Doktorska disertacija – Sažetak
D.Sc. Thesis – Extended abstract

TURBULENCIJA BURE IZNAD BRDOVITOG PRIOBALNOG TERENA

Bora wind turbulence above complex coastal terrain

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Sažetak:

Tema ovog rada su mikro- i submezoskalna svojstva bure u zavjetrini sjevernog dijela Dinarida. Rad je podijeljen u tri cjeline, pri čemu se dvije cjeline odnose na turbulenciju bure u prizemnom sloju atmosfere, specifično, njene statističke značajke i numeričku simulaciju. Treća se cjelina odnosi na horizontalne rotacijske značajke pulsacija bure – njihov opis i numeričko modeliranje.

U prvoj cjelini proučavam razlike u statističkim značajkama turbulencije bure u prizemnom sloju atmosfere, i to na dvjema bliskim postajama, Senju i Vratniku (jedna u podnožju, a druga na grebenu planine), za skup podataka u trajanju od približno 6 mjeseci. Slična analiza značajki turbulencije bure do sada nije provedena za ovako dug vremenski period. Analiza potvrđuje neka saznanja prijašnjih radova temeljenih na usporedbi ove dvije postaje za jedan izdvojen događaj bure, npr. da je kinetička energija turbulencije (TKE) u Senju dvostruko veća u odnosu na Vratnik. Raspodjela viskozne disipacije TKE (ε) na dvjema postajama približno je jednaka, što je u suprotnosti s prethodnim zaključcima utemeljenim na jednom događaju bure. Dvije vremenske skale koriste se za odvajanje turbulencije od mezoskale – konstantna (15 min) i varijabilna; potonja je korištena s ciljem odvajanja submezoskalnih gibanja od lokalne turbulencije. Zaključci su u pravilu nepromijenjeni s obzirom na odabir vremenske skale. Podaci na postajama uspoređeni su s obzirom na teoriju sličnosti neutralnog prizemnog sloja (NPS). Odstupanja od NPS-a na Vratniku su manja od onih u Senju, što znači da je ravnoteža TKE na Vratniku bliža NPS-u (tj. smično-disipacijskoj ravnoteži). Određena odstupanja karakteristična su za utjecaj sloja hrapavosti (SH), s obzirom da je visina mjernih uređaja na objema postajama usporediva s visinom elemenata hrapavosti u njihovoj blizini. Ovo je posebice zamjetno u pomacima spektralnih maksimuma prema nižim frekvencijama. Utjecaj SH također pomaže objasniti neočekivanu jednakost ε na dvjema postajama. Naime, jedna od značajki SH nelokalni su ponori TKE koji smanjuju ε, a koja uobičajeno samostalno uravnotežuje izvore TKE. Utjecaj SH je prisutan i kod ovisnosti statističkih momenata o azimutu prizemnog vjetra, što se može objasniti anizitropijom površinske hrapavosti. Izračunate su integralne duljinske skale turbulencije i intenzitet turbulencije. Postignute vrijednosti intenziteta u skladu su s preporučenim vrijednostima, ali odstupaju od vrijednosti izmjerenih na srednjem Jadranu.

Druga cjelina usredotočena je na izračun mikroskalnih svojstava bure (preciznije, TKE) numeričkim modelom. Za validaciju simulacije korišten je skup podataka prikupljen u zaleđu grada Rijeke na 100-m tornju s anemometrima na 5 visina. Ovo predstavlja dosad najviša neprekidna toranjska mjerenja brzine vjetra i turbulencije bure u prizemnom sloju atmosfere. Osim 10-min usrednjenih vrijednosti horizontalne brzine i smjera vjetra, anemometri su mjerili i standardne devijacije, što omogućava procjenu TKE i usporedbu sa simulacijom. Ovo je značajno jer je usporedba dosad provedenih simulacija, izuzev avionskih ili indirektnih mjerenja, u pravilu provedena s mjerenjima na relativno niskoj razini iznad tla. Simulacija koraka mreže 0,3 km je provedena za slučaj ekstremno dugotrajnog niza jakih do orkanskih bura iz

siječnja i veljače 2012. godine, a kojeg su mjerni uređaji na tornju zabilježili u cijelosti. Točnost simulacije usrednjene vrijednosti brzine i TKE je u rasponu od razumne do izvrsne, ovisno o brzini vjetra i dubini bure. Periodi s izvrsnim podudaranjem su zabilježeni pri brzini vjetra većoj od 20 ms^{-1} i tijekom plitke bure, dok je podudaranje tijekom duboke bure te pri početku i kraju događaja lošije. Podudaranje je usporedivo sa simulacijama bure na južnom Jadranu, također relativno kratkog koraka mreže, dok odstupanja zabilježena kod većeg koraka mreže naglašavaju važnost reprezentacije reljefa u brdovitom terenu.

U trećoj cjelini proučavam rotacijske značajke pulsacija bure u horizontalnoj ravnini – njihovu strukturu, orijentaciju i smjer rotacije – koristeći rotacijsku spektralnu analizu. Metoda je primijenjena na događaje bure iz istog skupa podataka u Senju kao u prvoj cjelini. Struktura pulsacija je kvazilinearna, tj. česti zraka osciliraju duž izduženih elipsa, a os oscilacije nije jednaka smjeru prizemnog vjetra, već je bliža smjeru vektora smicanja. Doprinos predstavlja rotacija pulsacija u horizontalnoj ravnini, a koja je gotovo isključivo pozitivna, tj. u smjeru suprotnom od kazaljke na satu. Ove značajke ukazuju da su na promatranom skupu događaja bure najvjerojatniji uzroci nastanka pulsacija Kelvin-Helmholtzova nestabilnost ili horizontalno propagirajući zavjetrinski valovi, iako ne nude objašnjenje prevladavajućeg smjera rotacije. Numerička simulacija ljetnog događaja bure je provedena s ciljem proučavanja ovog zapažanja. Simulacija je uspješna s obzirom na period, prevladavajući smjer rotacije i kut između smjera prizemnog vjetra i osi oscilacije pulsacija. Amplituda pulsacija osjetljiva je na vertikalni i horizontalni korak mreže, ali rotacijske značajke nisu. Uzrok pulsacija u simulaciji je Kelvin-Helmholtzova nestabilnost. Ohrabren podudaranjem simulacije i mjerenja, proučio sam prostornu raspodjelu rotacijskih značajki u Velebitskom kanalu. Pozitivna rotacijska komponenta nadjačava negativnu na gotovo čitavom području kanala, iako je njihova relativna jakost vremenski promjenjiva. Iznad Senja i u blizini planinskih vrhova, prevladavajući smjer rotacije pulsacija koreliran je s poljem vremenski usrednjene vertikalne komponente vrtložnosti, a iznad otvorenog mora sa smicanjem smjera vjetra na vrhu niske mlazne struje. Predlažem da je rotacija na frekvenciji pulsacija uzrokovana naginjanjem vrtložnih linija lateralne komponente vrtložnosti unutar ili ispod vrhova Kelvin-Helmholtzovih valova. U prisustvu smicanja smjera vjetra, naginjanje može imati prevladavajući smjer. Budući rad trebao bi se usredotočiti na analizu polja vertikalne komponente vrtložnosti u simulacijama sa stvarnim i idealiziranim reljefom.

Extended abstract:
1. Introduction

Bora is a strong, gusty wind that occurs along the eastern coast of the Adriatic. It belongs to the category of downslope windstorms (e.g. Ólafsson and Ágústsson, 2007), and it develops due to synoptic disturbances which pull or push air over the Dinarides. Interest in the study of bora is driven mainly by its gustiness (over 60 ms^{-1}; e.g. Grisogono and Belušić, 2009) and spatial heterogeneity, which causes a myriad of problems in tourism, architecture and traffic (e.g. Keresturi, 2014).

Bora research started at the end of the 19th century (Mohorovičić, 1889). It initially focused on the spatial and temporal variability of the mean wind speed and duration (e.g. Poje, 1992). The analysis of synoptic charts and radiosoundings yielded two classifications of bora events, one with respect to the synoptic disturbance causing the cross-mountain flow, and the second with respect to the flow depth. As a result, bora event can be cyclonic, anticyclonic or frontal (e.g. Yoshino, 1976; Jurčec, 1988; Heimann, 2001), and shallow or deep. Several subjective and objective weather-type classifications have been developed as a prognostic aid (e.g. Poje, 1965; Vozila et al., 2021), newest of which claim that the winter cyclonic bora events (associated with the highest wind speed) will become less frequent in the future warming scenarios (Vozila et al., 2021). When it comes to the understanding of the physical causes of severe bora, the most important development occured as a result of ALPEX (Küttner and O'Neill, 1981) and MAP (Bougeault et al., 2001) projects.

Works by Smith (1987) and Klemp and Durran (1987) did away with the notion of bora as a katabatic wind, showing instead that the flow speedup can be caused by two mechanisms, hydraulic transition from sub- to supercritical flow (can be described by two-layer shallow water models), and nonlinear amplification and breaking of mountain waves (the stratified fluid case). Both mechanisms can be present at the same time, and their relative importance depends on the stratification profile, presence and height of the critical level (level where the cross-mountain flow component is zero) and other effects (e.g., Smith and Skyllingstad, 2011). In both cases, the resulting lee flow structure is similar – a strong low-level jet (LLJ) develops, topped by a layer of low wind speed and near neutral static stability (the stagnation zone).

The breaking mountain wave and the LLJ present a „stage" of sorts for this thesis. It is split into three chapters; two deal with the turbulence developed at the lower boundary of the LLJ, and the third aims to describe the horizontal rotational characteristics of bora pulsations (submesoscale motion originating from the wave breaking region or the boundary between the LLJ and the stagnation zone; Fig. 3) using point measurements and a numerical model simulation. The next three subsections summarize the relevant literature and motivation for each chapter, while the fourth presents the goals and structure of the rest of the text.

1.1. Bora turbulence measurements

As a result of strong shear at the LLJ top and bottom, strong turbulence is developed in the lee of the mountain. Turbulence strength in the lower layer is characterized by a handful of statistical properties like the turbulence kinetic energy (TKE), its dissipation rate (ε) and turbulent fluxes of heat, momentum, moisture, etc. Specialized fields like wind engineering use different but related statistical properties like the turbulence intensity, gust speed and integral turbulence length scales. How these properties relate to each other and vary with height is published in engineering compendia as benchmarks in calculating wind loads on structures.

The first high-frequency measurements of bora-related turbulence were undertaken within ALPEX and MAP projects (aircraft-mounted instruments sampled alongshore and cross-shore profiles of TKE; Smith, 1987; Večenaj, 2012). First mast-mounted instrument was installed in 2001 at the town of Senj (cup anemometer; 1 Hz sampling rate); Belušić et al. (2006) used these measurements to distinguish local turbulence and low-frequency pulsations. From 2004 to 2006, a pair of 3D anemometers (4 Hz sampling rate) was mounted at Senj and at the Vratnik pass (~10 km to the east of Senj). Using this data, Belušić and Klaić (2006) show that TKE at Senj can reach values as high as 40 m^2s^{-2}. Večenaj (2012) compared a single bora event that occured simultaneously at the two stations, and concluded that both TKE and ε are twice as large at Senj; therefore, turbulence strength grew along the downslope (Senj is located at the foothill, and Vratnik at the mountain ridge). The importance of turbulence averaging interval selection was emphasized; overly large averaging interval can include motions such as pulsations into turbulence, inflating TKE and related statistics by as much as ~30%. Belušić et al. (2013) also used this dataset to identify simultaneous flow regimes between the two stations via clustering.

Sustained interest in bora turbulence lead to further experiments. Within the frame of the WINDEX project (Horvath et al., 2010a, b), a tower with ultrasonic anemometers at several heights was installed in the hinterland of the city of Split. This dataset was used to point out the error in applying established engineering codes (mostly developed from data measured over flat, homogeneous terrain) to areas under the influence of bora (Lepri et al., 2015; 2017), to test the applicability of the Monin-Obukhov (MOST) similarity theory (Babić, 2013; Babić et al., 2016b; Lisac, 2014), to evaluate higher statistical moments (Večenaj et al., 2021) and the TKE balance, etc. Further instruments were installed at the Maslenica bridge (Večenaj et al., 2015), and used to show that the distributions of the turbulence statistical properties do not depend on the bora synoptic type (Šoljan et al., 2018) and to study jugo wind turbulence (Zajec, 2022). The most recent measurement campaign – project SESAR – focused on the effect of the bora turbulence on the air traffic at the Dubrovnik airport (e.g. Jurković et al., 2018).

Within the context of the bora turbulence properties, these studies fall into one of the two categories. In the first, a large dataset at a particular station is analyzed (e.g. Lepri et al., 2017; Lepri, 2023). In the second, two measurement locations are compared for a single simultaneous bora event (Večenaj, 2012). A long-term comparison of bora turbulence statistics for two or more stations was not undertaken thus far. This represents the main motivation for this chapter. Best candidates for this comparison are the stations in Senj and at the Vratnik pass; the first is located at the foothill of the coastal mountain range, and the second one is located atop the ridgeline, ~10 km to the east of Senj. Both stations have recorded a large amount of simultaneous bora events spanning the 9-month interval from September 2004 to June 2005.

1.2. Numerical modeling of bora turbulence

Measurement campaigns outlined in the previous section were followed by numerical experiments with steadily decreasing numerical grid spacing. Along-coast jet and wake distribution was successfully reproduced even with ~3 km grid spacing (Enger and Grisogono, 1998; Grubišić, 2004; Belušić and Klaić, 2006). Decreasing the spacing to ~1 km enabled study of submesoscale structures such as pulsations, rotors and lee waves (Belušić et al., 2007; Stiperski et al., 2012; Horvath et al., 2013). This decrease was especially important for the reproduction of near-ground wind in the immediate lee of coastal mountains. A good recent example is the well-reproduced wind speed at the Dubrovnik airport (ZLD) in Večenaj et al. (2019); they used a 0.5 km grid spacing and achieved substantial improvements with respect to coarse 8- and 4 km simulations (Simić, 2019). A good example of errors caused by coarse grid spacing in the study of downslope windstorms is provided in e.g. Águstsson and Ólafsson (2014).

Micrometeorological measurements described in the previous section also sparked interest in studying the ability of numerical models and planetary boundary layer (PBL) schemes to reproduce bora turbulence statistics. Here as well, the errors tend to decrease with grid spacing, although it depends on the vicinity of complex terrain. Offshore, even coarse grid spacing may yield good agreement with the measurements of TKE and its dissipation rate (Večenaj et al., 2012). This is not true in the immediate lee of the mountains, e.g. Belušić and Klaić (2006) and Simić (2019) compared surface TKE measurements at, respectively, Senj and Vratnik and at the ZLD (~10 m instrument mounting height) with simulations with 3 and 4 km grid spacing. TKE is in both cases underestimated by a factor of 3–4. Večenaj et al. (2019) simulated a bora event at the ZLD, but they instead used a 0.5 km grid spacing and obtained very good agreement with the TKE measurements. Even finer simulations (in the so-called large-eddy mode) were used to study TKE balance in the hinterland of Split (Horvath et al., 2013); the model output was verified using measurements at 10 m, 22 m and 40 m above the ground.

One of the main issues regarding the simulation of turbulence in downslope windstorms, except the terrain representation which in principle can be solved by using more computational resources, concerns the parametrization schemes of the momentum, heat and moisture exchanges in the surface layer and the PBL. Most of these schemes were developed using data above flat and homogeneous terrain, often underestimating turbulence length scales (Grisogono and Belušić, 2009; Večenaj et al., 2010; Večenaj, 2015). Consequently, surface wind speed can be overestimated and position of the lee rotor can be misjudged (e.g. Muñoz-Esparza et al., 2016). These discrepancies are, in part, due to a lack of measurements, especially at heights above a few dozen meters above the ground level (a.g.l.). From the measurement campaigns outlined in the previous section, only the WINDEX campaign delivered high-frequency measurements above 20 m a.g.l., although this was partially supplemented by airplane (MAP project; Bougeault et al., 2001), sodar (Stiperski et al., 2012; Horvath et al., 2013) and lidar measurements (Jurković et al., 2018). Therefore, additional measurements of the mean wind speed and turbulence are needed, especially above ~20 m a.g.l. Using such measurements, the ability of the numerical model to reproduce vertical wind and turbulence profiles can be evaluated. In January 2012, a 100-m tower with anemometers at five heights was installed in the hinterland of the city of Rijeka. Besides the mean wind speed and direction, the instruments also recorded their standard deviations, thus enabling the estimation of the TKE and its comparison to numerical model results. In January and February of 2012, the instruments recorded a three-week series of strong to severe bora events. Presenting this dataset and comparing it to the model output presents the main motivation of this chapter.

1.3. Bora pulsations

Pulsations, i.e., quasi-periodic motions with periods of 1–20 min represent a type of secondary instability caused by the strong shear in the wave breaking region and at the LLJ-stagnation zone interface (e.g. Fig. 1). They were first studied in the famous Boulder windstorm (e.g. Zipser and Bedard, 1982), where structures with decoherence length of ~10 km could be observed (via lidar) moving with the mean wind (Neiman et al., 1988). In numerical experiments, three pulsation generation mechanisms were identified, Kelvin-Helmholtz instability (KHI; Scinocca and Peltier, 1989; Peltier and Scinocca, 1990), tilting of the base-state vorticity associated with the breaking mountain wave (Clark and Farley, 1984), and the trapped, travelling lee waves (Clark and Hall, 1994). A schematic view of all three mechanisms is shown in Figure 3. Pulsations exist in bora as well. First measurements and theoretical considerations originate in the late 1980s (Rakovec, 1987; Petkovšek, 1987). Further development occured at the start of 2000s due to the installation of a high-frequency (1 Hz) anemometer at the town of Senj. In a series of papers, Belušić et al. (2004; 2006; 2007) reveal the underlying phenomena regarding the cessation of pulsations and the appearance of a high-level jet. They simulate the pulsations using COAMPS model, identifying KHI as the generating mechanism for that particular bora event. Furthermore, Orlić et al. (2005) use 3D anemometer data (mounted at Senj in 2004) to point out the difference in pulsations and turbulence. Pulsations were studied at other locations at the Adriatic cost as well, e.g. Horvath et al. (2013) observed pulsations with periods of 3–15 min. They found that the latter are connected to the upstream variation in profiles of wind speed and static stability.

The research focus in the past was the period, wavelength and phase speed of the pulsations, as well as their numerical simulation. The aim of this chapter is to study the characteristic structure of pulsations in the horizontal plane using the rotational spectral analysis method – RSA (Gonella, 1972; O'Brien and Pillsbury, 1974). RSA (described in the Section 4.3.3) decomposes the 2D vector time series (at a certain frequency) into a positively and negatively rotating component, and can give insight into properties such as the preferred sense of rotation, coherence and the type of motion (rectilinear, circular or elliptical). RSA was previously used at the Adriatic coast in the study of diurnal rotation of sea breeze (Prtenjak et al., 2008) and the rotational characteristics of bora in the vertical plane (Orlić et al., 2005). Latter example is notable since RSA showed that pulsations and local turbulence exhibit different structures, and thus have different generating mechanisms. The choice of the subject and the method was motivated by observing a large set of bora events recorded by a 3D anemometer at the town of Senj. After the rotation of the data into the mean-wind system, I noticed large variability in the ratio of the pulsation energy in the along-wind and cross-wind directions, even within a single bora event. This variability implies change in either the orientation of the structure, or its type (i.e., from rectilinear to circular). Since different pulsation generation mechanisms produce different structures in the horizontal plane (Section 3.2), RSA can be used to deduce the dominant one. Finally, a numerical model (WRF-ARW) can be used to reproduce these characteristics and (if successful) study their spatial and temporal variability.

1.4. Objectives and structure

The aim of the first chapter is to compare the statistical properties of the bora turbulence at two nearby stations, one at the foot of the mountain and the other at a ridgeline, for a large number of bora events. The combination of length of the analyzed dataset and the comparison of turbulence statistical properties at two stations represents the original contribution of this chapter. After the selection of an appropriate turbulence averaging interval (constant or variable), I will calculate the TKE, ε, momentum flux and other relevant parameters. Because of the differences in the surface cover and instrument mounting height (Section 4.1.2), the data is compared in the context of the statically neutral surface layer similarity (Section 3.1). The deviation of the nondimensional statistical properties from theoretical values can point towards possible differences in the TKE balance between the two stations.

In the second chapter, I intend to verify the ability of the WRF-ARW numerical model to reproduce vertical profiles of the TKE. To do this, a dataset collected at a 100-m mast installed in 2012 in the hinterland of the city of Rijeka with anemometers at five levels (Section 4.1.1) is used. This represents the highest continuous tower measurements of bora wind speed and turbulence in the surface layer. At the end of January and through most of the February of 2012, the instruments recorded a series of consecutive strong bora events. The length of the recording enables a comparison of the obtained results and the simulation from the initial stages of the series to its termination, as well as during change in the bora flow depth.

In the final chapter, the horizontal rotational characteristics of pulsations in bora wind are studied using the RSA method, linking them to the dominant pulsation generation mechanism. I intend to verify if these characteristics can be reproduced by a numerical model (WRF-ARW), and if so, to study their spatial and temporal distributions. To the best knowledge, horizontal rotational characteristics of pulsations in bora have not been studied thus far.

The remainder of the thesis is structured in the following manner. Section 3 contains the theoretical background. Section 4 presents the measurements and measurement locations (Senj, Vratnik and the tower in the hinterland of Rijeka), as well as the methods employed in data analysis. Section 5 presents the results and it consists of three self-contained chapters. Section 6 recapitulates the results of all three chapters, and is followed by the optional appendix.

2. Data and methods

For the purposes of comparison of the measured and simulated profiles of the mean wind speed and TKE, a 100-m tower in the hinterland of the city of Rijeka is used. Among the instruments, cup anemometers and wind vanes were mounted at heights of 25 m, 50 m, 75 m and 98 m a.g.l. (Fig. 4), yielding 10-min values of the mean wind speed and its standard deviation, and the mean wind direction and its standard deviation (full list of measured variables is given in the Table 1). The standard deviations in particular enable the estimation of the TKE (Appendix A1). The tower was located at the windward side of the coastal mountains, but on the leeward side of the overall mountain chain (approximate location 45°N, 15°E), with its base at 625 m above the mean sea level (a.m.s.l.). Local terrain had a 10° slope in the SW–NE direction, and was covered by dense evergreen forest (average tree height of several meters) and large boulders (~1 m in diameter). This is, to the best knowledge, the tallest tower ever used for bora research. The period from January 23rd to February 16th was selected for comparison, when the northern Adriatic was battered by a series of strong to severe bora events (mean wind speed at times higher than 20 ms^{-1}) lasting for more than 20 days (e.g. Kuzmić et al., 2015).

To compare the turbulence statistics and study the pulsations' horizontal rotation, two towers at the town of

Senj and at the nearby Vratnik mountain pass are chosen (Fig. 5). The position of the towers and their height is given in Table 2. Both towers featured a 3D WindMaster (Gill Instruments) sonic anemometer with 4 Hz sampling frequency at a single height, but without the measurement of sonic temperature (hence, fluxes of heat are unavailable). The data collected at these towers spans the interval from March 2004 to June 2006 (Senj) and from October 2004 to September 2005 (Vratnik). The tower at Senj was located at the foothill of a coastal slope in a semi-urban environment, with the local house height (z_H) comparable to the height of the instrument (z; z/z_H ~ 1.3). The Vratnik mountain pass is located ~10 km to the east of Senj at a height of ~700 m a.m.s.l. The tower was surrounded by a dense evergreen forest with average tree height (at the time) of ~5 m (with the instrument at 9.5 m a.g.l., z/z_H ~ 2). The larger surface roughness in Senj and the contrast in z/z_H impacts the turbulence characteristics at the two stations.

Bora events were extracted at the two stations (defined as wind with azimuth from 0° to 90°, lasting for a minimum of 3 h). Only events that occured simultaneously at the two stations were further analyzed. A time scale (τ) was determined that separates the turbulence from the large-scale motions. To determine τ, the spectral gap method was used (e.g., Metzger and Holmes, 2008), which relies on the identification of a wide area of low energy in the (co)spectra of wind velocity components. The position of this gap can change in time, so the simultaneous bora events are split into 6-h segments. The time scale τ is then determined in two ways. First, a constant τ (equal to 15 min) is identified from the composite spectra (Fig. 8a), and used for all the 6-h segments at both towers. Alternatively, each 6-h segment is assigned a different τ based on the gap identified from the (co)spectra of that particular segment. This was done because time series at Senj (and to a much lesser extent at Vratnik) often exhibit submesoscale motions (like the pulsations) at periods of several minutes. These motions differ from turbulence (Belušić et al., 2006), so τ was chosen to lie in the gap betwen the turbulent and the submesocale peak (example shown in Figure 8b). τ determined in this manner is not the same at both stations for the same 6-h segment. By using two different time scales, the effect of submesocale motions on the turbulence properties can be evaluated.

Once τ is determined, every 6-h segment is split into subsegments of length T (equal to 1 h) and the statistical properties of turbulence are calculated. The length of 1 h is arbitrary; for the time-average statistics to converge to their ensemble values, T should in general be several times larger than τ (Lenschow et al., 1994). For each subsegment, the time series of velocity components are double-rotated into the system of the mean wind (Kaimal and Finnigan, 1994). They are further separated into a high-pass filtered fluctuation (cutoff frequency equal to τ^{-1}) and the low-frequency remainder. The following parameters are then calculated for each 1-h subsegment: the mean longitudinal velocity, TKE dissipation and the components of the Reynolds stress tensor (Eqn. 4.2). Intervals which do not satisfy the Taylor hypothesis (e.g. Stull, 1988), or which exhibit high degree of non-stationarity, are flagged and not used in the analysis. The result is that each station (Senj and Vratnik) has two sets of statistics, one for constant and one for variable τ. TKE dissipation is calculated using the inertial dissipation method (Eqn. 4.4; e.g. Tennekes and Lumley, 1972), justified by the presence of the -5/3 slope in the spectra of the wind velocity components, even if the strict criterion of isotropic turbulence was not observed.

To analyze the rotational characteristics of the pulsations in the horizontal plane, I used the rotational spectral analysis method – RSA (Gonella, 1972; O'Brien and Pillsbury, 1974). The horizontal velocity vector is represented as a complex number (w=u+iv, where u and v are the zonal and meridional velocity), and its Fourier transform is calculated, giving complex amplitudes ($w_\pm$) associated with positively and negatively rotating component at a given frequency (Eqn. 4.5). Several parameters can be calculated from these amplitudes, characterizing the type of structure (R_{ab}; circular, elliptical or rectilinear), its orientation (α; Eqn. 4.7) and its coherence (E; Eqn. 4.7). Figure 10 shows the types of motion associated with different values of R_{ab} and α. RSA was previously used to study the diurnal sea breeze rotation (Prtenjak et al., 2008) and the vertical-plane structure of the bora flow (Orlić et al., 2005) at the Adriatic coast.

3. Results, discussion and conclusions

3.1. Bora turbulence characteristics in Senj and at Vratnik

The distributions of the statistical properties (TKE, ε and Reynolds stresses) at the two stations are compared. The TKE and the turbulent fluxes are 1.5–2 times larger in Senj (depending if the submesocale motions are filtered out or not), which is similar to the results found in previous studies which analysed only single episodes (Večenaj, 2012). This is probably due to the contrast in the surface roughness. The distributions of ε are nearly equal at the two stations, contrasting with the previous analyses (Večenaj, 2012) which found that, like the TKE, ε was also ~2 times larger at Senj. This mismatch is caused by large variability in the ratio of ε at the two stations, meaning that conclusions on their relative magnitudes at the two stations cannot be drawn on the basis of a single bora episode.

Since the magnitudes and the profiles of statistical quantities in the PBL depend on the balance of sources and sinks of the TKE, I estimated the deviation of the TKE balance at the two stations from the neutral surface layer (NSL). A detailed TKE balance analysis requires measurements at several levels, so instead I compared the relationships between TKE, ε and U, which in the NSL (where the dominant TKE balance terms are shear production and ε; Eqn. 1.1) is expected to yield $\varepsilon \propto U^3$, TKE$\propto U^2$ and $\varepsilon \propto$TKE$^{3/2}$. The exponents at Vratnik are closer to these values (2.76, 2.09 and 1.19, respectively) than those at Senj (1.52, 1.35 and 1.30, respectively), indicating that the TKE balance at Vratnik is closer to the shear-dissipative balance (Table 4 and Figure 12). Large spread of data in the scatter plots in Senj is partly due to the surface roughness anisotropy, meaning that the statistical properties at Senj exhibited the wind direction effects (Fig. 13).

Instruments at the stations are located relatively close to the rough ground surface, so the measurements can be influenced by the roughness sublayer (RSL). Turbulence in the RSL exhibits deviations from the shear-dissipative balance of the NSL (Section 3.1), so I explored if the deviations from this balance at the two stations are characteristic of the RSL. Kaimal and Finnigan (1994; KF94 from now on) and Roth (2000) compiled the profiles and values of nondimensional spectra, variances etc. in the RSL above urban and forested surfaces, and were used as benchmarks. Several markers of the RSL influence exist at the two stations. The nondimensional variances of the u and v velocity component are smaller than the NSL values (Fig. 14). The nondimensional velocity spectra show a shift in their peak values towards the low-frequency end of the spectrum (Fig. 15; Tab. 5). The latter shows that the RSL effect is stronger at Senj since both the longitudinal (u) and vertical (w) components are shifted, while at Vratnik only the w component is shifted (KF94). Finally, the nondimensional dissipation (ϕ_ε; Eqn. 3.5) is close to the NSL value (one) at Vratnik, and ~0.6 at Senj. The reduced dissipation is expected deeper in the RSL since ε is no longer the only sink of the TKE (as is the case in the NSL; KF94). Therefore, I conclude that both stations show deviation from the shear-dissipative balance of the NSL indicative of the RSL, but at Senj it is larger since the anemometer is, relative to the height of the roughness elements, installed at a lower height. This also helps to explain the unexpectedly identical distributions of ε at the two stations, since the much larger shear production at Senj and comparable effective instrument mounting height would, if both stations were above the RSL, produce larger ε in Senj.

The final section (Section 5.1.4) asseses the turbulence length scale (Λ; e.g., Mellor and Yamada, 1974) and the turbulence intensity commonly used in wind engineering. Λ is 2–3 times larger in Senj (Figure 16) due to the larger surface roughness, and depends on the choice of τ (filtering out pulsations reduced its value by 20–30%). The turbulence intensities ($I_{u,v,w}$; Eqn. 12) are in the expected range of values characteristic for the rural and urban surroundings (I_u between 0.2 and 0.35 at Senj and between 0.1 and 0.2 for Vratnik; Counihan, 1975). The ratios between the I_u, I_v and I_w are in line with the expected range of values (for both constant and variable τ), but differ from the ratios found in the hinterland of the city of Split (Lepri et al., 2017).

3.2. Reproduction of TKE by numerical model

WRF model (version 4.2; Skamarock et al., 2021) was chosen for the simulation of the bora event. The detailed description of the model setup is given in the Section 5.2.1, but the most important features are the higher-order closure level turbulence parametrization scheme (MYNN; Nakanishi and Niino, 2006) and the small grid step combined with high-resolution terrain elevation model (1'' horizontal resolution; NASA, 2019). Inadequately resolved terrain is associated with most of the errors in the simulations above complex terrain, and can significantly alter the wave breaking mechanics (Águstsson and Ólafsson, 2014). The simulation ran from January 23rd to February 16th, capturing the series of events from its initial phase to cessation.

The quality of the simulation was assesed with respect to the mean values of wind direction, speed and the TKE. Wind direction was steady (~60° on all heights) during the majority of the event, and is excellently reproduced, except at the 50 m level where the wind vane shows signs of malfunction in the latter part of the event (Fig. 19). Reproduction of mean wind depended on the bora „flow regime" (Fig. 20), with best results (negligible bias and 10–15% RMSE) associated with shallow bora flow, somewhat worse agreement associated with deep bora flow (20–25% RMSE; positive bias) and worst results in the startup/cessation phases (RMSE up to 60%). Dependency of the simulation quality on flow depth was noted at the southern Adriatic as well (Keresturi, 2014). Errors depended on height, with a large positive bias at 20 m a.g.l. due to the presence of a low-level maximum in the simulation. This maximum is not present in the measurements which instead show a logarithmic profile. The values of TKE were estimated using the 10-min mean values of wind speed and the standard deviations of wind speed and direction. The estimation method is provided in Appendix A1. Note that the anemometers did not measure the vertical velocity, so this estimate underestimates the real TKE by roughly 16% (e.g. Panofsky and Dutton, 1984). A comparison with the simulated TKE shows the same dependence on the „flow regime", with the smallest errors in the shallow bora regime (~20% RMSE) and largest in the startup/cessation phase (RMSE as large as 100%). TKE was in general overestimated by the simulation at all levels. Finally, the model reproduced the TKE decreasing with increasing height.

3.3. Rotational characteristics of bora pulsations

From the same dataset of bora events used in the first chapter, forty 6-h intervals were selected. The criteria for selection are stationarity of wind speed and direction, and strong pulsations present throughout the interval. Using the RSA, a set of rotational parameters (R_{ab}, α and E; Section 4.3.3) is calculated for every 6-h interval. In general, the ellipse semiaxis ratio (R_{ab}) is small but positive (Fig. 25a), indicating that the characteristic motion at the frequency of pulsations is an ellipse traced in the positive (anticlockwise) manner by the horizontal wind velocity vector. The orientation of the ellipse's major axis (α) is not along the near-ground wind, instead being offset by 10°–50° to its right. When the offset is smaller, the pulsations tend to have a smaller R_{ab} and larger stability (i.e., coherence). There is some difference in the rotational parameters between the bora events associated with a surface high and a surface low, but the difference is not statistically significant (Fig. 26b). The small values of R_{ab} and high stability indicate that the pulsations are most of the time associated with wave-like motion. Thus, KHI or the trapped travelling lee waves are the most probable pulsation-generating mechanism. Additionally, examination of running rotational spectra (Fig. 27) and comparison with ERA5 profiles (Hersebach et al., 2020) of wind shear nearest to the Senj station show that α is equal to the direction of the shear vector at the top of the LLJ, as expected from KHI or trapped travelling lee waves (Fig. 29; e.g. Metcalf and Atlas, 1973; Gossard and Hooke, 1975). However, these mechanisms do not have a preferred sense of rotation in the horizontal plane, at least not above flat terrain.

To explore this mismatch, a high-resolution numerical simulation using the WRF-ARW model (version 4.3.3; Skamarock et al., 2021) was performed. The grid step in the innermost domain is 0.2 km, putting it into the „gray zone“ of turbulence (e.g. Honnert et al., 2020). The choice of physical parametrizations and domain nesting is described in the Section 5.3.5 (Tab. 10 and Fig. 32). While the existence and the amplitude of the pulsations depend on the choice of the horizontal and vertical grid step, the pulsations' rotational parameters such as ellipse semiaxis ratio (R_{ab}) and its orientation (α) do not. The same summer bora event shown in Figures 27 and 29 was chosen for the simulation, beginning on May 31st and lasting until June 2nd, 2005. The event was anticyclonic and shallow due to the presence of an inversion and a critical level at the 700–800 mb level.

Comparison of the data output at the gridpoint closest to the tower in Senj shows satisfactory simulation of wind speed and direction (Fig. 33a). The spectral amplitude of the pulsations is overestimated, and their cessation during the day is not reproduced well, which is a typical problem for most meteorological models. However, orientation of the axis of oscillation and the preferred sense of rotation are (Figs. 33b, 34). Therefore, just as in the measurements, the characteristic motion at the frequency of pulsations is an ellipse traced by the horizontal velocity vector in the positive (anticlockwise) manner. The mechanism responsible for the pulsations is KHI, evidenced by the vertical cross-section of potential temperature (θ) and the Richardson gradient number (Ri), with negative Ri below the crests of the overturning waves and $Ri < 0.25$ along the mountain slope. Additionally, α was aligned perpendicular to the troughs and crests of the KH waves, and parallel to the shear vector at the LLJ top (Figure 35), as expected from KH waves (e.g. Metcalf and Atlas, 1973; Gossard and Hooke, 1975).

Based on the agreement between the simulation and the measurements, running rotational spectra were calculated for a grid of points spanning the area in the lee of the mountain, over the Velebit channel (Figure 36). This enabled the examination of spatial distributions of rotational parameters. The energy of the positive rotational component (E_+) is larger than the negative (E_-) over most of the domain, and the stability (i.e., coherence) decreased with the distance from the shoreline. The decorrelation length is ~10 km, similar to Neiman et al. (1988). Interestingly, the degree to which E_+ was larger than E_- (i.e., R_{ab}) depended significantly on the directional shear at the LLJ top (Figs. 38, 39); if there was no directional shear, there was no preferred sense of rotation, but when the mean wind at the LLJ top turned clockwise (i.e., negative), the preferred sense of rotation was positive ($R_{ab} > 0$).

I suggest that the link between the preferred sense of rotation and the directional shear at the LLJ top can be interpreted – under the assumption that the KH waves can locally be represented as travelling plane waves (Appendix A3) – via the dynamics of the vertical component of vorticity (ζ). In the immediate lee of the mountain, the sign of the time-averaged ζ and R_{ab} often coincide, while this is not so over the open sea of the Velebit channel. Instantaneous fields of ζ suggest that in this area, ζ is produced by the tilting of the horizontal vortex lines within and below the crests of the breaking KH waves. Similar nonstationary production of ζ was noted by Rotunno and Bryan (2020), however in their case it was caused by the transient breaking of the stationary mountain wave. This tilting process could be influenced by the directional shear at the LLJ top, thus favouring production of anomalies of positive (or negative, depending on the direction of the shear) vorticity. Simulations with idealized orography and synoptic flow, as well as the analysis of the vorticity budget with and without directional shear are planned to test this hypothesis. The data analysis for other stations at the Adriatic coast are expected to help generalize these findings.