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Quasi-periodic bora gusts related to the structure of the troposphere

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SUMMARY

This study provides a new insight into the behaviour of the bora wind gusts. Wind speed and direction measured with a 1 s sampling interval between 1 December 2001 and 31 January 2002 at Senj (east Adriatic) provided a sufficiently large database for a study of the gusts behaviour. The performed spectral analysis confirmed the occurrence of pulsations in the bora flow. Moreover, a new type of dynamics, involving the onset, cessation and reappearance of the pulsations within a single episode, has been observed in several cases. Suggested mechanisms responsible for generating these phenomena have been determined from comparisons of surface wind data with the upstream tropospheric thermodynamical structure derived from Zagreb radiosonde data. In particular, it has been shown that the appearance of an upper-tropospheric jet stream results in cessation of the pulsations, and the decrease in the jet stream supports quasi-periodic gust behaviour. As the pulsations are generated by wave breaking, the jet stream appearance has been related to the disappearance of the wave-breaking region in the lee of the mountain, which is in accordance with previous studies of downslope windstorms.

KEYWORDS: Downslope windstorm Jet stream Quasi-periodic pulsations

1. INTRODUCTION

The bora is a strong, cold and gusty north-easterly wind blowing over the Dinaric Alps along the eastern Adriatic coast. Its most prominent feature is strong gustiness. In severe bora cases mean hourly wind speeds exceed 17 m s^{-1}, while gusts may reach values of up to 60 m s^{-1}. Time series of the bora wind speed and direction, measured with small sampling intervals (1–16 s) and used in previous spectral analyses of the bora gusts (e.g. Petkovšek 1982, 1987) did not exceed a few hours in length. Therefore, although those studies revealed some spectral properties of the bora gusts, found at periods between 3 and 11 minutes, behaviour of the gusts over entire bora episodes could not be examined. Recent measurements carried out at Senj provide that opportunity: having a 1 s sampling interval over a 2-month period they have resulted in a sufficiently large database for detailed study of the characteristics of the bora gusts.

Observational (Smith 1987) and modelling (Klemp and Durran 1987; Enger and Grisogono 1998) studies of the bora point out the similarity of the bora dynamical structure to downslope winds in other parts of the world (e.g. the Boulder downslope windstorm). However, synoptic patterns differ. Synoptic situations during the bora are usually related to a strong pressure gradient between an anticyclone over middle and eastern Europe and a depression over the central Mediterranean (e.g. Poje 1992). This ensures a supply of cold air impinging on the mountain. The airflow also remains relatively cold in the lee, because adiabatic heating cannot compensate for the temperature difference between the incoming air and the warm air in the lee. Thus, the bora is a relatively cold wind, as opposed to the typical foehn or chinook for example. However, it seems that in spite of the differences there are no significant dynamical distinctions between the underlying processes (e.g. Durran 2003a).

Generally, downslope winds can be qualitatively described using a hydraulic-jump model (e.g. Smith 1985; Smith and Sun 1987; Durran 1990). There are three basic dynamical situations which favour the development of high downslope winds: (i) wave overturning and breaking due to growth of the amplitude of a standing mountain wave

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(deep cross-mountain flow); (ii) breaking and dissipation of standing mountain waves at a mean-state critical level (shallow cross-mountain flow); and (iii) presence of a stable layer near mountain-top level, when a high-wind state may form even without wave breaking (Durran 2003a). The mean-state critical level (h_c) for mountain waves is defined as $u(h_c) = 0$, i.e. the level where the cross-mountain component of the flow, u, disappears. Most of the bora cases are associated with the vertical wind structure that is analogous to the second situation, i.e. the north-easterly (cross-mountain, because the Dinaric Alps are oriented north-west to south-east) winds extend only through the lower troposphere and reverse direction at higher levels (e.g. Jurčec 1981; Smith 1987; Grubišić 1989). Henceforward this situation will be referred to as a standard bora model. It should be mentioned that Klemp and Durran (1987) found that wave breaking (situation (i)) is responsible for the high bora winds, regardless of the existence of the critical level or the low-level stable layer (i.e. an inversion layer), at least while the wave overturning layer is located beneath the inversion layer. However, in real downslope windstorms the low-level stable layer may coexist with wave breaking, and thus lead to even higher wind speeds.

Due to the aforementioned dynamical similarity, it is appropriate to extend some results obtained in the studies of the Boulder windstorms to the bora flow, more specifically those arising from the modelling experience. In several of those studies, using either idealized (Clark and Farley 1984; Scinocca and Peltier 1989, 1993) or more realistic (Clark *et al.* 1994, 2000) numerical simulations, possible explanations of the origin of the downslope windstorm gusts have been proposed. Clark and Farley (1984), using a three-dimensional (3D) simulation, obtained gusts separated by 10–12 minutes, which they attributed to the 3D instabilities occurring in the flow after the onset of wave breaking. On the other hand, Scinocca and Peltier (1989) were successful in obtaining pulsations using a 2D model. In a series of papers they proposed the shear, i.e. Kelvin–Helmholtz (K–H) instability, as the generating mechanism (Peltier and Scinocca 1990; Scinocca and Peltier 1993, 1994). Similar results were obtained using a theoretical approach (Smith 1991). Contrary to that, Clark *et al.* (1994) found an additional source of surface gustiness, besides the aforementioned 3D instabilities, which was related to propagating nonlinear lee waves. This mechanism was present in both the 2D and 3D experiments and is opposed to the K–H instability. However, the occurrence of K–H instability in the severe wind state and the results of Scinocca and Peltier (1993) was confirmed more recently by Wang and Lin (1999).

In spite of the above mentioned differences, the authors agree that the source of the pulsations is related to the wave-breaking region. It is also always assumed that the quasi-periodic transience in surface wind speed is maintained during the whole downslope windstorm state. Thus, the present picture of generation and maintenance of the pulsations is best summarized by the statement from Scinocca and Peltier (1989): '. . . the occurrence of this surface transience would seem to depend only on whether or not the bifurcation into the downslope windstorm configuration occurs and not on the incident upstream profiles . . . '. This scenario might seem appropriate for the bora, especially since wave breaking is assumed to be the most important mechanism in bora generation (Klemp and Durran 1987). Also, all previous studies dealing with spectral properties of the bora gusts agree with this picture (e.g. Petkovšek 1987).

However, we here propose a different possible explanation for the behaviour of the bora pulsations, based on the high-frequency wind speed data measured at Senj and the upstream dynamical structure of the troposphere. Specifically, we demonstrate not only the fact that the transience may cease, and even reinitiate after a while, within a single bora episode, but also that the surface pulsations in the bora flow are highly

TABLE 1. OVERALL STATISTICS FOR BORA EPISODES

Episode	Onset	Duration (h)	$\overline{U}$ (m s^{-1})	σ_U (m^{2}s^{-2})	U_{MAX} (m s^{-1})	U_{min} (m s^{-1})	T (minutes)	r
1	00 UTC 08 December	20	18.5	6.8	43.0	−19.5	6.2	0.80
2	22 UTC 08 December	22	17.3	6.3	40.1	−16.4	6.2	0.82
3	09 UTC 11 December	19	14.4	5.3	34.9	−12.8	–	0.81
4	05 UTC 13 December	16	16.6	4.9	36.9	−8.0	6.8	0.90
5	07 UTC 14 December	54	17.9	5.3	40.8	−16.8	3.6; 4.5	0.87
6	08 UTC 23 December	43	14.8	4.6	33.8	−10.6	6.8	0.87
7	23 UTC 26 December	17	14.2	4.4	31.2	−8.7	4.9; 7.6	0.86
8	15 UTC 30 December	24	14.2	4.4	33.1	−7.2	6.2	0.75
9	06 UTC 07 January	18	11.6	3.6	26.0	−5.8	6.2	0.78
10	15 UTC 08 January	16	10.9	4.0	28.6	−8.4	–	0.76

$\overline{U}$ is the average, and σ_U is the standard deviation of the wind speed over the bora episode; U_{MAX} and U_{min} are the maximum and minimum wind speeds over the episode; T is the dominant period of the pulsations; and r is the correlation coefficient (see text).

dependent on the upstream conditions. We relate this to the state-of-the-art theories of the downslope windstorm dynamics in general, as well as those explaining gust generation, and consequently we propose possible dynamical situations leading to the observed phenomena.

2. DATA AND METHODS

The wind data analysed in this paper were measured during a two-month winter period (1 December 2001 to 31 January 2002) at Senj (44.99°N, 14.90°E, 2 m above mean sea level (AMSL)), which is known to be the location of severest bora events (e.g. Yoshimura *et al.* 1976). A Micro-m-asta cup anemometer, positioned on the coast at 15 m AMSL, recorded horizontal wind at 1 s intervals (Orlić *et al.* 2003). In order to focus on strong bora events we projected wind vectors in the direction of maximum variance of wind speeds exceeding 10 m s^{-1}. The wind at Senj is strongly polarized. The bora (the component aligned 60° from north) takes as much as 92% of the wind variance. Hence, all subsequent analyses will be restricted to the 60° east of north (u) wind component. During the 2-month observation period a number of strong bora episodes were recorded; an episode is defined as a period with repeated occurrences of u stronger than 10 m s^{-1}, and of duration longer than 3 h. Ten episodes were chosen here for detailed study (see Table 1). The study involves the calculation of power spectra for all episodes and, in addition, 'time-running' power spectra (energy density of u plotted against frequency and time) for three episodes of interest. The latter spectra were obtained by calculating a series of power spectra over shorter (4 h) sliding sub-intervals, progressing in time with a 30-minute time step. Within each sub-interval, the spectrum was calculated and averaged over four Hanning windows (e.g. Papoulis 1977) of length 4096.

In addition to the high-frequency wind data, for each bora episode we examined vertical profiles derived from the atmospheric soundings at Zagreb (45.82°N, 16.03°E, 128 m AMSL), which were available every twelve hours (at 00 and 12 UTC). Due to the aforementioned north-easterly pressure gradient related to bora synoptic situations, Zagreb, which is north-east of Senj (Fig. 1), may be regarded as representative of the upstream bora conditions (Yoshino 1976; Smith 1987). This is substantiated by many studies dealing with the bora upstream vertical structure, which used only Zagreb radiosonde data (e.g. Yoshimura 1976; Jurčec 1981; Klemp and Durran 1987; Glasnović and Jurčec 1990; Ivančan-Picek and Tutiš 1995, 1996). However, in order to further

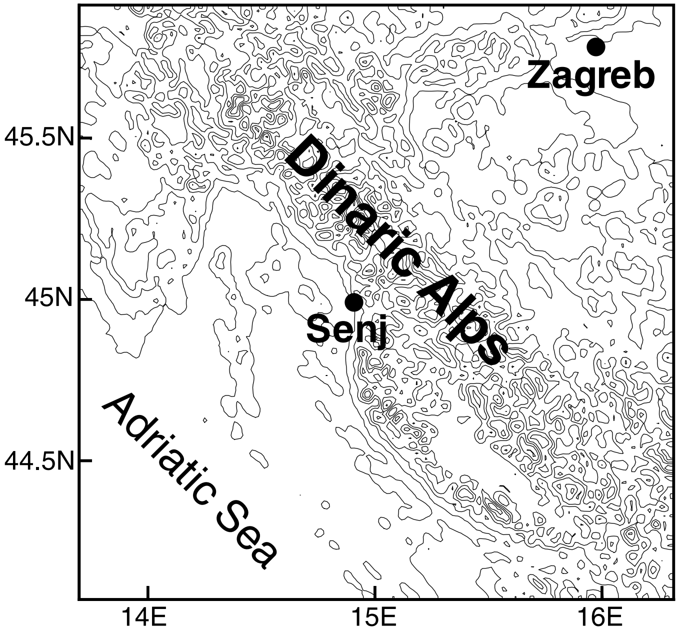


Figure 1. Locations of Senj and Zagreb with respect to the Dinaric Alps and Adriatic Sea. Contours are given every 200 m.

validate adequacy of the upstream data we calculated the correlation coefficient (r) between the MSLP difference between Zagreb and Senj (p) and the wind speed (u) at Senj for each bora episode (see Smith 1987). The large values of r shown in Table 1, and Fig. 2 showing p and u plots for episode 7, clearly indicate a high consistency between the pressure difference and the wind speed, and thus imply that the Zagreb data satisfactorily represent the upstream conditions. A few hours before and after the bora were included in our calculations to reproduce clearly the relation between the two quantities. Also, for each sounding used in the study estimates of the internal Froude number ($Fr = U/NH$) and the mountain Rossby radius ($L_R = NH/f$) were performed. Here, U is the ambient wind speed, N is the Brunt–Väisälä frequency, H is the mountain height and f is the Coriolis parameter.

For air flowing towards the mountain, $Fr > 1$ indicates that the air will easily go over the mountain and result in laminar mountain waves, while $Fr < 1$ means that either wave breaking or flow splitting will occur (e.g. Stull 1988). The latter situation favours development of the bora and should thus appear in the radiosonde data if Zagreb is representative of the upstream conditions. L_R identifies the upstream distance over which the mountain influences the flow in such a way that it becomes ageostrophic and winds point down the pressure gradient (e.g. Nuss 2003). Thus, since in the upstream region of the bora flow winds point down the pressure gradient, Zagreb should be located within radius L_R in order to adequately represent the upstream flow. The distance between Zagreb and Senj is 125 km, and the distance between Zagreb and the mountain ridge is around 115 km. It is thus important to verify whether Zagreb lies within the Rossby radius and to test if the properties of the flow agree with the $Fr < 1$ requirement.

All calculations were performed in the layer capped by a low-level inversion or, in its absence, by a critical level. N and U were taken as mean values in the layer, and H was set to 1000 m, which is approximately the difference in height between the Zagreb

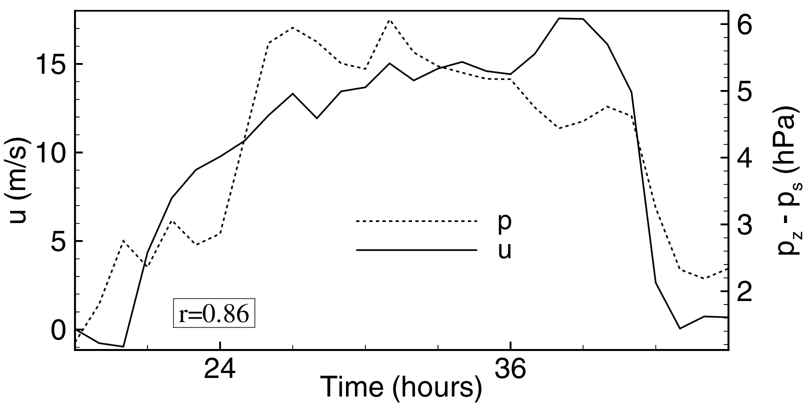


Figure 2. Hourly mean values of 60° east of north component of wind speed (u) at Senj and differences between MSL pressure at Zagreb (p_Z) and Senj (p_S) for bora episode 7, from 2300 UTC 26 December to 1600 UTC 27 December 2001. Data for 5 h before and after the episode are added to give a better view of the dependence between the two variables. Time is in hours after 00 UTC 26 December, and r denotes the correlation coefficient.

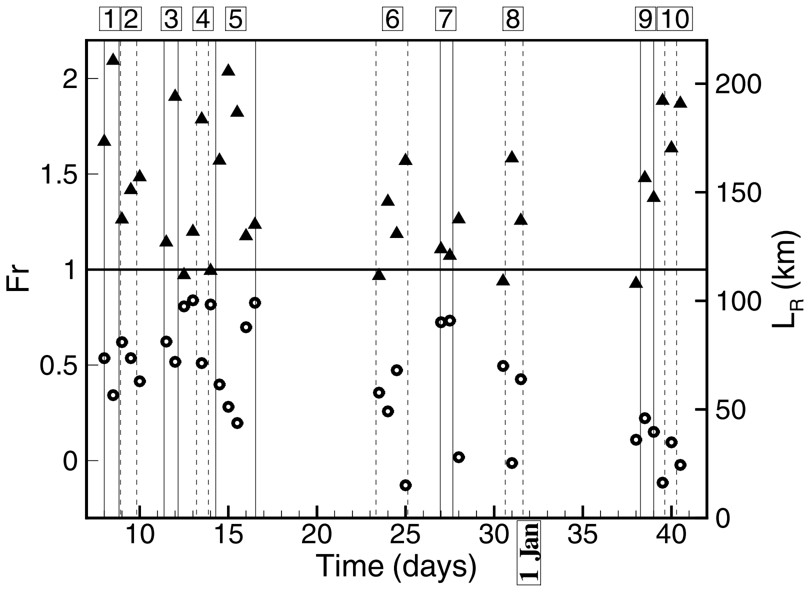


Figure 3. Internal Froude numbers (Fr, circles) and the mountain Rossby radii (L_R, triangles) for ten bora episodes; the vertical lines and numbers above them indicate the bora episodes. The thick solid horizontal line represents the limit between the two distinct dynamical situations with respect to $Fr = 1$ and also the horizontal distance between Zagreb and the mountain ridge. Time is given in numbers of days after 1 December 2001. See text for further details.

radiosonde measuring site (128 m) and the mountain ridge (around 1100 m). The results for all bora episodes are shown in Fig. 3. In most cases L_R exceeds the Zagreb–mountain ridge distance, therefore locating Zagreb within this radius. Those that fall below that distance are, nevertheless, very close to it, thus remaining within acceptable limits. It should be noted that due to the sparsity of the radiosonde data several soundings are shown even though they were not measured during a bora episode; the resulting parameters might therefore be non-representative in those cases. This also explains the appearance of few Froude numbers with negative values. At those times U was less than zero, meaning that there was no airflow towards the mountain in the inversion/critical layer, which is possible since all those soundings were made either before or after the bora. All other values of Fr are between 0 and 1, and imply that the bora upstream conditions are fulfilled in the Zagreb data.

Some upstream quantities that are important for the discussion need to be defined. The upstream bora layer is usually defined as a layer with the wind direction between 0 and 90° (i.e. 45±45°; Yoshimura 1976). Glasnović and Jurčec (1990) introduced into their study of the upstream bora layer depth the 'bora component', i.e. the cross-mountain component of the flow, and extended the previous definition by stating that all wind directions from 45±90° would have a positive bora component, thus defining the bora depth. However, based on the actual (local) orientation of the mountains we find this definition somewhat exaggerated and suggest an intermediate value of 45±75°. In some cases the bora layer defined in this way extends throughout the troposphere (e.g. Grubišić 1989; Ivančan-Picek and Tutiš 1995).

The nominal bora wind direction at Senj is 60°; therefore we observe only this component in the wind speed measurements from Zagreb, and it is taken to be representative of the upstream bora wind speed. This can be justified by the fact that downslope windstorm dynamics is generally treated as a 2D problem (e.g. Smith and Sun 1987).

3. RESULTS

As an example of the original wind data, a 1 s time series of episode 5 is shown in Fig. 4(a), together with a 1 h interval taken from the episode in Fig. 4(b). Clearly distinguishable are the pulsations with periods of the order of few minutes. The power spectra for all bora episodes are shown in Fig. 5. Clearly noticeable is the distinction between the two diverse behaviours in the spectra: some episodes exhibit quasi-periodic behaviour, i.e. they demonstrate significant amplification of energy at certain frequencies (episodes 1, 2, 4, 5, 6, 7, 8, 9), whereas some are almost entirely non-periodic (episodes 3 and 10). However, as we shall see later, the quasi-periodic behaviour may sometimes only be present during a part of an episode and cease afterwards (e.g. episode 2). In longer episodes it may even re-initiate, cease again and so on. This series of alternations between quasi-periodic and non-periodic behaviour is probably limited only by the duration of the bora itself. For instance, during the longest bora episode here (episode 5), a total of three non-periodic situations interchanging with two quasi-periodic interludes was reached (cf. Fig. 7). The term 'quasi-periodic' is employed because the amplification is not shaped as a narrow peak, but rather extends over a broader range of frequencies, thus it is not strictly periodic. We may, therefore, only talk about structures appearing as amplifications in the spectra between certain values of frequencies (periods). On the horizontal axis in Fig. 5 frequencies ($Freq$) are plotted in cycles per second (cps), but for the sake of clarity we examine the spectra in terms of periods ($T = 1/Freq$) given in minutes.

With the purpose of finding appropriate dynamical explanations for the appearance and cessation, or absence, of the structures in the spectra, we try to relate this kind of behaviour to the corresponding upstream vertical profiles of wind speed and direction. The vertical profiles in Fig. 6 are shown for each episode separately. Since the soundings were only available at 00 and 12 UTC, some of them are shown even if they do not coincide with the specific bora episode, but were taken few hours before or after. This has been done so that one can at least get some idea of the changes with time in the upstream conditions.

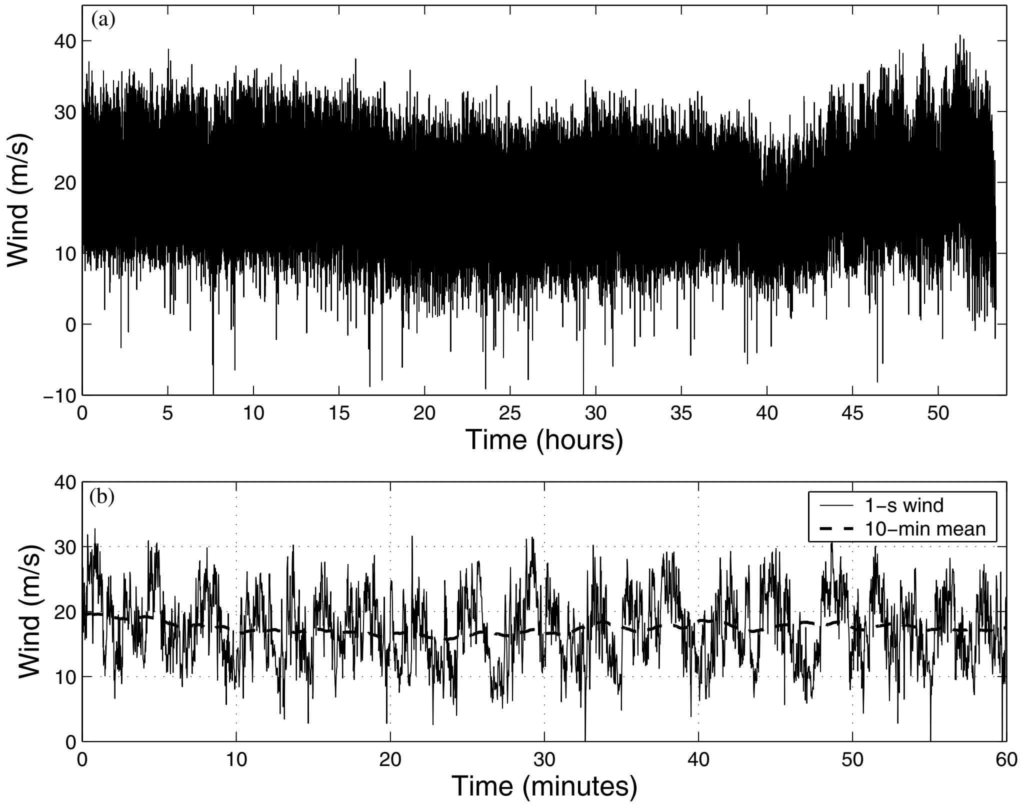


Figure 4. Time series of the 60° east of north component of wind speed at Senj for bora episode 5 from 07 UTC 14 December: (a) original 1 s values; (b) an expanded 1 h interval extracted from the same episode, with 10 minute average wind speeds superimposed on the 1 s data.

To begin with, let us inspect the first group of episodes, i.e. those exhibiting the quasi-periodic pulsations. Figure 4(b) shows how periods fluctuate in the course of time, causing the aforementioned broad amplified signals in the spectra. Figure 5 reveals that in various episodes amplifications are found at different periods. However, all those periods range between approximately 3 and 11 minutes. In Table 1 the dominant periods (T) are listed for each episode. In some cases there are two (or more) dominant periods within a single episode (e.g. episode 7). We subdivide the first group into episodes with 'well-behaved' spectra, where the quasi-periodic structures are present throughout the episode (episodes 1, 4, 6, 7, 8, 9), and the most interesting ones where the quasi-periodic behaviour ceases (episode 2) and even reinitiates (episode 5) in the course of time. From Fig. 6 it can be seen that for all well-behaved episodes except episode 1 a critical level is present above which the airflow undergoes an obvious change in direction and has a westerly component throughout the remainder of the troposphere; it is usually located at about 2 or 3 km but may reach heights from 1.5 to 5 km. This is perhaps partly veiled in episode 4, but since only the sounding of 12 UTC 13 December was taken during the episode, this alone should be regarded as representative of the upstream conditions. Hence, there is no cross-mountain flow aloft, except in episode 4 where a north-easterly component appears again at about 10 km, but remains small in amplitude. Therefore, this set-up can be regarded as the standard bora model, having a well-defined upstream bora layer.

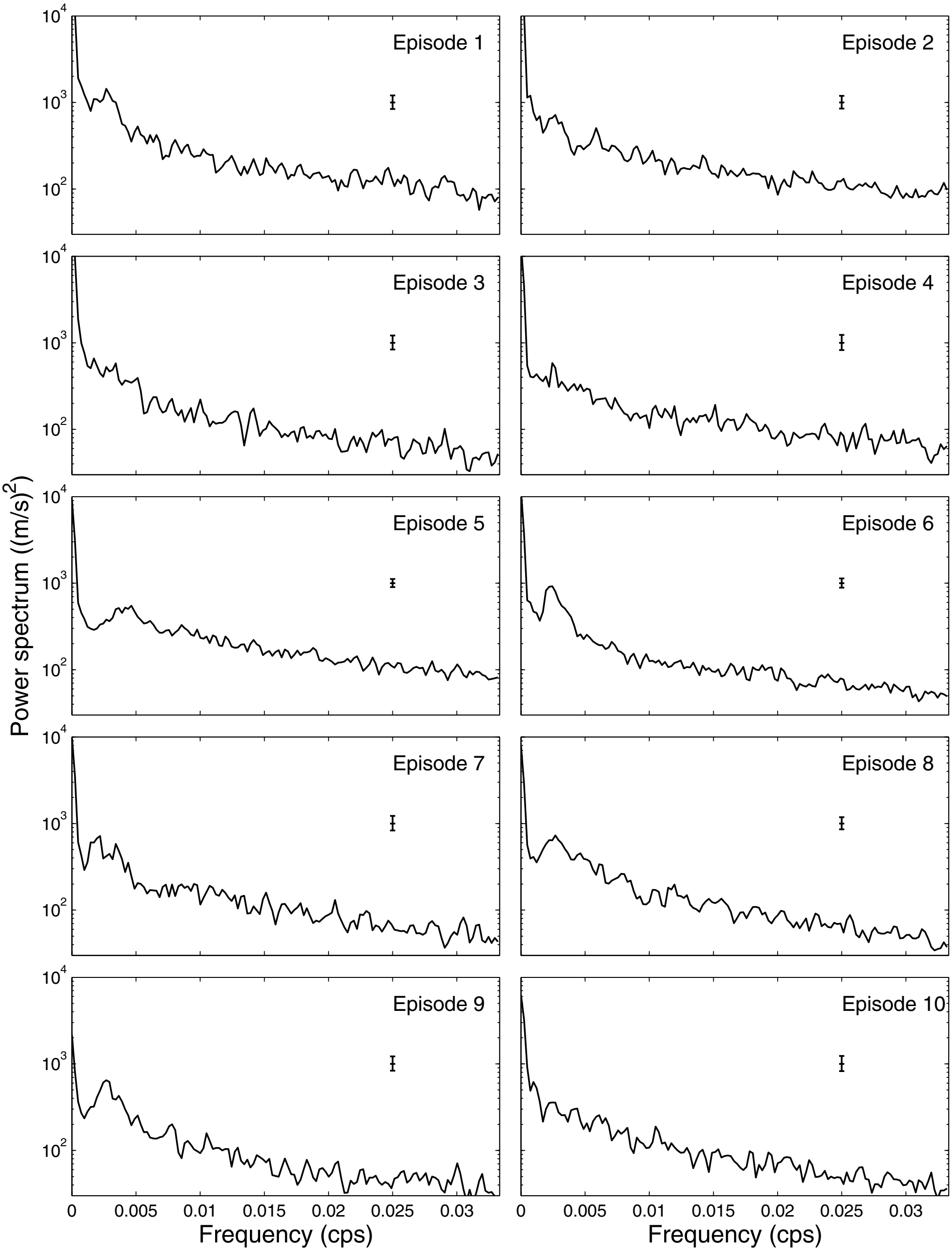


Figure 5. Power spectra of the 1 s wind speed at Senj for the ten bora episodes studied (see text). Vertical error bars show 95% confidence intervals.

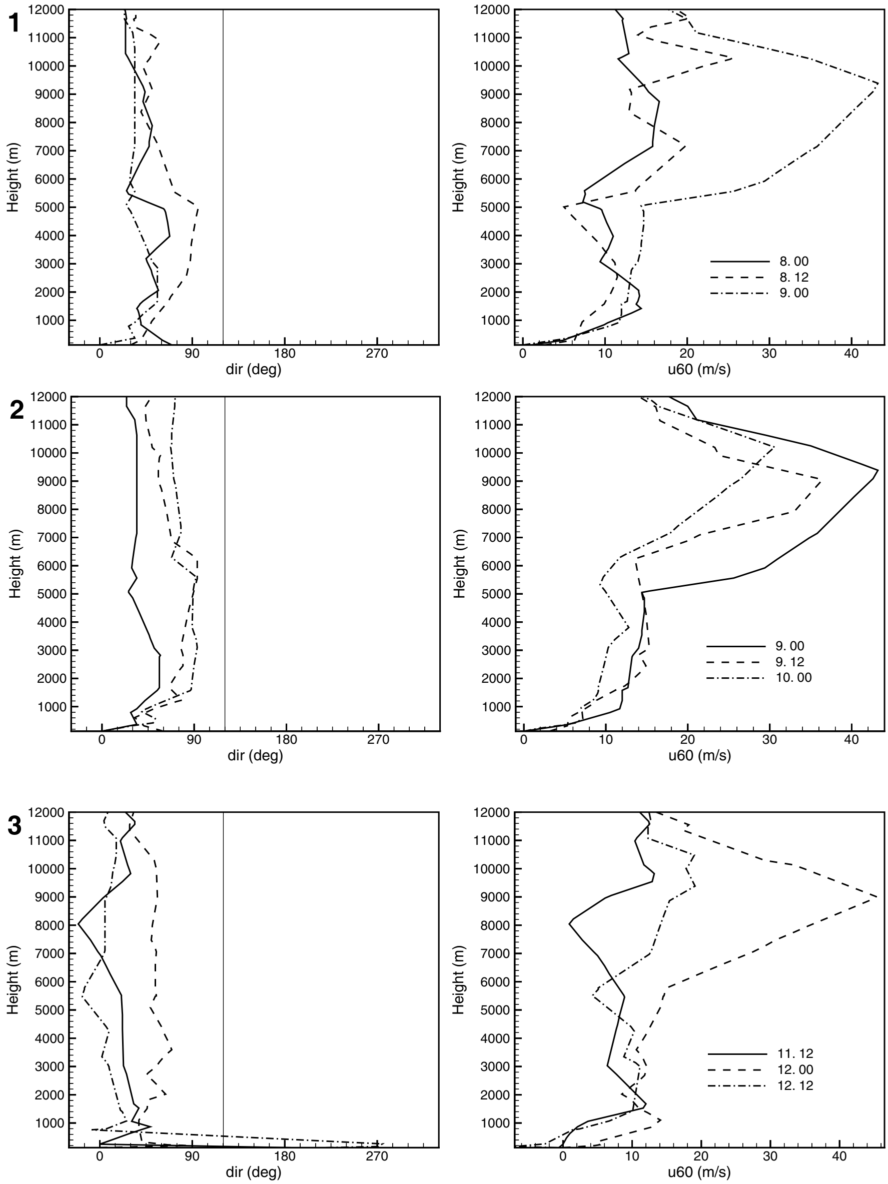


Figure 6. Upstream vertical profiles of wind direction, and 60° east-of-north component of wind speed from Zagreb soundings corresponding to ten bora episodes (see text). Numbers in the upper-left corners correspond to the particular episode. The vertical line (at 120°) and the y-axis (at $-30°$) on each wind direction plot represent limits of the sector defining the bora layer ($45 \pm 75°$).

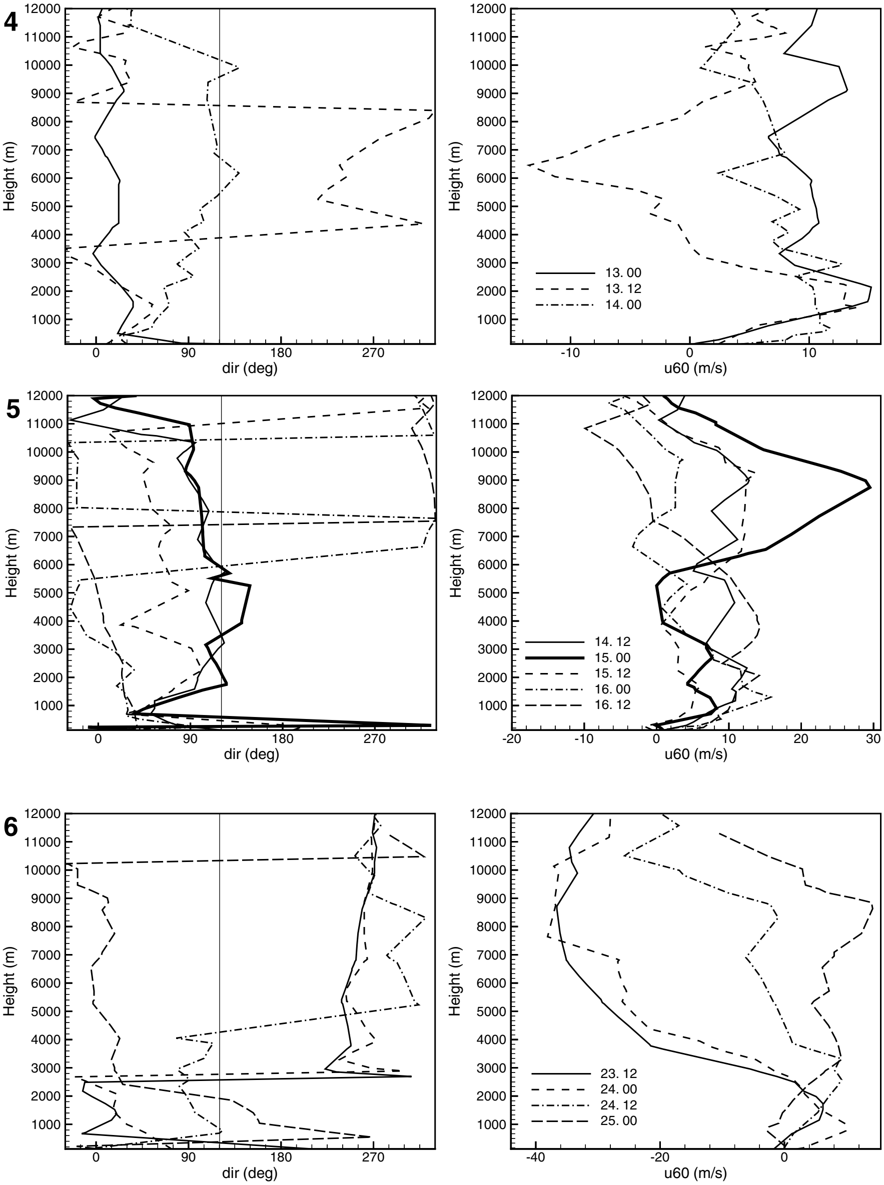
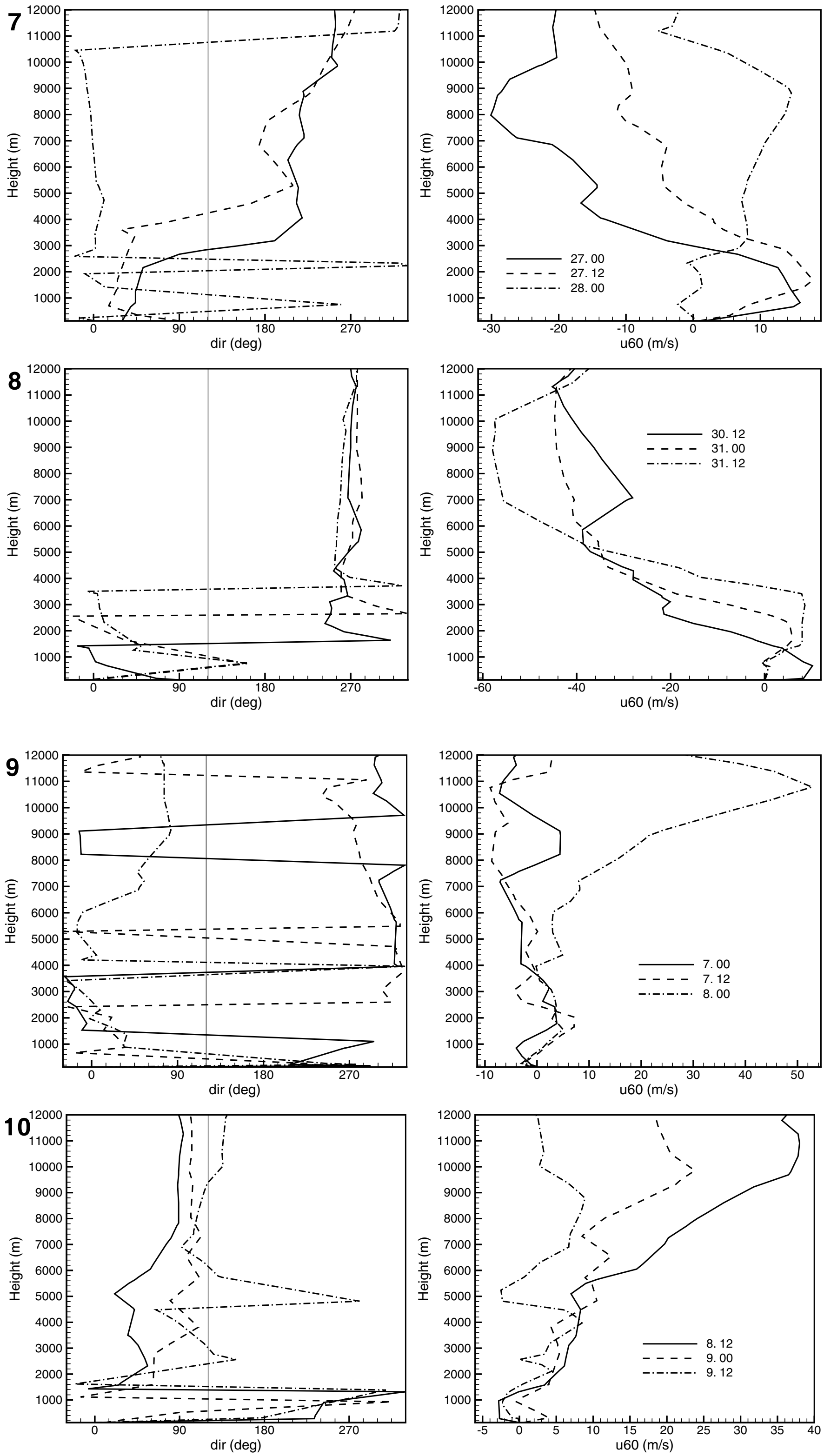


Figure 6. Continued.



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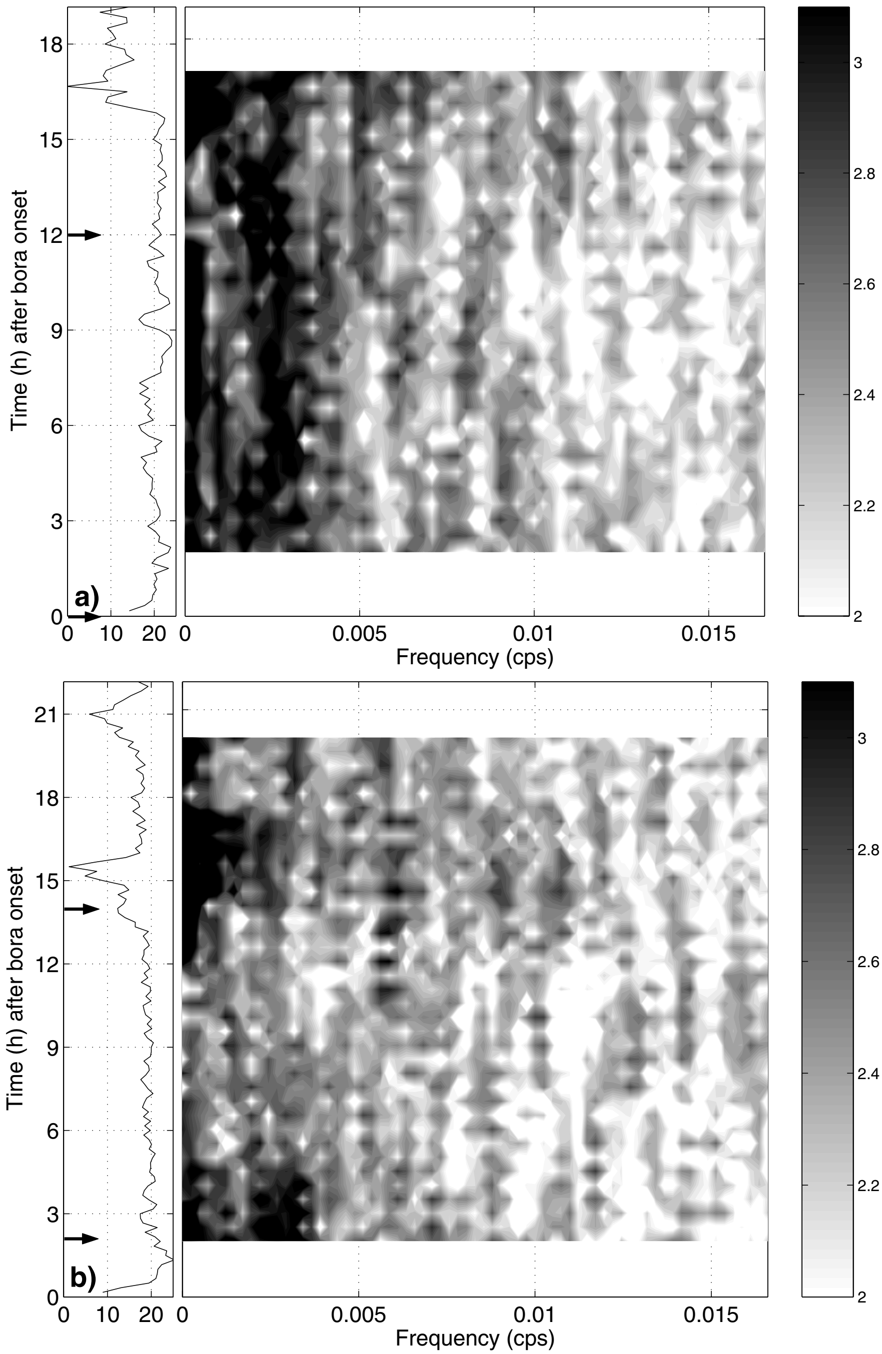

Figure 7. Time evolution of the energy spectrum of the 1 s wind speed at Senj for bora episodes: (a) 1, (b) 2 and (c) 5; the scale on the right shows the logarithm of energy density ($m^2s^{-2}cps^{-1}$). Along the time axes the 10-minute mean wind speed values ($m\ s^{-1}$) are also shown. The arrows indicate approximate times when the soundings were taken. See text for further details.

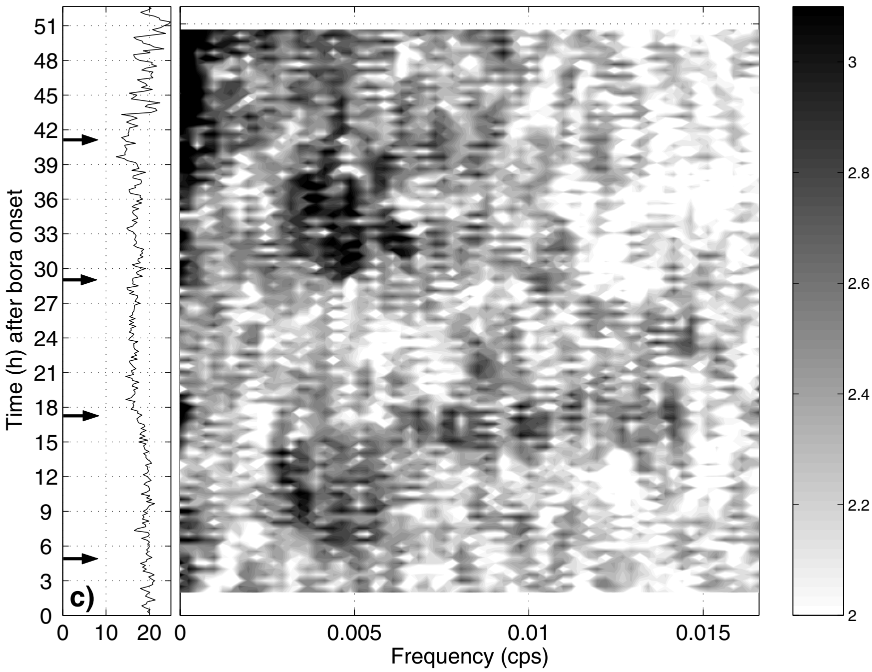

Figure 7. Continued.

An interesting feature here is the appearance of a very strong jet stream (over 50 m s^{-1}) above 10 km at 00 UTC 8 January. At that exact time episode 9 ended, i.e. the wind speed fell below 10 m s^{-1} which is the threshold defining a bora episode. Hence, the appearance of the jet stream did not affect the gust structure of this episode but rather led to its decline. This is a unique case, since the appearance of a jet stream influences the dynamics of other episodes in a different manner. We shall refer to this briefly in the next section.

For episode 1, the soundings of 00 and 12 UTC 8 December are representative, since the episode ended at 20 UTC 8 December. There is no critical level and the bora layer extends throughout the troposphere, i.e. the north-easterly winds do not change direction with height. However, the wind speed is approximately constant with height, especially if compared with the difference between the lower and upper levels for the sounding of 00 UTC 9 December, when the upper-tropospheric jet stream appeared. This will be shown to be essential for the processes leading to gust generation. The 9 December sounding is also shown to enable comparison with the next episode, which will be seen to possess a substantially different structure.

The time-running spectra for episodes 1, 2 and 5 are shown in Figs. 7(a), (b) and (c), respectively. In episode 1, which has been seen to be entirely quasi-periodic, the energy density around a period of 6.2 minutes (i.e. frequency of 0.0027 cps) is amplified at all times. Other episodes from the well-behaved group look similar and are therefore not shown. Episode 2, on the other hand, shows quite different behaviour. Energy is amplified during the first few hours, thus producing a rather small peak in the spectrum shown in Fig. 5; the rest of the episode is, however, non-periodic. We find this to be a very important finding, especially since there is no conspicuous change in the mean wind speed during the episode. Thus, the bora pulsations seem to disappear without stopping or diminishing the bora flow. Very similar behaviour appears in episode 5, except that it is substantially longer and thus shows more variations. When the corresponding upstream profiles (Fig. 6) are examined, an interesting phenomenon comes to light. It seems that the appearance of the jet stream at 00 UTC 9 December is somehow related to the cessation of the pulsations in episode 2. Although the jet stream weakens in time, it remains present throughout the episode, and consequently the episode stays non-periodic. In episode 5 the situation is somewhat different. The jet stream appearing at 00 UTC 15 December coincides with the energy reduction around a period of 4 minutes in the spectrum. However, new in this case is the jet stream disappearing after 12 h, which leads to onset of the pulsations once again. These findings lead to the hypothesis that the appearance of the jet stream may change the dynamics of the bora in such a way that the pulsations cease but the high downslope wind state remains unaffected.

To test this hypothesis we turn to the remaining two entirely non-periodic cases and inspect their upstream structure. Here, the appearance of the jet stream would support the hypothesis. In episode 3 the jet stream is present at 00 UTC 12 December. Due to the sparse radiosonde data, it is difficult to verify whether it appeared before this, but on the basis of other cases it is likely that it did. Nevertheless, as the bora ceases at 04 UTC 12 December, this sounding represents the tropospheric structure, at least during a part of the episode. Episode 10 begins 3 h after the sounding of 12 UTC 8 January and lasts until 07 UTC 9 January, so that only the sounding of 00 UTC 9 January is strictly applicable. In this sounding the jet stream appears, though a little weakened compared to the previous one (see Fig. 6). However, if one observes the sequence of soundings starting from 00 UTC 8 January (the last sounding in episode 9) until 12 UTC 9 January, it is obvious that the very strong jet stream, which appeared at 00 UTC 8 January and was probably responsible for the diminishing of the bora in episode 9, gradually decreases with time. Thus, after weakening a little (after 12 UTC 8 January) the bora flow forms again, leading to episode 10. Nevertheless, the jet stream remains sufficiently strong throughout episode 10 to act as a mechanism responsible for the cessation of the pulsations. Thus, both non-periodic episodes are characterized by the presence of the jet stream and agree well with the hypothesis.

The theory of the standard bora model is well explained and is known to be related to wave breaking. Also, situations resembling episode 1 are sufficiently well understood, especially after the modelling study of Klemp and Durran (1987), and are also associated with wave breaking. However, we have seen that in the situations characterized by the appearance of the jet stream the pulsations cease but the bora remains at full strength. Because of that we believe that these situations are likely to be accompanied by a different kind of dynamics, namely the potential disappearance of wave breaking (e.g. Durran 1990). We, therefore, additionally inspect the upstream thermal structure for these cases in order to gain better understanding of the underlying processes. The tropopause heights, together with the heights and maximum wind speeds of the jet streams for the soundings corresponding to the ten episodes, are listed in Table 2. All jet streams are located below and very close to the tropopause, except one which is at the same height (00 UTC 10 December). Figure 8 shows the upstream vertical profiles of the potential temperature in the lowest 5 km for the soundings with the jet stream. An inversion is defined as a layer over which the temperature rises with height. It is seen here that there is at least one low-level inversion in each sounding shown. This is not generally the case; for instance, there are no inversions throughout the troposphere in the soundings related to episode 7 (not shown). This fact, as discussed in the next section, agrees with previous findings. It should be noted, however, that the inversions at 00 UTC 10 December are very weak but by that time the bora has already ceased. Also, the

TABLE 2. THERMODYNAMICAL PARAMETERS DURING BORA EPISODES

Episode	Sounding	Tropopause height (m)	Jet stream height (m)	Jet stream wind speed (m s^{-1})
1	00 UTC 08 December	10 438	–	–
	12 UTC 08 December	10 881	–	–
2	00 UTC 09 December	11 177	9 385	43.2
	12 UTC 09 December	9 830	9 059	36.4
	00 UTC 10 December	10 208	10 208	30.6
3	12 UTC 11 December	10 133	–	–
	00 UTC 12 December	10 137	8 991	45.3
	12 UTC 12 December	8 865	–	–
4	00 UTC 13 December	8 760	–	–
	12 UTC 13 December	6 454	–	–
	00 UTC 14 December	8 777	–	–
5	12 UTC 14 December	8 989	–	–
	00 UTC 15 December	9 313	8 739	29.5
	12 UTC 15 December	10 155	–	–
	00 UTC 16 December	8 953	–	–
	12 UTC 16 December	10 838	–	–
6	12 UTC 23 December	8 721	–	–
	00 UTC 24 December	9 935	–	–
	12 UTC 24 December	9 988	–	–
	00 UTC 25 December	9 467	–	–
7	00 UTC 27 December	8 733	–	–
	12 UTC 27 December	8 351	–	–
	00 UTC 28 December	9 969	–	–
8	12 UTC 30 December	11 202	–	–
	00 UTC 31 December	11 370	–	–
	12 UTC 31 December	10 378	–	–
9	00 UTC 07 January	11 614	–	–
	12 UTC 07 January	10 762	–	–
	00 UTC 08 January	11 683	10 783	52.8
10	12 UTC 08 January	12 842	10 907	38.0
	00 UTC 09 January	13 583	9 851	23.8
	12 UTC 09 January	13 578	–	–

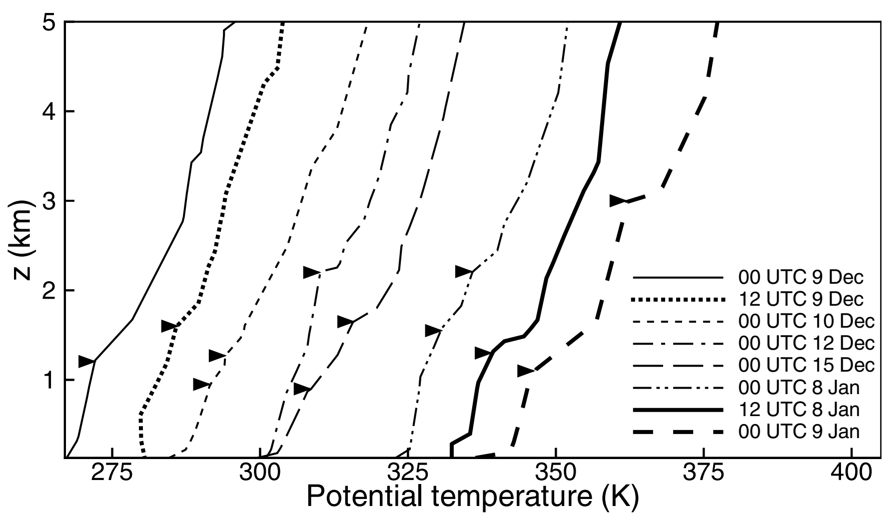

Figure 8. Upstream vertical profiles of potential temperature for soundings with a jet stream. For clarity the curves for times after 00 UTC 9 December 2001 have been progressively offset by 10 K. Arrows indicate inversions.

inversions at 00 UTC 8 January are much weaker than subsequent ones. As the bora (episode 9) ceased at that time, and reinitiated afterwards (episode 10), this weakening inversion may be the cause, along with the already mentioned very strong jet stream. We refer to this in the next section.

4. DISCUSSION

In the previous section we demonstrated the dependence of the bora gust structure on the upstream tropospheric conditions for ten bora episodes. Although based on sparse upstream data (with soundings only every 12 h), several important results have been observed which to a certain extent agree with previous studies.

Primarily, the distinction has been made between two qualitatively different behaviour patterns of the gusts: quasi-periodic and non-periodic. In some cases, the behaviour can be attributed to the entire bora episode; however, it is also evident that interchange is possible within an episode without any conspicuous change in the mean wind speed. Based on those results we can assert that the upstream tropospheric structure pertaining to the standard bora model is related to existence of the pulsations, as are the situations without the critical level but also without strong cross-mountain winds in the upper troposphere. On the other hand, when the upper-tropospheric jet stream appears the quasi-periodic structures languish. Also, the low-level inversion is present in all situations with the jet stream.

The first situations to be examined are those episodes with quasi-periodic structures. Similar phenomena were considered, as mentioned earlier, by the scientists involved in the study of the Boulder windstorms. A few distinct generating mechanisms for the pulsations were recognized, all having one thing in common: the source was related to the wave-breaking region in the lee of the mountains. It is noteworthy that all episodes from this first group (i.e. those that exhibit the pulsations) have an upstream structure which favours wave breaking. Firstly, this is because of the standard-bora-model conditions; for mountain waves the mean-state critical level, which appears in the standard bora model, presents a singularity and forces the onset of wave breaking. Furthermore, as mentioned earlier, Klemp and Durran (1987) showed that wave breaking may occur in the bora regardless of the presence of the mean-state critical level. This additionally means that episode 1, although not of the standard-bora-model type, is also characterized by wave breaking. Thus, the results obtained here overlap with the experience of modelling gust generation.

Considering the cessation of the quasi-periodic behaviour, the dependence on the appearance of the upper-tropospheric jet stream is evident. Although no conspicuous change in the strength of the bora occurs when the jet stream appears, the quasi-periodic pulsations vanish. Since the wave-breaking region is the generator of the pulsations, the disappearance of the pulsations should be related to the absence of wave breaking. Thus, it can be asserted that the jet stream acts on the dynamics of the bora in such a way that it diminishes low-level wave breaking. A similar effect of the jet stream has been recognized previously; Durran (2003b) states that the appearance of the upper-tropospheric jet stream prevents wave breaking in the troposphere and focuses it in the lower stratosphere. This is due to the fact that in the troposphere below the jet stream the increase in the cross-mountain wind speed with height causes weakening of the local nonlinearity, which impedes formation of wave breaking. However, above the tropopause wave breaking is enhanced with both reversed wind shear and the increase in the static stability. Furthermore, Clark *et al.* (2000) used a very high-resolution numerical simulation, together with detailed Doppler lidar and wind-profiler measurements, of a strong jet-stream episode of the Colorado downslope windstorm to document the absence of wave breaking in the troposphere and its occurrence in the stratosphere. That case was characterized by only intermittent reports of strong surface gusts.

In addition, from the inspection of the time-running spectra for all episodes (here shown only for episodes 1, 2 and 5) we can see that the alteration in the bora dynamics affects only the variance in the 3–11 minute range. The spectrum below 3 minutes remains unaffected. This part of the spectrum can probably be attributed to frictional effects (Richard *et al.* 1989) which are more or less the same regardless of alterations to the dynamics. However, the part between 3 and 11 minutes is highly dependent on the active windstorm dynamics, because the upstream structures encouraging wave breaking result in the addition of extra energy, while the jet stream appearance results in its decrease. This also agrees with previous studies where exact periods between 5 and 15 minutes were found to be produced by wave breaking (e.g. Scinocca and Peltier 1989; Clark *et al.* 1994). Now the claim that the jet stream diminishes wave breaking is further substantiated.

If we now state that the appearance of the jet stream causes the disappearance of low-level wave breaking, then a question justifiably arises: how is it possible that the bora flow remains at its full strength when there is no wave breaking, which should be its main generating mechanism? To answer that, let us turn to the thermal structure. Each case with a jet stream also has a low-level inversion layer. Thus it is possible that dynamical situation (iii) in favour of high downslope winds (see the Introduction) is responsible for the continuation of the bora. Klemp and Durran (1987) studied the nature of the bora flow in situations that prevent wave breaking: when the low-level nonlinearity is insufficient to produce breaking of waves, and when the inversion is located beneath the overturning level. They obtained hydraulic-like flow with very high wind speeds in the lee for inversion heights up to 3 km above the mountain crest. This means that the inversions in the Zagreb soundings that are located between 1 and 4 km (since the height of the mountain crest is approximately 1 km) could be responsible for hydraulic-like shooting flow in the lee. Figure 8 shows that the required inversions are present in all high-wind cases. Concerning the different behaviour of episode 9, where the appearance of the jet stream is related to the abatement of the bora itself (00 UTC 8 January), one would expect the absence of the inversion to be responsible for the decrease. However, the inversion is present even in this case, though it is rather weak particularly when compared to the following soundings (those from episode 10), which are also characterized by appearance of the jet stream. On the other hand, this case has the strongest jet stream from all inspected soundings, and it was hypothesized earlier that increasing upper-tropospheric winds may cause the cessation of the bora flow (Vučetić 1984). It is, therefore, not completely clear what mechanism or, to be more precise, its lack, is responsible for the bora attenuation in this case.

Especially interesting is the fact that the transition between the wave-breaking and inversion-generated bora flow may occur during an episode without being detectable from variations in the wind speed magnitude, but only in the spectral characteristics. The dynamics causing the transition still remains obscure. Furthermore, dominant periods of the pulsations have different values in different episodes. Also, several distinct periods within a single episode may occur (see Fig. 5). Specifically, it means that in the course of time first one period is dominant and then some other period becomes more pronounced. It seems that then the first one usually gets diminished, and we believe that certain changes in the dynamics should occur at that time. All these phenomena open the way to future investigations; these should be based on either sufficiently detailed measurements, especially of vertical profiles upstream and downstream of the mountain, or very detailed high-resolution numerical studies.

5. Conclusions

We performed a detailed spectral analysis of high-frequency wind speed data for ten bora episodes measured at Senj during December 2001 and January 2002, in order to gain better understanding of the behaviour of the bora gusts. Previous findings of the existence of 3–11 minute pulsations in the bora flow (e.g. Petkovšek 1987) have been confirmed. Also, the possibility of cessation and even reappearance of the pulsations in the course of a single bora episode has been shown. The connection between the behaviour of the quasi-periodic pulsations and the upstream tropospheric thermodynamical structure has been investigated. The existence of the pulsations has been related to weak cross-mountain upper-tropospheric wind speeds and, in most cases, the existence of the critical layer in the lower troposphere, i.e. the upstream bora layer height not exceeding few kilometres. On the other hand, the cessation of the pulsations has been ascribed to the appearance of the upper-tropospheric jet stream.

Given that wave breaking is the main mechanism responsible for the generation of the pulsations, it has been proposed that the jet stream influences the bora dynamics in such a way that it diminishes wave breaking. As the bora strength remains preserved when the pulsations disappear, it is the low-level inversion that takes over the role of the bora generator. These results are in good agreement with the theory, where it has been found that the main process responsible for the bora high winds is wave breaking, but also that the high-wind state may form without wave breaking provided that the low-level inversion is present (Klemp and Durran 1987). The shifting between the two bora mechanisms (wave breaking versus inversion layer) within a single episode still remains unclear, and its explanation would require a comprehensive experimental and modelling study. This remains a possibility and it could provide new understanding of the problem of the dynamics of the bora.

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