3.3 THE DYNAMICS OF PULSATIONS IN THE BORA FLOW

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1 INTRODUCTION

Bora is a strong, cold and gusty north-easterly downslope wind blowing over the Dinaric Alps along the eastern Adriatic coast. Severe bora episodes are characterized by the mean wind speeds close to 20 m/s, while gusts may reach 60 m/s. Analysis of the previously measured high-resolution (sampling intervals from 1–16 s) time series of the bora wind revealed the existence of pulsations with periods ranging from 1 to 10 min, similarly to downslope winds in other parts of the world. However, those time series did not exceed a few hours in length and thus could not provide a sufficiently long database for inspection of the possible variations throughout episodes. Also, the physical mechanisms responsible for their generation remained unclear. Recent measurements carried out at Senj present a step towards the explanation.

2 DATA AND METHODS

During the 2-month winter period (December 2001–January 2002) wind speed and direction were measured with a 1 s sampling interval at Senj (east Adriatic) and a number of strong bora episodes were recorded (see Fig. 1). All subsequent analysis will be restricted to the bora component (60° from the north) as it carries over 90% of the wind variance.

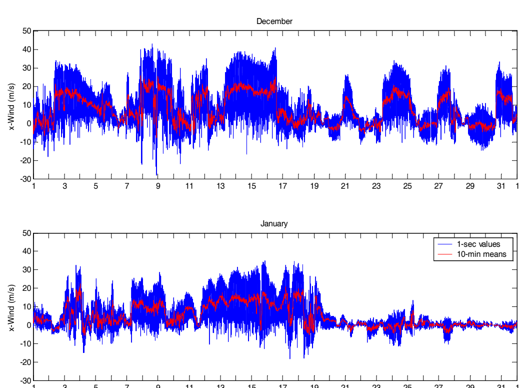

Figure 1. Original 1 s time series measured during December 2001 and January 2002 and 10 min averages.

A bora episode is defined as a repeated occurrence of wind speed greater than 10 m/s lasting over 3 h. The analysis of the bora time series included calculation of power spectra, time-running power spectra and the comparison of temporal development of 10 min mean wind with turbulence over three different period ranges (2 s–1 min, 2 s–10 min and 1 min–10 min). Also, their standard deviations were determined since they provide a clearer insight to the possible relations.

Additionally, upstream vertical structure of the troposphere has been studied and related to the phenomena observed in the time series.

3 RESULTS

Figure 1 shows the original 1 s time series over the 2 month period. Spectral analysis reveals a pronounced peak in energy at periods between 1 and 10 minutes, emerging during most of bora episodes. Figure 2 shows power spectra of four episodes indicating various possibilities. First, it is seen that different episodes generally have peaks at different periods (episode 9 (upper left panel)–4 min, episode 11 (upper right panel)–7 min). Second, an episode may have two or more distinct peaks (episode 12 (lower left panel)–8 and 5 min), and also there is a possibility of completely non-periodic behavior (episode 19 (lower right panel)). We refer to the energy peaks as to pulsations. In order to deduce the temporal evolution of the pulsations within an episode, we have performed spectral analysis on shorter subintervals evolving in time (time-running spectra). Figure 3 shows the time-running spectra for the episodes shown in Fig. 2. Particularly interesting is the spectrum of the first episode shown, where it can be seen that the pulsations disappear and reappear within the episode. There were several other episodes exhibiting that kind of behavior.

In order to find possible causes responsible for the cessation and reappearance of the pulsations, we compared the temporal development of 10-min averages of the wind speed (thus representing the mean wind) with the turbulence over three period intervals (represented by wind variance in period ranges from 2 s–1 min, from 2 s–10 min and from 1 min–10 min). This is shown for the bora episode 18 in Fig. 4, together with the temporal development of standard deviations of the above mentioned variables. Several things can be seen here: first, the turbulence between 2 s and 1 min (blue line) is very well correlated with the mean wind (black line), meaning that the turbulence in this range is generated by the frictional effects exerted by the mean wind. Similar effect has been observed in all other episodes. Second, the turbulence between 1

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and 10 min (green line) becomes substantially larger in second half of the episode, indicating the onset of the pulsations. When compared to the mean wind, it is seen that there is no relationship between the two variables. This is similar to all other episodes with the pulsations. Also, when the total turbulence between 2 s and 10 min is inspected (red line), it appears related to the mean wind before the pulsations onset, and unrelated after that, similarly to the green line at that time. This is also well seen form the standard deviation plot in Fig. 4.

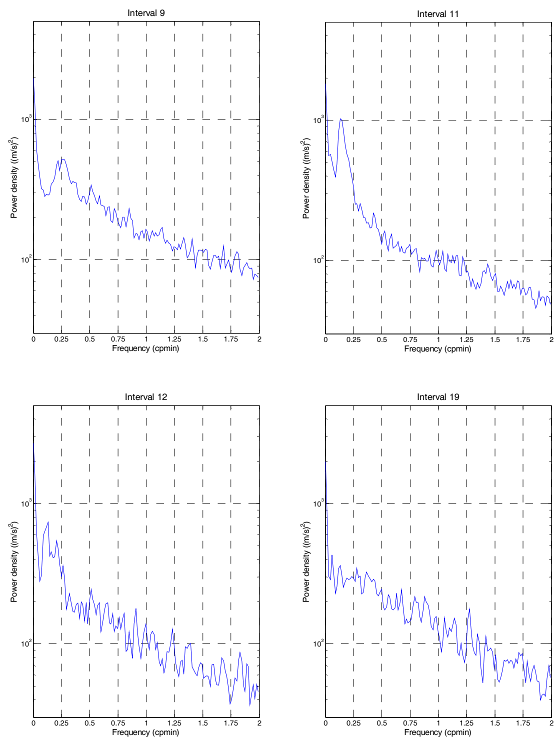

Figure 2. Power spectra of 4 bora episodes.

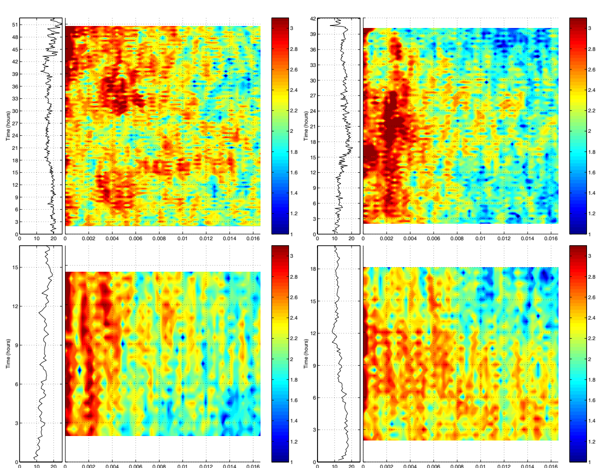

Figure 3. Time-running power spectra of the 4 episodes of Fig. 2 together with the 10 min mean wind speed (left panel).

Thus, one may conclude that the mean wind does not influence the generation of the pulsations. As the mean wind primarily represents the local dynamics, it may additionally be claimed that the pulsations will be of non-local origin. Even more, the fact that the mean wind remains essentially unchanged after the change in the appearance of the pulsations implies that the physics of the non-local effects will be such that they will modify the pulsations without affecting the mean wind speed. So, the next step is to find which mechanism can have such physical characteristics.

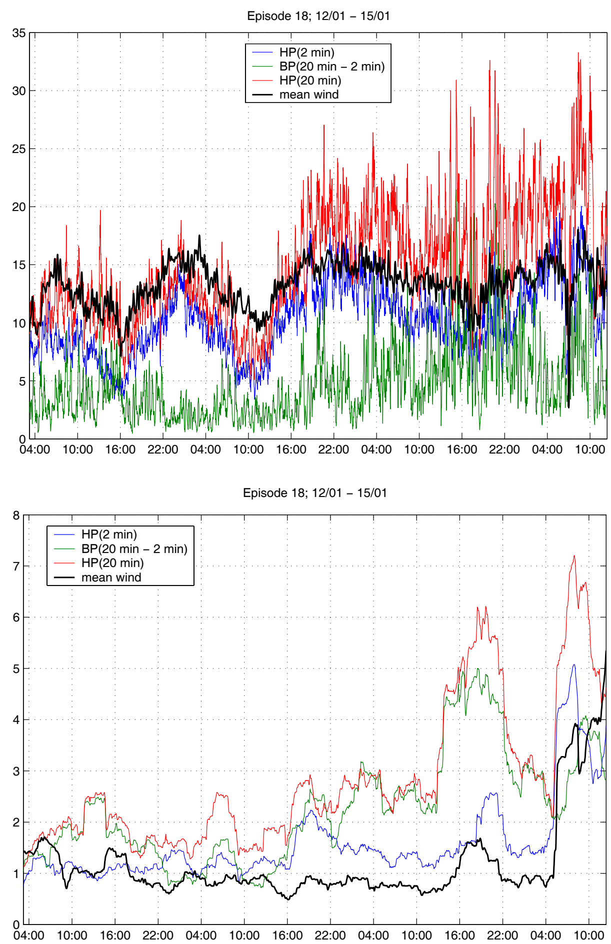

Figure 4. Upper panel: time development of the mean wind and variances of wind high-pass filtered at 2 min, 20 min and band-pass filtered between 2 and 20 min (representing turbulence in regions 2 s–1 min, 2 s–10 min and 1 min–10 min, respectively). Lower panel: temporal development of corresponding standard deviations.

For that purpose, we inspected the bora upstream vertical structure for 10 chosen cases (Belušić *et al.*, 2004). As a representative of the upstream conditions a Zagreb-Maksimir radiosonde station has been used. Figure 5 shows comparison for 3 episodes of the time-running spectra with the Zagreb-Maksimir vertical profiles of the 60° component wind speed and wind direction related to each episode.

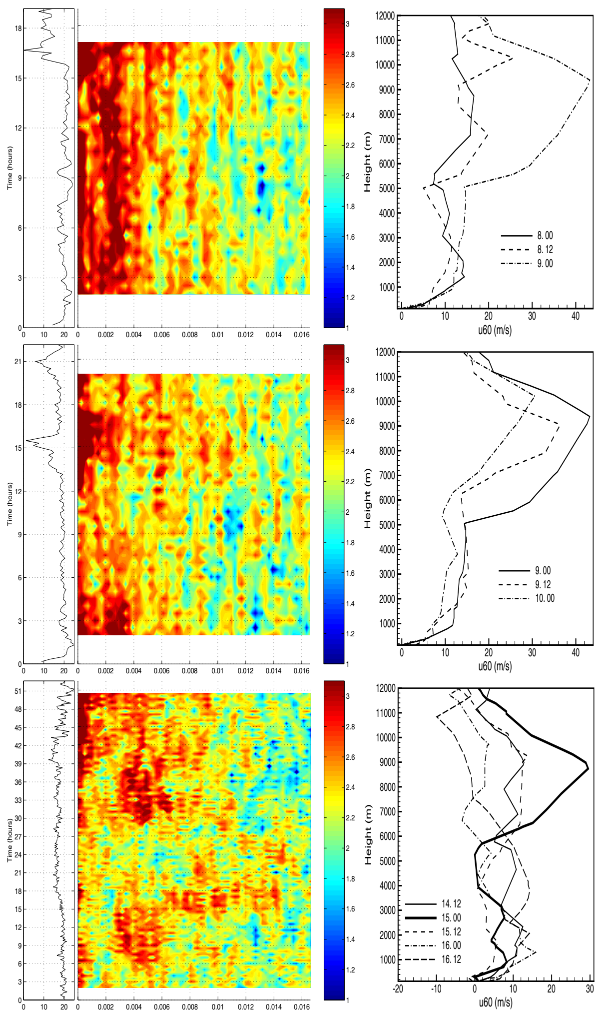

Figure 5. Time-running spectra related to the upstream vertical profiles of the 60° wind speed component.

The upper two panels in Fig. 5 show the case with the pulsations throughout the episode. Only the first two soundings (right panel–bold and dashed line) correspond to the episode, and the wind is approximately constant with height there. The third sounding is shown for comparison with the next case, which was only few hours after this one, when an upper-tropospheric jet-stream appeared. Thus, middle two panels show the next episode, where pulsations were present only during the first few hours. The first sounding (bold line), i.e. the third sounding from the upper panel, showing the jet-stream appearance, was measured shortly after the beginning of the episode. Approximately at that time the pulsations disappeared. The jet-stream was present throughout the episode and the pulsations did not reappear. The lower two panels show the case with the appearance, cessation and reappearance of the pulsations. The wind speed was almost constant with height in all soundings except the one that was measured at the time when the pulsations disappeared (thick bold line). At that time a jet-stream appeared in the upper troposphere.

From this it may be concluded that the appearance of the upper-tropospheric jet-stream leads to a reduction of the pulsations in the bora flow (Belušić *et al*., 2004).

4 DISCUSSION AND CONCLUSIONS

We have seen from the results of spectral analysis and the upstream vertical wind profiles that the appearance and disappearance of the pulsations in the bora is a non-local effect and it seems that the disappearance is related to the appearance of the jet-stream in the upper troposphere. Possible explanation, which is in accordance with previous studies of downslope winds, calls upon two mechanisms.

First, the pulsations are probably related to the existence of the wave breaking (Clark and Farley, 1984; Scinocca and Peltier, 1989; Peltier and Scinocca, 1990; Clark *et al.*, 1994). This agrees with the fact that the bora dynamics is primarily controlled by wave breaking (Klemp and Durran, 1987), and hence most of the measured bora episodes exhibit pulsations.

Second, the upper-tropospheric jet-stream prevents low-level wave breaking (Durran, 2003). This agrees with our conclusion based on the observations. Thus, it seems that the jet-stream reduces wave breaking, which then results in the disappearance of the pulsations.

The only remaining issue is why are there no changes in the mean wind speed if, as is believed, wave breaking is usually responsible for the bora. The answer lays in the existence of the low-level inversion. It seems that the inversion, when present, somehow takes over the role of the bora generator after the wave breaking disappears. Although the mechanism of the interchange is not known, the fact that the inversion may generate the bora has been established by Klemp and Durran (1987).

The next step in the investigation is to use a high-resolution numerical model to inspect the dynamics of these phenomena in detail.

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