Near-ground turbulence of the Bora wind in summertime

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Abstract. Bora is a strong, temporally and spatially variable downslope wind that blows along the Eastern Adriatic Coast and many other dynamically similar places around the world. Bora mean velocity rarely exceeds 20 m/s, while its strong gusts create significant problems for engineering structures, traffic and agriculture. Previous meteorological and geophysical studies laid foundations on Bora large- and mesoscale motions, but further research is necessary to fully understand and resolve Bora turbulence in a form usable for engineers. In this study, unique high-frequency measurements, carried out simultaneously in three heights on a meteorological tower in the hinterland of the city of Split, Croatia, are analyzed for a single summertime Bora episode. Time histories and vertical profiles are studied for turbulence intensity, Reynolds shear stress and turbulence length scales in comparison with values recommended in major international wind engineering standards. Turbulence intensity and Reynolds shear stress proved to be not that sensitive to meandering of the mean wind velocity, as the observed values remain within the same range during the time record. This trend applies on mean wind velocities larger than 5 m/s, as for smaller velocities the spread of values increases considerably. Turbulence length scales are observed to increase with increasing mean wind velocity and vice versa. With increasing height from the ground, turbulence intensity and absolute Reynolds shear stress decrease, turbulence length scales increase, all in agreement with the atmospheric physics. However, while turbulence intensity, Reynolds shear stress and longitudinal turbulence length scales generally agree well with the values recommended in international standards for the respective terrain type,

turbulence length scales related to lateral and vertical velocity fluctuations are much larger than the standard values.

Keywords: Gusty Bora wind; Turbulence; Turbulence intensity; Reynolds shear stress; Turbulence length scales; Field measurements.

1. Introduction

The gusty Bora wind characteristics are quite unknown to the wind engineering community, thus preventing accurate prediction of Bora wind loads on structures and vehicles. While most of the previous Bora research is performed for the Adriatic Coast, this type of wind commonly blows in other world regions as well, such as Japan, Russia, Kurdistan, Iceland, Austria, Rocky Mountains in the Northern America, etc. (e.g. Jurčec 1981, Neiman et al. 1988, Ágústsson and Ólafsson 2007, Jackson et al. 2013) thus making the Bora research globally applicable.

Along the Eastern Croatian Coast, Bora blows from the North East across the mountain ranges, from Trieste to Dubrovnik and further South (e.g. Yoshino 1976, Makjanić 1978, Bajić 1988, 1989, Tutiš 1988, Vučetić 1991, Belušić and Klaić 2004, 2006). Generally, Bora is a very strong, commonly dry and always gusty wind, which significantly influences optimal functioning of transportation networks, the agriculture, local wind energy yield as well as the fatigue of energy structures (e.g. Kozmar et al. 2012a, 2012b, 2014, 2015). While previous geophysical and meteorological studies laid ground on the macro-and meso-scale features of the Bora, (Jurčec 1981, Smith 1987, Grubišić 2004, Grisogono and Belušić 2009), further work is necessary to fully elucidate Bora turbulence in a form usable for wind engineers.

Bora mean wind speed, usually between 5 m/s and 30 m/s, is not that significant to wind engineers as the Bora gusts that can sometimes reach velocities up to three or even five time the average wind speed (e.g. Petkovšek 1987, Belušić and Klaić 2004, 2006, Grisogono and Belušić 2009, Večenaj et al. 2010, Belušić et al. 2013). Spatially and temporally very variable, Bora is more common in winter when it can last from just a few hours up to several days (e.g. Jurčec 1981, Poje 1992, Enger and

Grisogono 1998, Jeromel et al. 2009). Due to its extreme spatial variability, a precise and strict definition of the Bora wind is not available (e.g. Poje 1992, Horvath et al. 2009, Večenaj et al. 2012). Nevertheless, a certain data series is considered to belong to Bora event if the recorded time series of the horizontal wind component has the azimuth from the first quadrant and remains persistent for at least three hours with the mean wind speed larger than 5 m/s and the standard deviation comparable to the mean value.

The occurrence of the long lasting Bora is commonly associated with a persistent cyclone over the Adriatic region or/and a high pressure centre over the Central or Eastern Europe, as the continental air is drawn by the cyclone from the lower troposphere across the mountains (e.g. Jurčec 1981, Heimann 2001, Belušić et al. 2013). Simultaneously, the air from the Pannonia Basin and the Central Europe is forced across the mountains towards the Adriatic by the anticyclone. A short lasting Bora can be triggered by the passage of the cold front across the Adriatic. Depending on the intensity and evolution of the cyclogenesis and its synchronization with the upper tropospheric flow, shallow or deep Bora may occur (e.g. Grisogono and Belušić 2009). Bora can be cyclonic, bringing clouds with high possibility for precipitation, anticyclonic, related to fair weather, and frontal (e.g. Jurčec and Visković 1994). The frequency of the Bora occurrence in the Eastern Adriatic decreases from North West to South East (e.g. Poje 1992), and its strength weakens seaward from the shore in a way that it is rarely stormy in the Western Adriatic (e.g. Enger and Grisogono 1998).

Development of advanced measuring techniques and numerical atmospheric models contributes to the progress of the Bora research, causing a change in basic understanding of the triggering system for a severe Bora. Originally, a katabatic-type perspective prevailed (e. g. Yoshino 1976, Jurčec 1981), while the issue with this approach was that simple katabatic flows are generally unable to continuously create mean wind velocities of around 20 m/s and larger that is characteristic to Bora. At this moment, a hydraulic theory of strong to severe Bora with orographic wave breaking is commonly accepted in the mesoscale community, at least for the North Eastern Adriatic coast (Smith 1987, Enger and Grisogono 1998, Grubišić 2004, Grisogono and Belušić 2009). It was previously reported that the strong Bora flow can be treated, to a very good approximation, as a nonlinear hydraulic flow, which

also means a lack of significant stratification effects (Klemp and Durran 1987, Smith 1987). A strong resonance between the flow and underlying terrain allows for the wave breaking phenomena to diminish stratification effects near the surface (e.g., Grisogono and Belušić 2009). Quasi-periodic behavior is a typical characteristic of downslope windstorm gusts (Petkovšek 1976, 1982, 1987, Rakovec 1987, Neiman et al. 1988). Belušić et al. (2004, 2006, 2007) showed that Bora pulsations usually emerge between 3 and 11 minutes. Due to the less complex orography with minor influence from the upwind mountains on the incoming flow, Bora has historically been more studied over the Northern Adriatic (e.g. Grisogono and Belušić 2009, Belušić et al. 2013).

Near surface Bora wind profile agrees well with the power-law and logarithmic-law approximations (Lepri et al. 2014). A decrease in the power-law exponent and aerodynamic surface roughness length, and an increase in friction velocity with increasing Bora wind velocity indicates a rural-like velocity profile for larger wind velocities and urban-like for smaller wind velocities. Due to strong mechanical mixing, Bora proved to be nearly neutrally thermally stratified. While for friction velocity and the power-law exponent the arithmetic mean and the median yield similar values independent on the averaging period, the more robust median proved to be more suitable when determining the aerodynamic surface roughness length.

In this study, detailed high-frequency Bora wind measurements carried out on a meteorological tower close to the city of Split, Croatia, at the Eastern Adriatic Coast, are analyzed to resolve some fundamental properties of the Bora turbulence. A particular focus is on the Bora turbulence intensity, Reynolds shear stress and turbulence length scales.

2. Methodology and the data

Turbulence intensity, as a measure of magnitude of turbulence intensity in x -, y - and z -direction in height z is respectively defined as provided in Simiu and Scanlan (1996),

$$I_u = \frac{\sqrt{\overline{u'^2(z)}}}{\bar{u}_z}, \quad I_v = \frac{\sqrt{\overline{v'^2(z)}}}{\bar{u}_z}, \quad I_w = \frac{\sqrt{\overline{w'^2(z)}}}{\bar{u}_z}, \quad (1)$$

by applying the Reynolds decomposition,

$$u(t) = \bar{u} + u'(z), \quad v(t) = \bar{v} + v'(z), \quad w(t) = \bar{w} + w'(z), \quad (2)$$

where $\bar{u}, \bar{v}, \bar{w}$ are time-averaged mean wind velocities in the longitudinal x -, lateral y - and vertical z - direction; z in subscript is the height, while u', v' and w' are the respective fluctuating wind velocity components.

Turbulent Reynolds shear stress represents a measure for transporting the retarding forces exerted on the wind near the Earth's surface. It is calculated by using the fluctuating velocity correlations $-\rho \overline{u'v'}, -\rho \overline{v'w'}, -\rho \overline{u'w'}$, where ρ is air density.

The length scale of turbulence represents a comparative measure of the average size of a wind gust (e.g. Holmes, 2007). The length scales of turbulence in x -direction related to u', v', w' fluctuations are calculated from the time scale of turbulence using autocorrelation functions and assuming the validity of the Taylor's frozen turbulence hypothesis (e.g. ESDU 74030 1976),

$$T_i = \int_0^{\infty} R_{ii}(\tau) d\tau. \quad (3)$$

Here, R_{ii} represents the autocorrelation function, τ represents incremental time lag and $i = u', v', w'$. Taylor's hypothesis of frozen turbulence implies that for mean wind speed $\bar{V}_z$ larger than the fluctuating wind velocity component along the x -axis, $u(t)$, the turbulence field can be considered to be frozen in space and convected past a point with the mean wind velocity $\bar{V}_z$. Assuming the validity of the Taylor's hypothesis of frozen turbulence, turbulence length scales for $i = u', v', w'$ components measured along the x -axis are defined as (e.g. ESDU 74030 1976),

$$^x L_i = T_i \cdot \bar{V}_z. \quad (4)$$

The measurements analyzed in this study were performed on Pometenno brdo, a location in the hinterland of the town of Split, Croatia (Fig 1a). The exact geographical coordinates of this measurement site are 43°36'28.9"N, 16°28'37.4"E with the elevation 618 m above the sea level. The main hill axis extends from North West to South East. The hill is less steep at the leeward side than on the windward side. In the vicinity of the measurement place there are a few crevices and sinkholes

126 several tens of meters deep. The vegetation around the tower consists mostly of brushwood and
 127 shrubbery not higher than 2 m. The location is easily accessible by several regional roads.

(a)

(b)

(c)

(d)

128 Fig. 1: (a) Geographic position of the measurement site Pometeno brdo: $43^{\circ}36'28.9''\text{N}$, $16^{\circ}28'37.4''\text{E}$). To the
 129 West and South is the Adriatic Sea. Lower left corner is the map of Europe with the position of Croatia. (b)
 130 Anemometer setup on the meteorological tower at Pometeno brdo, Croatia. (c) Topography of the measurement

site. A position of the meteorological tower is denoted with a cross. (d) Vegetation and surroundings of the meteorological tower.

In the time period between April 2010 and June 2011, Eastern, Northern and vertical wind velocity components as well as the ultrasonic temperature were measured using Windmaster Pro (Gill instruments) ultrasonic anemometers on a 60 m high meteorological tower at three height levels, i.e. 10 m, 20 m and 40 m (Fig. 1b). Each anemometer was mounted on one end of the 2 m long aluminum boom whose other end was fixed to the tower in such a way that the anemometers were facing the main Bora wind direction. The measurements were sampled at the frequency of 5 Hz and collected using Campbell Scientific data logger CR1000, while the whole system was solar powered.

An isolated summertime Bora wind event analyzed in this study lasted from July 24 to 27, 2010, in the overall duration of 62 h. During this particular Bora episode, the wind was long lasting and relatively strong, with mean hourly wind velocities larger than 15 m/s. During this episode, the lower troposphere was thermally neutrally stratified, Lepri et al. (2014). The weather conditions over most of Europe were largely influenced by low pressure weather systems. However, from the West side of the continent a ridge of high pressure strengthened causing sporadically stormy Bora gusts. The weather conditions on the ground in the area considered were mostly clear sky with good visibility, i.e. the typical Bora conditions (e.g. Grisogono and Belušić 2009). Minimal temperatures in the observed period were between 12 °C and 20 °C and maximal between 23 °C and 27 °C with relative humidity between 25 % and 60 %. The air pressure at the standard mean sea level was slightly reduced with values between 1005 mbar and 1010 mbar.

For this Bora event, turbulence intensity I_u , I_v , I_w , Reynolds shear stress components $-\overline{\rho u'v'}$, $-\overline{\rho v'w'}$, $-\overline{\rho u'w'}$ and turbulence length scales, xL_u , xL_v and xL_w are analyzed. The selected coordinate system is the one with the x -axis aligned along the mean wind direction. Since the anemometers used for the measurements have a specific coordinate system, with abscissa pointed Northwards and ordinate pointed Westwards, the raw data for the two horizontal velocity components are modified accordingly. Because the mean wind direction at 10 m height was $\approx 54^\circ$, at 20 m height

$\approx 51^\circ$ and $\approx 43^\circ$ at 40 m height, linearly interpolated value at the 25 m height (the middle height level between 10 m and 40 m) is 49° . Hence, the coordinate system is accordingly rotated for 221° counter clockwise.

Time-averaged wind velocity is calculated using the moving average approach. To test the sensitivity of Bora turbulence intensity, Reynolds shear stress and turbulence length scales on the choice of the time record length of the moving average, four different time-averaging periods are studied. There are some strong indications that for this particular episode the quasi-periodic Bora pulsations occur at the time period of about 8 min (Belušić et al. 2007, Horvath et al. 2012, Večenaj et al. 2010, 2012). It was also previously reported that the time period of 17 ± 3 min represents a suitable turbulence averaging scale (the scale which separates turbulence at small scales from the mean flows at large scales) for this Bora episode, (Magjarević et al. 2011, Večenaj 2012, Lepri et al. 2014). While the appropriate time averaging scale for this particular Bora episode is determined using the ogive approach (e.g. Oncley et al. 1996), other methods can be used for this purpose as well (e.g. Solari et al. 2015). To extend the analysis on this two dynamically important scales and to encompass all the relevant time/length scales, one shorter scale of 5 min, and one longer time scale of 20 min, are assessed as well. Fluctuating wind velocity components are analyzed in the following way. First, the respective time history of the running mean wind velocity is removed from the original time histories, so the velocities are fluctuating around zero wind velocity after performing this action. By normalizing the velocities and velocity correlations in those modified time histories (fluctuating around zero wind velocity) with the respective running mean wind velocity, final values for turbulence intensity and Reynolds shear stress are obtained. This way of analysis is performed as the long-lasting meandering motions of the Bora wind are not considered as a part of the Bora turbulence, so those long-lasting motions are removed in order to allow for unbiased analysis of the Bora turbulence. The velocity time history for each wind component consists of more than 10^6 data points. Figure 2 shows original data for all three velocity components in the modified coordinate system with x -axis aligned along the mean Bora direction with superimposed mean wind velocities averaged over the time scale of 17 min.

Fig. 2: Original data with superimposed mean wind velocities averaged over the time scale of 17 min at 10 m height (left), 20 m (middle) and 40 m (right) at the Pometeno brdo tower; longitudinal (u), lateral (v) and vertical (w) velocity components, up, middle and down, respectively, recorded from 24 to 27 July 2010.

Turbulence intensity is calculated according to Eq. (1), while the fluctuating wind velocity components are obtained from Eq. (2) using the method described above. The fluctuating wind velocity components are averaged using the same averaging period as for the mean wind velocities and then normalized with the corresponding mean wind velocity value for each time record. The same procedure is applied for all three wind velocity components, for all four averaging periods and for each height level separately.

The Reynolds shear stress components $-\overline{\rho u'v'}$, $-\overline{\rho v'w'}$, $-\overline{\rho u'w'}$ are calculated by applying the moving average on the product of the fluctuating wind velocity values for each height level separately. Four previously specified averaging periods are used in further calculations. The length scales of turbulence in x -direction related to u' , v' and w' fluctuating velocity component are calculated using Eq. (3) and Eq. (4). In particular, autocorrelation functions are calculated on point by point sliding blocks of a length that corresponds to the length of the time-averaging period that is used (5, 8, 17 or 20 min). For each block, obtained values of the autocorrelation function are numerically integrated providing the value of the corresponding time scale of turbulence. By multiplying this scale with the corresponding mean wind velocity, the length scale of turbulence is obtained. Median values and

arithmetic mean values of the observed parameters are analyzed, because for this particular Bora event considerable differences between the median and arithmetic mean values are previously reported for the aerodynamic surface roughness length (Lepri et al. 2014).

3. Results and discussion

In this section, the obtained values for turbulence intensity in x -, y - and z -direction, three components of Reynolds shear stress and length scales of turbulence in x -direction related to the u' , v' and w' fluctuating velocity components are presented.

In Tables 1 - 4 summary statistics for turbulence intensity in x -, y - and z -directions for the four time averaging periods at 10 m, 20 m and 40 m height is reported.

Table 1: Summary statistics for turbulence intensity on 10 m, 20 m and 40 m height for averaging period of 5 min.

Parameter	Height								
	10 m	10m	10m	20 m	20 m	20 m	40 m	40 m	40 m
	I_u	I_v	I_w	I_u	I_v	I_w	I_u	I_v	I_w
Median (-)	0.21	0.16	0.09	0.15	0.14	0.08	0.13	0.12	0.07
Arithmetic mean (-)	0.21	0.18	0.10	0.16	0.15	0.08	0.16	0.15	0.08
Min. value (-)	0.10	0.09	0.06	0.05	0.06	0.03	0.04	0.03	0.02
Max. value (-)	1.75	1.48	0.53	1.70	1.53	0.58	2.00	1.55	0.59
Standard deviation (-)	0.06	0.07	0.03	0.06	0.06	0.03	0.06	0.06	0.04

Table 2: Summary statistics for turbulence intensity on 10 m, 20 m and 40 m height for averaging period of 8 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	I_u	I_v	I_w	I_u	I_v	I_w	I_u	I_v	I_w
Median (-)	0.21	0.17	0.09	0.15	0.14	0.08	0.13	0.13	0.07
Arithmetic mean (-)	0.22	0.18	0.10	0.16	0.16	0.09	0.15	0.14	0.08
Min. value (-)	0.12	0.10	0.06	0.07	0.08	0.03	0.05	0.04	0.03
Max. value (-)	1.02	0.81	0.28	0.98	0.77	0.27	1.06	0.71	0.29
Standard deviation (-)	0.06	0.06	0.02	0.06	0.06	0.03	0.06	0.06	0.03

Table 3: Summary statistics for turbulence intensity on 10 m, 20 m and 40 m height for averaging period of 17 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	I_u	I_v	I_w	I_u	I_v	I_w	I_u	I_v	I_w
Median (-)	0.22	0.17	0.09	0.16	0.15	0.08	0.14	0.14	0.07
Arithmetic mean (-)	0.23	0.19	0.10	0.17	0.17	0.09	0.15	0.15	0.08
Min. value (-)	0.14	0.12	0.06	0.09	0.09	0.04	0.06	0.06	0.03
Max. value (-)	0.76	0.70	0.22	0.70	0.66	0.21	0.69	0.64	0.23
Standard deviation (-)	0.05	0.07	0.02	0.05	0.06	0.03	0.05	0.06	0.03

Table 4: Summary statistics for turbulence intensity on 10 m, 20 m and 40 m height for averaging period of 20 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	I_u	I_v	I_w	I_u	I_v	I_w	I_u	I_v	I_w
Median (-)	0.22	0.17	0.09	0.16	0.15	0.08	0.14	0.14	0.07
Arithmetic mean (-)	0.23	0.19	0.10	0.17	0.17	0.09	0.16	0.15	0.08
Min. value (-)	0.14	0.12	0.06	0.09	0.09	0.04	0.06	0.06	0.03
Max. value (-)	0.67	0.65	0.20	0.62	0.63	0.20	0.61	0.60	0.23
Standard deviation (-)	0.05	0.07	0.02	0.05	0.06	0.03	0.05	0.06	0.03

For different averaging periods median values of turbulence intensity in x -direction are between 0.21 and 0.22 on 10 m height, between 0.15 and 0.16 on 20 m height and between 0.13 and 0.14 on 40 m height. Medians of turbulence intensity values in y -direction for different averaging periods are between 0.16 and 0.17 on 10 m height, between 0.14 and 0.15 on 20 m height and between 0.12 and 0.14 on 40 m height, while medians of turbulence intensity values in z -direction vary between 0.09 on 10 m height, 0.08 on 20 m height and 0.07 on 40 m height. From Tables 1-4 it can be observed that the median values agree well with the corresponding arithmetic mean values, while it can be noticed that both the median and the arithmetic mean values for all three components slightly increase for longer averaging periods. The standard deviation, which defines data variations from the average or expected value (e.g. Wilks 1995), with the observed values between 0.02 and 0.07, for all intensity components and for all four averaging periods, indicates that the data differs considerably from the corresponding average value. Significant variations of the Bora wind higher-order statistical moments, corresponding to the Bora characteristic gustiness (e.g. Grisogono and Belušić 2009, Kozmar et al. 2012a, Večenaj et al. 2012), are the typical properties of the general Bora flows (Poje 1992, Belušić et al. 2006, 2007).

255 In order to investigate the dependence of I_u , I_v and I_w on the average wind velocity, the time series for
 256 the turbulence intensity components for time averaging period 17 min at all three height levels are
 257 presented in Figs. 3 – 5. The time series for other three time averaging periods indicate the same trends
 258 and are therefore not reported.

259
 260 Fig. 3: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 10 m
 261 height; time series of (b) turbulence intensity in x -direction (c) turbulence intensity in y -direction (d) turbulence
 262 intensity in z -direction for averaging period of 17 min at 10 m height.

Fig. 4: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 20 m height; time series of (b) turbulence intensity in x -direction (c) turbulence intensity in y -direction (d) turbulence intensity in z -direction for averaging period of 17 min at 20 m height.

Fig. 5: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 40 m height; time series of (b) turbulence intensity in x -direction (c) turbulence intensity in y -direction (d) turbulence intensity in z -direction for averaging period of 17 min at 40 m height.

These plots confirm the features already determined by the statistical methods used (Tables 1-4). The vertical turbulence intensity component is in average two times smaller than the two horizontal components for all averaging periods and on all height levels. Another interesting characteristic is that for the mean wind velocities larger than ~ 5 m/s the turbulence intensity components remain nearly constant during the time record, i.e. they are not that strongly dependent on the varying 17-min running mean wind velocity. In particular, during the period with mean wind velocities larger than 5 m/s, the average wind velocity deviation is around 30 % from the the mean wind velocity calculated through the entire time record of 62 h. At the same time, the respective average deviation of I_u , I_v and I_w is between 14 % and 24 % with respect to the corresponding mean turbulent intensity component calculated through the entire time record, 62 h. No clear day-to-night trends can be observed in the behaviour of the observed turbulence intensity components. Regarding the wind speeds less than 5

m/s, these may be related to either Bora rapid and short transience, or to a totally different, thermally driven, katabatic flow type (Grisogono and Belušić 2009, Grisogono et al. 2015).

Bora turbulence intensities, I_u , I_v and I_w do not completely agree with the equation,

$$I_u : I_v : I_w = 1 : 0.75 : 0.5, \quad (5)$$

suggested by Counihan (1975), nor with the equation proposed by Holmes (2007),

$$I_u : I_v : I_w = 1 : 0.88 : 0.55, \quad (6)$$

both originally provided for the atmospheric boundary layer (ABL). In particular, Table 5 shows turbulence intensity ratios obtained for this Bora event. Although it can be noticed that the ratio between I_w and I_u agrees well with Eqs. (5) and (6), on the other hand, the values for I_v and I_u are quite similar, particularly higher above the ground. This indicates that lateral pulsations of the Bora flow are stronger if compared to the longitudinal velocity fluctuations typical for the usual ABL. The ratios between the various turbulence intensity components for the time averaging periods of 5 min, 8 min and 20 min are not reported (Večenaj 2012), as they are basically the same as for the time averaging period of 17 min.

Table 5: Turbulence intensity ratios for the time averaging period of 17 min on the three height levels.

Height	I_v/I_u	I_w/I_u
10 m	0.84	0.45
20 m	0.95	0.50
40 m	1.00	0.50

To additionally investigate the trends in turbulence intensity with increasing height, vertical I_u , I_v , I_w profiles for the time averaging period of 17 min are presented in Fig. 6. The trends observed in respective vertical turbulence intensity profiles for other time-averaging periods are basically the same. The data is compared with international standards ESDU 85020 (1985), ISO 4354 (1997), EN 1991 Eurocode 1 (2005), ASCE 7-05 (2006) and AIJ (2006).

Fig 6: Vertical profiles of observed turbulence intensity for the averaging period of 17 min in the (a) x -, (b) y - and (c) z -direction calculated through the entire time record and compared with the values in international standards with the tolerance range of $\pm 20\%$. Legend: star is average turbulence intensity, grey solid line is ESDU 85020 (1985) for $z_0=0.03$ m, black solid line is ISO 4354 (1997) and EN 1991 Eurocode 1 (2005), black dotted line is ASCE 7-05 (2006), grey dotted line is AIJ (2006).

The values reported as stars in Fig. 6 represent average values calculated through the entire time record, meaning one value in each height for the entire recording period. It can be observed that for this particular Bora episode the obtained values for all three intensity components decrease with increasing height, in agreement with atmospheric physics (e.g. Stull, 1988). I_u and I_w agree well with the values proposed in ESDU 85020 (1985) for surface roughness length $z_0 = 0.03$ m, which corresponds to an open country with a few trees and hedges and isolated buildings. This type of terrain is a good description of the terrain characteristics at the measuring site Pometeno brdo. The values obtained for I_v are a bit larger than the recommended values. The values obtained for I_u agree reasonably well with the values recommended in ISO 4354 (1997), EN 1991 Eurocode 1 (2005), AIJ (2006) and ASCE 7-05 (2006) as well.

In Tables 6–9 the statistical parameters for Reynolds shear stress are presented.

Table 6: Summary statistics for Reynolds shear stress on 10 m, 20 m and 40 m height for averaging period of 5 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	$\frac{-\overline{u'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{10}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{20}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{40}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{40}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{40}}$
Median (-)	0.005	0.002	0.002	0.002	-0.001	0.004	0.002	-0.000	0.002
Arithmetic mean (-)	0.006	0.003	0.003	0.003	-0.000	0.005	0.002	0.000	0.003
Min. value (-)	-0.073	-0.123	-0.010	-0.044	-0.071	-0.006	-0.147	-0.073	-0.014
Max. value (-)	0.057	1.673	0.173	0.129	1.597	0.192	0.197	1.922	0.143
Standard deviation (-)	0.004	0.035	0.005	0.004	0.031	0.006	0.005	0.033	0.006

Table 7: Summary statistics for Reynolds shear stress on 10 m, 20 m and 40 m height for averaging period of 8 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	$\frac{-\overline{u'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{10}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{20}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{40}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{40}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{40}}$
Median (-)	0.006	0.003	0.002	0.002	-0.001	0.004	0.002	-0.000	0.002
Arithmetic mean (-)	0.006	0.003	0.003	0.003	-0.000	0.005	0.002	0.000	0.003
Min. value (-)	-0.011	-0.082	-0.009	-0.017	-0.050	-0.007	-0.028	-0.051	-0.011
Max. value (-)	0.035	0.516	0.044	0.063	0.461	0.047	0.056	0.437	0.054
Standard deviation (-)	0.003	0.020	0.003	0.003	0.017	0.004	0.003	0.016	0.005

Table 8: Summary statistics for Reynolds shear stress on 10 m, 20 m and 40 m height for averaging period of 17 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	$\frac{-\overline{u'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{10}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{20}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{40}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{40}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{40}}$
Median (-)	0.006	0.004	0.002	0.003	0.000	0.004	0.002	0.000	0.002
Arithmetic mean (-)	0.006	0.004	0.003	0.003	0.001	0.005	0.002	0.001	0.003
Min. value (-)	-0.000	-0.039	-0.001	-0.013	-0.032	-0.003	-0.022	-0.045	-0.007
Max. value (-)	0.024	0.297	0.029	0.023	0.269	0.035	0.022	0.235	0.045
Standard deviation (-)	0.003	0.017	0.003	0.003	0.015	0.004	0.003	0.013	0.004

336

337 Table 9: Summary statistics for Reynolds shear stress on 10 m, 20 m and 40 m height for averaging period of 20
338 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	$\frac{-\overline{u'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{10}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{10}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{20}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{20}}$	$\frac{-\overline{u'w'}}{\overline{u}^2_{40}}$	$\frac{-\overline{u'v'}}{\overline{u}^2_{40}}$	$\frac{-\overline{v'w'}}{\overline{u}^2_{40}}$
Median (-)	0.006	0.004	0.002	0.003	0.000	0.004	0.002	0.000	0.002
Arithmetic mean (-)	0.006	0.005	0.003	0.003	0.001	0.005	0.002	0.001	0.003
Min. value (-)	-0.004	-0.042	-0.000	-0.014	-0.038	-0.003	-0.022	-0.042	-0.007
Max. value (-)	0.025	0.235	0.028	0.022	0.210	0.032	0.023	0.177	0.037
Standard deviation (-)	0.003	0.015	0.003	0.003	0.013	0.004	0.003	0.010	0.004

339

340 It can be observed that the median values for the dominant turbulent Reynolds shear stress component
341 (since $\rho \approx \text{const}$ here) $-\overline{u'w'}$ normalized with the respective wind velocity in mean (x) direction range
342 between 0.005 and 0.006 at 10 m height, between 0.002 and 0.003 at 20 m height and around 0.002
343 at 40 m height. The median values for the normalized turbulent Reynolds stress component $-\overline{u'v'}$ range
344 between 0.002 and 0.004 at 10 m height, between -0.001 and 0.000 at 20 m height and around 0.000 at
345 40 m height. The median values for the normalized $-\overline{v'w'}$ turbulent Reynolds stress component are
346 scattered around 0.002 at the 10 m height, 0.004 at 20 m height and 0.002 at 40 m height. For all three

turbulent Reynolds shear stress components it can be noticed that the median value and the arithmetic mean value agree well. The normalized $-\overline{u'w'}$ and $-\overline{u'v'}$ components decrease with height. The standard deviations, which define data variations for the normalized $-\overline{u'w'}$ and $-\overline{v'w'}$ components, with the observed values between 0.003 and 0.006 for all four averaging periods, indicate that the data differ moderately from the corresponding average value. At the same time the standard deviations for the normalized $-\overline{u'v'}$ component are significantly larger, with values ranging from 0.010 to 0.035, indicating a larger dispersion in comparison with two other Reynolds shear stress components.

To analyze the Reynolds shear stress dependence on the average wind velocity, the respective time series for the averaging period of 17 min are presented in Figs. 7 - 9. The time series for the averaging time periods of 5 min, 8 min and 20 min are not reported because the trends are basically the same.

Fig. 7: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 10 m height; time series of the calculated Reynolds shear stress components (b) $-\overline{u'w'}$, (c) $-\overline{u'v'}$, (d) $-\overline{v'w'}$ all normalized with the mean wind velocity in the main (x) wind direction at 10 m height for the time averaging period of 17 min.

Fig. 8: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 20 m height; time series of the calculated Reynolds shear stress components (b) $-\overline{u'w'}$, (c) $-\overline{u'v'}$, (d) $-\overline{v'w'}$ all normalized with mean wind velocity in the main (x) wind direction at 20 m height for the time averaging period of 17 min.

Fig. 9: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 40 m height; time series of calculated Reynolds shear stress components (b) $-\overline{u'w'}$, (c) $-\overline{u'v'}$, (d) $-\overline{v'w'}$ all normalized with mean wind velocity in the main (x) wind direction at 40 m height for the time averaging period of 17 min.

The graphical representation of the three Reynolds shear stress components confirms the statistics presented in Tables 6 - 9. In particular, the $-\overline{u'w'}$ component is the strongest one, while the $-\overline{u'v'}$ component shows the largest dispersion of the data. Similarly as for the turbulence intensity, the Reynolds shear stress components on all three heights remain nearly constant during the time record for the mean wind velocities larger than ~ 5 m/s. The trends remain the same during the day and the night.

Furthermore, the vertical profiles of the Reynolds shear stress components normalized with the mean wind velocity at the respective height for the averaging period of 17 min are presented in Fig. 10. The trends in vertical profiles of the Reynolds shear stress components for the other time averaging periods are the same as those reported in Fig. 10 and therefore are not shown.

Fig. 10: Vertical profiles of the (a) $-\overline{u'w'}$, (b) $-\overline{u'v'}$, (c) $-\overline{v'w'}$ Reynolds shear stress components for the averaging period of 17 min calculated through the entire time record and normalized using the 17 min average wind velocity in the main (x) wind direction at the corresponding height for each height level.

Vertical profiles of the Reynolds shear stress indicate decreasing values with increasing height for the $-\overline{u'w'}$ and $-\overline{u'v'}$ components. Nearly identical values for the $-\overline{u'w'}$ component at 20 m and 40 m height indicate a likely existence of the Prandtl constant-flux layer. At the same time, an interesting

and unexpected behavior can be observed for the $-\overline{v'w'}$ component at 20 m height indicating a strong momentum exchange between the lateral and vertical velocity fluctuations. This is possibly due to the very local characteristics (e.g. surface roughness elements) of the terrain surrounding the meteorological tower, which effect was previously reported in Babić et al. (2015) as well. A comparison of the observed $\overline{u'w'}$ component normalized with respective variances and the ESDU 85020 (1985) data provided for $z_0=0.03$ m with the tolerance range $\pm 20\%$ is reported in Fig. 11. The measured value is averaged during the entire time record, i.e. one value at each height for the entire time record. It can be noticed that the values agree well with the values recommended in the ESDU 85020 (1985) standard for open country with a few trees and hedges and isolated buildings.

Fig. 11: Reynolds shear stress profile compared with the ESDU 85020 (1985) data provided for $z_0=0.03$ m with tolerance range $\pm 20\%$. Legend: star is average observed $\overline{u'w'}/\sigma_u \sigma_w$, grey solid line is ESDU 85020 (1985).

The turbulence length scales in x -direction related to u' , v' and w' components are studied as well. First the applicability of Taylor's hypothesis of frozen turbulence to our data needs to be confirmed. Criterion of the applicability is that the ratio between the standard deviation of mean horizontal wind velocity and the mean horizontal wind velocity needs to be less than 0.5 (e.g. Stull, 1988). The analysis of the measured data comply with the requirements, and the validity of Taylor's hypothesis of frozen turbulence on all three height levels is confirmed. Therefore, Eq. (3) and (4) are used to

calculate turbulence length scales. Summary statistics of the obtained values for the four time averaging periods at 10 m, 20 m and 40 m height is provided in Tables 10 - 13.

Table 10: Summary statistics for the xL_u , xL_v and xL_w turbulence length scales for the time averaging period of 5 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20m	40 m	40 m	40 m
	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w
Median (m)	97	61	29	124	97	51	165	143	78
Arithmetic mean (m)	97	66	30	125	105	55	159	143	82
Min. value (m)	28	21	8	28	20	16	32	34	21
Max. value (m)	222	168	77	272	243	163	308	306	192
Standard deviation (m)	34	24	10	45	43	21	56	53	27

Table 11: Summary statistics for the xL_u , xL_v and xL_w turbulence length scales for the time averaging period of 8 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40m
	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w
Median (m)	103	65	30	134	105	53	176	156	82
Arithmetic mean (m)	103	70	31	132	112	58	166	152	85
Min. value (m)	35	26	10	41	28	20	42	39	27
Max. value (m)	215	164	73	264	245	154	302	306	190
Standard deviation (m)	34	23	9	45	44	20	57	55	26

Table 12: Summary statistics for the xL_u , xL_v and xL_w turbulence length scales for the time averaging period of 17 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w
Median (m)	112	70	32	143	114	55	183	166	87
Arithmetic mean (m)	109	75	32	141	120	60	174	161	88
Min. value (m)	39	35	12	47	45	25	48	50	34
Max. value (m)	192	146	61	246	240	141	295	280	175
Standard deviation (m)	34	22	8	46	43	18	57	55	25

Table 13: Summary statistics for the xL_u , xL_v and xL_w turbulence length scales for the time averaging period of 20 min.

Parameter	Height								
	10 m	10 m	10 m	20 m	20 m	20 m	40 m	40 m	40 m
	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w	xL_u	xL_v	xL_w
Median (m)	113	71	32	145	115	56	184	169	88
Arithmetic mean (m)	110	76	32	142	121	60	176	163	89
Min. value (m)	43	36	13	50	48	26	51	52	37
Max. value (m)	193	146	59	251	244	135	297	281	173
Standard deviation (m)	34	22	8	46	43	18	57	55	24

As for turbulence intensity and Reynolds shear stress, the median and arithmetic mean values of turbulence length scales remain nearly the same for different averaging times. The median values obtained for the xL_u component range between 97 m and 113 m at 10 m height, between 124 m to 145 m at 20 m height and between 165 m and 184 m at 40 m height; the median values of xL_v range between 61 m and 71 m at 10 m height, between 97 m and 115 m at 20 height and between 143 m and

169 m at 40 m height; the median values of xL_w range between 29 m and 32 m at the lowest height level, between 51 m and 56 m at the middle height level and between 78 m and 88 m at the highest height level. Standard deviation for the turbulence length scales, which is approximately 30% of the respective measured value, suggests moderate dispersion of the obtained data.

To investigate the dependence of turbulence length scales on the average wind velocity, the time series of turbulence length scales are presented in Figs. 12 - 14 for the averaging period of 17 min. The trends in the respective time series for other averaging periods are the same.

Fig. 12: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 10 m height and time series of the (b) xL_u , (c) xL_v and (d) xL_w turbulence length scales for averaging time 17 min.

Fig. 13: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 20 m height and time series of the (b) xL_u , (c) xL_v and (d) xL_w turbulence length scales for averaging time 17 min.

Fig. 14: (a) Mean wind velocity in the main (x) wind direction averaged over the time scale of 17 min at 40 m height and time series of the (b) xL_u , (c) xL_v and (d) xL_w turbulence length scales for averaging time 17 min.

The time series of xL_u , xL_v and xL_w in Figs. 12 - 14 confirm the data obtained by statistical analysis, while an increase in the xL_u , xL_v and xL_w values with increasing mean wind velocity and vice versa can be noticed. There are no day to night trends.

Moreover, to investigate vertical variations of turbulence length scales, vertical profile of the observed parameters for the time averaging period of 17 min is presented in Fig 15. The vertical profiles for the other three time averaging periods are not reported because the trends are basically the same.

Fig 15: Vertical profiles of turbulence length scales (a) xL_u , (b) xL_v and (c) xL_w component for the averaging time 17 min calculated through the entire time record compared with the values in international standards with tolerance range of $\pm 30\%$. Legend: star is observed turbulence length scale, grey solid line is ESDU 85020 (1985) with $z_0=0.03$ m, black solid line is EN 1991 Eurocode 1 (2005), black dotted line is ASCE 7-05 (2006).

The values reported as stars in Fig. 15 represent the average values calculated through the entire time record, meaning one value in each height for the entire recording period. It can be observed that for this particular Bora episode, turbulence length scales increase with height, which is in agreement with atmospheric physics (e.g. Stull, 1988) and previous studies (e.g. Večenaj et al. 2010, 2011). In comparison with the international standards, it can be noticed that xL_u is in good agreement with the international standards ASCE 7-05 (2006), EN 1991 Eurocode 1 (2005) and ESDU 85020 (1985). The other two measured components, xL_v and xL_w , are considerably larger compared to the values predicted in ESDU 85020 (1985) for $z_0=0.03$ m. This is likely due to plausible terrain-induced boundary-layer flow separation, recirculation and reattachment phenomena that is to be further investigated in more detail in the future.

4. Conclusions

Field measurements are carried out on the meteorological tower close to the city of Split, Croatia to further elucidate the Bora wind turbulence near the ground. These unique three-level high-frequency measurements focus on the analysis of turbulence intensity, Reynolds shear stress and turbulence length scales for one summertime Bora wind episode in comparison with the values in major international wind engineering standards. This is for the first time that the Bora Reynolds stress is assessed directly from a suitable data set ever. Turbulence intensity and Reynolds shear stress are not very sensitive to changes in the mean wind velocity, as the observed values remain within the same range during the time record. This behavior applies on mean wind velocities larger than 5 m/s, while for smaller velocities the spread of values increases considerably. Turbulence length scales increase with increasing mean wind velocity and vice versa. With increasing height from the ground, turbulence intensity and absolute Reynolds shear stress decrease, while turbulence length scales increase. This is in agreement with characteristics of the standard ABL. However, while turbulence intensity, Reynolds shear stress and longitudinal turbulence length scales generally agree well with the values recommended in international standards for the respective terrain type, turbulence length scales related to the lateral and vertical velocity fluctuations are much larger than the standard values. The trends observed are not influenced by the choice of the time averaging period; there are no day to night trends, while the median and arithmetic mean values are nearly the same. In order to understand the real importance of the Bora wind characterization from the engineering point of view, further work is still required with respect to Bora turbulence for other terrain types, seasons and elevations from the ground, as well as the extreme value distributions in comparison with cyclonic events.

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