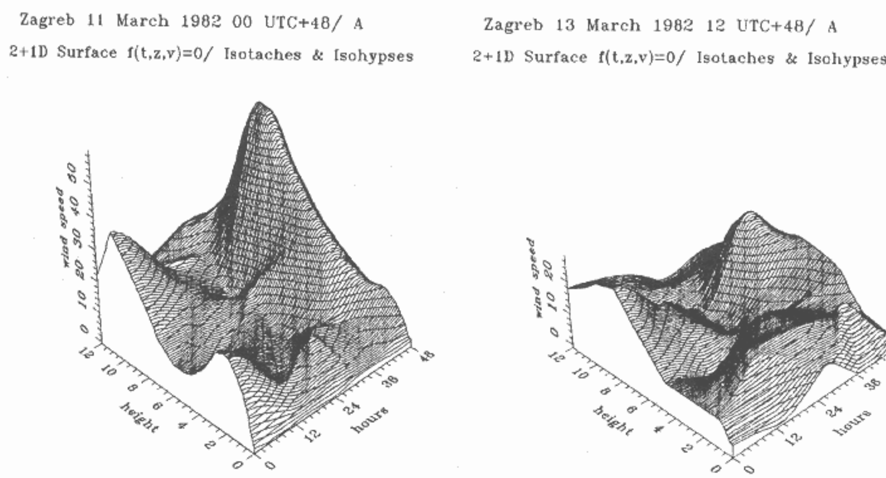

Figure 8. 2+1 D topography of isotachs and isohypses for 48 hours in Zagreb, 11–13 March 1982, 00 UTC (left) and 13–15 March 1982, 12 UTC.

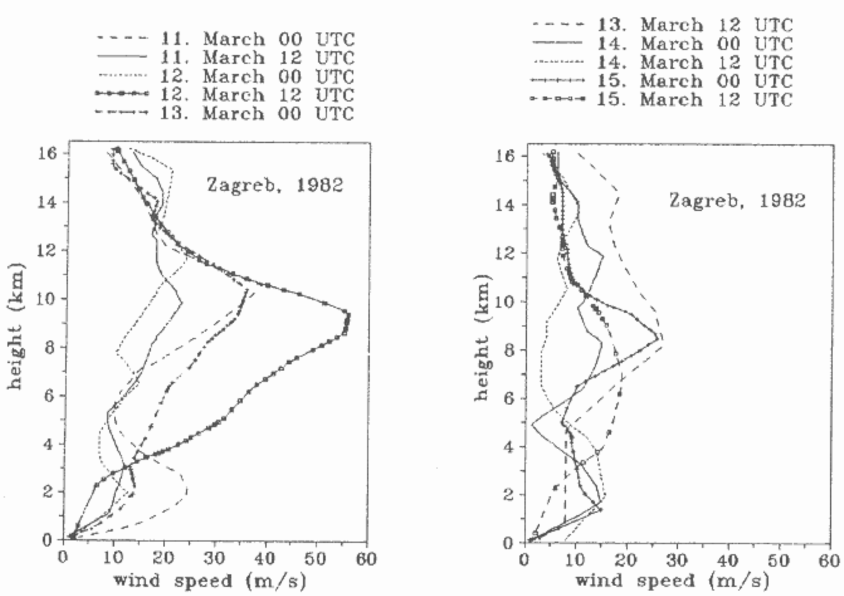

Figure 9. 12-hourly vertical wind speed profiles in Zagreb, 11–15 March 1982.

ture for Dalmatian bora. Future research and observation planning for Mesoscale Alpine Project (MAP) will hopefully answer many questions concerning the Dalmatian bora and make a further step forward in our knowledge of Dalmatian bora mechanism as it was the case in north Adriatic bora following ALPEX in 1982.

5. Remarks on theoretical approach

The analyses of southern Adriatic bora cases clearly show that the mechanism could not be explained by 2-D hydraulic theory as it was mainly the case in north Adriatic with simpler upstream condition. Some clue could be expected from the theoretical approach by Smith (1988) using 3-D linear theory.

The theory predicts two incipient stagnation points, one above the mountain top, leading to wave breaking as in 2-D theory, and another on the windward slope responsible for flow splitting. The theory does not predict which stagnation point will form first. If stagnation aloft forms first, local wave breaking and consequently modification of flow field might occur. If the surface stagnation point occur first, the low-level flow splitting may reduce the mountain wave amplitude which could prevent the occurrence of stagnation point aloft.

Some observations of windward conditions during southern Adriatic bora indicate the flow splitting and low-tropospheric divergence in the Pannonian Plain (Vučetić, 1993; Ivančan-Picek and Tutiš, 1994) causing lowering of isentropic surfaces toward the Adriatic. Due to broad and high Bosnian mountains low-level isentropes intersect the ground. This condition does not seem to be convenient for the higher level stagnation and wave breaking, but the surface blocking of cold air and steeply inclined isentropic trajectories could bring the cold air through many mountain passes to the coast, which is the main reason for well known large differences in bora speed at particular localities along the entire Adriatic coast.

6. Conclusion

The analysis of southern Adriatic bora shows that the wind speed and gusts are comparable to those well known in the north Adriatic, and in some cases could be even higher. Selected cases in Split indicate that severe bora with mean hourly speed higher than 17.2 m/s and gusts above 30 m/s lasts only for several hours and occurs in cold months (December to March).

The mesoscale characteristics are illustrated by the mean surface and upper level charts constructed from these cases. They emphasize the appearance of the mesoscale low in the southern Adriatic. This low and deeper upper level trough characterize »dark bora« of cyclonic type with clouds and precipitation in contrast to the anticyclonic »clear bora« occurring in a postfrontal state with higher surface pressure and cut-off low in the mid-troposphere. The mesoscale low plays an essential role in *downstream* effects on the southern Adriatic severe bora storms, since deeper cyclone causes a stronger wind speed on its rear side, where as the more pronounced cut-off process influences the wind speed as well as wind direction above the surface bora flow. This does not diminish the importance of upstream effects on the bora flow since most of the bora onsets are associated with the frontal passage from the north. From the theoretical approach it is considered that upstream condition for the southern Adriatic bora should be based on 3-D theories and numerical simulation which must explain the flow splitting, divergence and steep lowering of isentropic surfaces. The final conclusion must therefore wait for direct observations of vertical atmospheric structure in upstream and downstream region of Dalmatian bora as well as for fine mesh numerical model experiments which would allow the presentation of mountain passes responsible for the local differences in bora occurrence and strength along the Adriatic coast.

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