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Wind measurements in Senj – underestimation of true bora flows

1. Introduction

It is well known that the strongest and most frequent bora over the Croatian coast of the Adriatic Sea is found in the region of Senj (Figure 1) (e.g., Yoshino, 1976; Makjanić, 1978; Vučetić, 1991; Orlić et al., 1994; Penzar et al., 2001; Grubišić, 2004:, Dorman et al., 2006). According to field measurements (Yoshino, 1976), the strongest winds appear in the mountainous areas northeast of Senj, between the Alan and the Vratnik Pass (Figure 2). An investigation of the wind-shaped trees in the area (Figure 3) was performed to estimate the speed and direction of the prevailing winter winds (Yoshino, 1976). It re-

Figure 1. During the bora wind, the sea surface has a typical appearance. Bora tears up wave crests which bubble up like a boiling water, spraying small particles of foam and water into air. Thus, visibility above the sea is reduced. This photo was taken in Senj during severe bora on 17 November 2007. According to MHS (2007), during this episode wind gusts were occasionally of hurricane strength (wind speeds over 40 ms^{-1}). (Photo by Damir Senčar, copyright by Hina.)

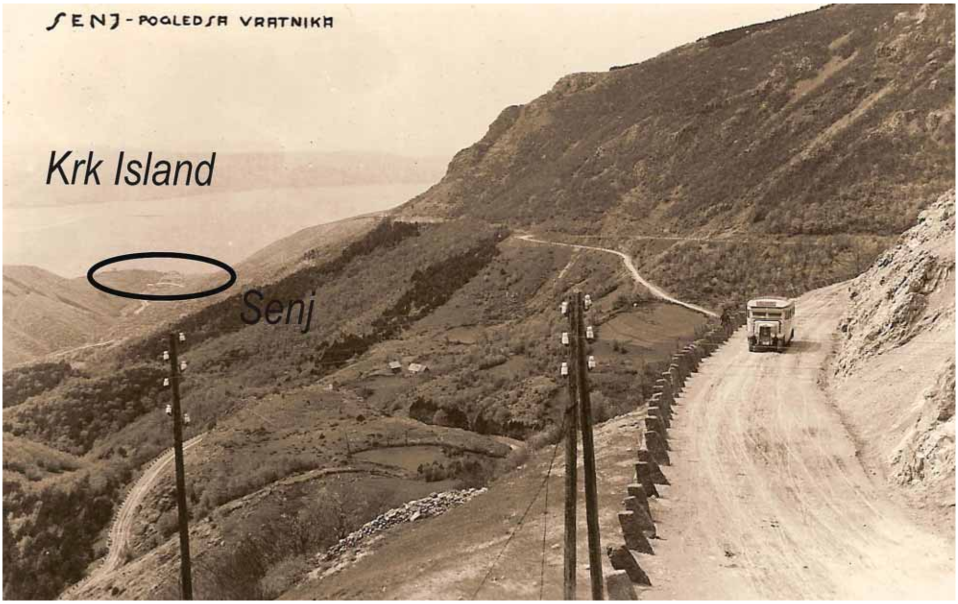

Figure 2. Old postcard shows the northern portion of the Vratnik Pass (698 m) looking toward the town of Senj, and further away, the Island of Krk. Due to the downwind position, the climate of Senj is strongly affected by bora.

vealed that the strongest ENE winds, which blow out of the pass, hit the southern part of the Krk Island, then turn gradually into NNE winds, and finally reach the Lošinj Island. They thus define the strongest bora region as that at the Adriatic coast, extending as far as 50–60 km inland. Consequently, a sharp contrast between the windward (bare) and leeward slopes (with vegetation) of islands is seen (Figures 3 and 4).

Since bora affects human activities (particularly traffic), induces rather complex responses on the Adriatic Sea (e.g., Orlić et al., 1994; Beg Paklar et al., 2001; Pasarić and Orlić, 2004) and occasionally causes some specific phenomena (Figures 4 and 5), it is the primary area of study for a number of scientists. (For a comprehensive review of recent findings, see Grisogono and Belušić (2009)).

Thus, wind measurements in the Senj region are of the utmost importance. Nevertheless, several modeling studies point to the underestimation of wind speeds measured operationally at the Senj measuring site (44.99°N, 14.90°E, 2 m above the mean sea level (ASL)) during bora flow (e.g., Klaić et al. 2003; Belušić and Klaić, 2004; Gohm et al., 2008). These motivated us to compare operationally measured winds with special measurements data that

Figure 3. Due to frequent bora winds, trees at the leeward slopes in the greater Senj area are wind-shaped. The windward side of the Krk Island (left) is bare. The photo was taken on a calm day in August 2009, a few kilometers north of Senj. (Photo by ZBK.)

were available for two winter months. Here we show that true bora winds in Senj are stronger than those reported from operational measurements.

2. Measuring sites and wind measurements

Figure 6 shows the positions of measuring sites. Site 1 belongs to the network of main meteorological stations operated by Meteorological and Hydrological Service of Croatia (MHS) (http://vrijeme.hr/aktpod_e.php?id=karta&param=GMP). It routinely provides hourly meteorological data. A cup anemometer is placed on the 10 m high mast located in the flat grassy backyard of the MHS premises. As seen from the lowermost two photos, site is surrounded by nearby houses and trees.

Special wind measurements were performed during the two-month winter period (1 December 2001–31 January 2002), i.e., during the season generally

Figure 4. On 5 September 2009, bora over the northern Adriatic induced the onset of Langmuir cells (e.g., Evans and Taylor, 1980), tubes of rotating water with the axes aligned roughly with the wind. Adjacent tubes rotate in opposite directions. At the water surface, parallel lines of foam, seaweed or other debris are seen. Photo is taken a few km north of Senj. Zečevo islet and further away a bare, windward side of the Island of Krk is seen (photo by ZBK).

favorable for the strongest bora occurrence (e.g., Vučetić, 1991). A Micro-m-asta cup anemometer was placed on the roof of a city tower, at the height of 15 m ASL (13 m above ground; Belušić et al., 2006), next to the sea (uppermost photo in Figure 6). Wind measurements were performed at the resolution of 1 s.

3. Results and conclusion

Figure 7 shows that the differences between hourly mean wind speeds recorded at two measuring sites (v2–v1) generally increase with the increase of the wind speed. Thus, for weak winds (speeds at site 2 between 0 and 5 m s^{-1}), wind speeds measured at the operational site were on average 0.7 m s^{-1} weaker than the speeds measured at site 2, while for strong winds (speeds at site 2 over 15 m s^{-1}), wind speeds at site 2 were on the average 6.8 m s^{-1} higher compared to site 1. Minimum absolute differences |v2–v1| varied between 0.0

m s^{-1} (weak winds) and 2.4 m s^{-1} (strong winds), while corresponding figures for maximum differences (v2–v1) were 4.1 and 15.0 m s^{-1}, respectively.

Figure 8 shows average differences between the hourly mean wind speeds measured at the two sites (v2–v1) with respect to the wind direction recorded at site 2. It clearly illustrates that discrepancies between the two sites are the largest for the northeastern quadrant, i.e., for the bora directions (note that due to the geometry of Vratnik Pass, direction of bora in Senj is predominately east-northeastern). During the investigated period, which according to Belušić et al. (2006) was characterized by a number of strong bora episodes, wind speeds at site 2 were on average 2.4, 2.4 and 0.9 m s^{-1} higher than speeds at site 1 for the northeastern, eastern and northern winds, respectively. Simultaneously, the smallest discrepancies are found for southwestern and western winds (around 0.2 m s^{-1}), while for sirocco directions they are on the average about 0.5 m s^{-1}.

To some extent differences between wind speeds at sites 1 and 2, with speeds at site 2 on the average higher than at site 1 for all eight main directions and for all wind speed classes, may be attributed to the difference in anemometers' altitudes. Thus, somewhat higher speeds are expected at 13 m (Site

Figure 5. A large stationary cumulus cloud (rotor) (e.g., Belušić et al., 2007; Gohm et al., 2007; Grubišić and Orlić, 2007; Orlić, 2007) observed from Vrataruša (approximately 5 km north-northeast of Senj) on 6 August 2008. Picture shows a view in the bora's direction. The rotor is located behind a 600 m high hill top, above the slope that is adjacent to the sea. Upwind of the rotor, smaller fragments of cumulus clouds are found. (Photo by ZBK.)

Figure 6. The measuring sites in Senj. The operational site is denoted by (1). Two lowermost photos show views approximately from the northwest (second from below) and north (lowermost photo), respectively. Site with special wind measurements is denoted by (2). Dashed arrow shows approximate direction of bora flow (i.e., orientation of the Vratnik Pass). (Photos by ZBK.)

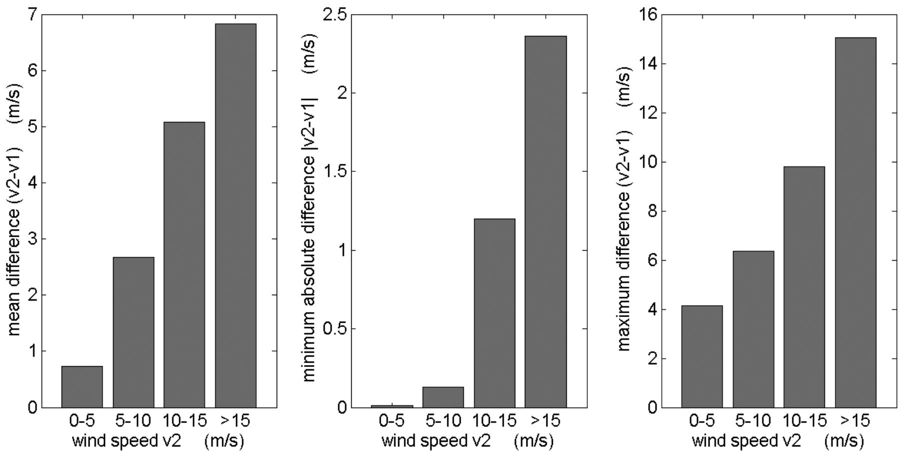

Figure 7. Differences between hourly mean wind speeds obtained by special (v2) and routine (v1) measurements (m s^{-1}) for the period 1 December 2001–31 January 2002. Left, center and right panel correspond to mean, minimum absolute and maximum difference between v2 and v1 with respect to the wind speed recorded at site 2.

2) than at 10 m above ground (Site 1). Nevertheless, Figures 7 and 8 together with the modeled winds for Senj (Klaić et al. 2003; Belušić and Klaić, 2004; Gohm et al., 2008) suggest that the true bora flows, and particularly strong and severe boras, are substantially stronger than operationally measured winds. This, together with the fact that the location of the operational site (Site 1) is sheltered with respect to bora flow, indicates that the bora winds at Senj are systematically underrepresented. This implication should be taken into ac-

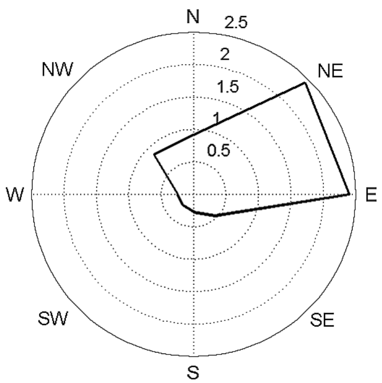

Figure 8. Mean differences between hourly mean wind speeds obtained by special (v2) and routine (v1) measurements (v2 – v1) (m s^{-1}) for the period 1 December 2001–31 January 2002. Differences are shown with respect to the wind direction measured at site 2.

count when dealing with the Senj data. A more comprehensive study based on a longer set of additional simultaneous measurements could offer speed and direction-dependent corrections to the operationally measured winds.

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