ISSN 1849-0700
ISSN 1330-0083
CODEN HMCAE7

Hrvatsko meteorološko društvo
Croatian Meteorological Society

HRVATSKI METEOROLOŠKI ČASOPIS
CROATIAN METEOROLOGICAL JOURNAL

56

Hrv. meteor. časopis	Vol. 56	p. 1-216	ZAGREB	2023

HRVATSKI METEOROLOŠKI ČASOPIS
CROATIAN METEOROLOGICAL JOURNAL

Izdaje
Hrvatsko meteorološko društvo
Ravnice 48, 10000 Zagreb
Hrvatska

Published by
Croatian Meteorological Society
Ravnice 48, 10000 Zagreb
Croatia

Glavna i odgovorna urednica / Chief Editor
Tanja Likso, Zagreb
hmc@meteohmd.hr
Zamjenik glavne i odgovorne urednice / Assistant Editor
Krešo Pandžić, Zagreb

Tajnica / Secretary
Ljilja Ivušić, Zagreb
ljiljaivusic@gmail.com

Urednički odbor / Editorial board
Tanja Likso, Zagreb
Goran Gašparac, Zagreb
Antun Marki, Zagreb
Vinko Šoljan, Split
Ljilja Ivušić, Zagreb
Krešo Pandžić, Zagreb
Branko Grisogono, Zagreb
Katarina Stanković, Zagreb
Ivan Toman, Zadar

Recenzenti / Reviewers
Simon Berkowicz, Izrael
Kristan Horvath, Hrvatska
Jadran Jurković, Hrvatska
Giora Kidron, Izrael
Tanja Likso, Hrvatska
Renata Sokol Jurković, Hrvatska
Ivana Tošić, Srbija
Ksenija Zaninović, Hrvatska
Vesna Đuričić, Hrvatska
Branka Ivančan-Picek, Hrvatska
Ján Kaňák, Slovačka
Gabin Koto N'Gobi, Bėnin
Krešo Pandžić, Hrvatska
Lidija Srnec, Hrvatska
Josip Vuković, Hrvatska

Lektura / Proofreading
Neoplazam (hrv.), Alpha (eng.)

Korektura / Corrections
Vesna Đuričić, Hrvatska

Časopis se referira u / Abstracted in
Scopus
Geobase
Elsevier/Geoabstracts
Zugänge der Bibliotheke des Deutschen Wetterdienstes
Meteorological and Geoastrophysical Abstracts
Abstracts Journal VINITI

Adrese za slanje radova / Addresses for papers acceptance
hmc@meteohmd.hr
likso@cirus.dhz.hr

Časopis izlazi godišnje
Web izdanje: *http://hrcak.srce.hr/hmc*
Prijelom i tisak: ABS 95

Naklada: 150 primjeraka

Hrvatsko meteorološko društvo
Croatian Meteorological Society

HRVATSKI METEOROLOŠKI ČASOPIS
CROATIAN METEOROLOGICAL JOURNAL

56

Hrv. meteor. časopis	Vol. 56	p. 1-216	ZAGREB	2023

Znanstveni časopis *Hrvatski meteorološki časopis* nastavak je znanstvenog časopisa *Rasprave* koji redovito izlazi od 1982. godine do kada je časopis bio stručni pod nazivom *Rasprave i prikazi* (osnovan 1957.). U časopisu se objavljuju znanstveni i stručni radovi iz područja meteorologije i srodnih znanosti.
Objavom rada u Hrvatskom meteorološkom časopisu autori se slažu da se rad objavi na internetskim portalima znanstvenih časopisa, uz poštivanje autorskih prava

Scientific journal *Croatian Meteorological Journal* succeeds the scientific journal *Rasprave,* which has been published regularly since 1982. Before the year 1982 journal had been published as professional one under the title *Rasprave i prikazi* (established in 1957). The *Croatian Meteorological Journal* publishes scientific and professional papers in the field of meteorology and related sciences.
Authors agree that articles will be published on internet portals of scientific magazines with respect to author's rights.

Doktorska disertacija – Sažetak
D.Sc Thesis – Extended abstract

ZNAČAJKE BURE U PRIZEMNOM SLOJU ATMOSFERE IZNAD BRDOVITOG TERENA

Bura wind characteristics in the surface layer above complex terrain

PETRA LEPRI

Datum obrane: 27. 4. 2023.
Trajna poveznica: *https://urn.nsk.hr/urn:nbn:hr:217:880109*

Sažetak: Bura je vrlo jak, najčešće suh i mahovit vjetar koji puše iz smjera sjeveroistoka preko priobalnih gorskih lanaca na istočnoj obali Jadranskog mora. Prostorno i vremenski bura je vrlo promjenjiva. Češće se javlja zimi kada može potrajati i do nekoliko dana. Najčešće na Jadran bura donosi hladan i suh zrak. Usrednjena satna vrijednost brzine puhanja bure od 10 do 30 ms^{-1} je manje značajna od udara bure koji mogu dosegnuti brzinu nekoliko puta veću od usrednjene brzine, čak do 70 ms^{-1}. Sukladno definiciji Svjetske meteorološke organizacije udar vjetra je maksimalna vrijednost 3-s klizne usrednjene vrijednosti brzine vjetra u 10-min periodu (https://space.oscar.wmo.int/variables/view/wind_gust).
Bura bitno utječe na život ljudi i brojna područja društvenih djelatnosti, posebice promet. Budući da značajke različitih tipova zavjetrinskog vjetra, a posebno bure, trenutno nisu poznate na način da budu izravno primjenjive prilikom projektiranja inženjerskih konstrukcija, potrebno je analizirati njihove karakteristike i prikazati ih u obliku pogodnom za inženjersku primjenu. Na taj način će biti omogućeno točno određivanje aerodinamičkog opterećenja bure i drugih tipova zavjetrinskog vjetra na konstrukcije i vozila. Na temelju mjerenja brzine vjetra na tri visine na lokaciji Pometeno brdo blizu Dugopolja u zaleđu Splita, u razdoblju od travnja 2010. do lipnja 2011. godine analizirani su vertikalni profili brzine puhanja bure kao i vremenski nizovi intenziteta turbulencije, Reynoldsovog smičnog naprezanja, integralnih duljinskih mjera turbulencije i ostalih relevantnih parametara.

Vrijednosti postignute analizom navedenih parametara uspoređene su s odgovarajućim preporučenim vrijednostima danim u mjerodavnim inženjerskim međunarodnim normama i standardima (npr. ESDU 85020, 1985; ISO 4354, 1997; HRN EN 1991 Eurocode 1 2005; ASCE 7-05, 2006; AIJ, 2006). Također, analiziran je i spektar gustoće snage fluktuacija brzine puhanja bure i termička stabilnost prizemnog sloja atmosfere za vrijeme trajanja pojedinih epizoda bure. Zbog snažnog mehaničkog miješanja strujanja zraka, bura je približno neutralno termički stratificirana. Rezultati analize epizoda bure ukazuju na činjenicu da se usrednjene vrijednosti puhanja bure podudaraju s empirijskim zakonom potencije i logaritamskim zakonom. Sa smanjenjem brzine vjetra dolazi do porasta eksponenta zakona potencije i aerodinamičke duljine hrapavosti tla kao i smanjenja brzine trenja što ukazuje na profil brzine tipičan za urbana područja pri manjim brzinama vjetra i profil brzine tipičan za ruralna područja pri većim brzinama vjetra. Iznos perioda usrednjavanja ne utječe na usrednjenu vrijednost brzine trenja, medijan i usrednjenu vrijednost eksponenta zakona potencije. Usrednjene vrijednosti aerodinamičke duljine hrapavosti tla značajno se razlikuju za različite periode usrednjavanja dok robustniji medijan nema te karakteristike. Vrijednosti intenziteta turbulencije i lateralne duljinske mjere turbulencije podudaraju se s vrijednostima preporučenim u međunarodnoj normi ESDU 85020 (1985). Longitudinalna i vertikalna komponenta duljinskih mjera turbulencije, Reynoldsovo smično naprezanje i spektar gustoće snage fluktuacija bure svih triju komponenti brzina značajno odstupaju od vrijednosti preporučenih u ESDU 85020 (1985).

Preporučene vrijednosti u različitim normama i standardima zakonski su propisane vrijednosti koje je nužno koristiti pri projektiranju inženjerskih konstrukcija s ciljem postizanja aerodinamičke stabilnosti konstrukcija. Budući da diljem svijeta postoje različiti zavjetrinski vjetrovi slični buri, rezultati postignuti u okviru ovog doktorskog rada bit će relevantni i primjenjivi diljem svijeta.

Extended abstract:

1. Introduction

Bura is a strong, temporally and spatially transient downslope wind. Its mean wind velocities rarely exceed 30 ms^{-1}, while one of *bura* main characteristics is the gustiness when the wind velocity may reach up to five times the mean wind velocity, up to 69 ms^{-1} (e.g., Bajić and Peroš, 2005). *Bura* is more common in winter when it can last for several days, (e.g., Poje, 1992). It is more frequent at the eastern Adriatic and weakens seaward from the shore in a way that it is rarely stormy over the western Adriatic (e.g., Grisogono and Belušić, 2009). Depending on the triggering system, *bura* can be cyclonic, bringing clouds with a high possibility for precipitation, anticyclonic, accompanied with clear weather, or frontal (e.g., Jurčec and Visković, 1994). Previous meteorological and geophysical studies laid groundwork regarding *bura* large- and mesoscale motions, but further research is still required to fully understand and resolve *bura* turbulence in a form usable for engineers. *Bura* is characteristic for the eastern Adriatic Coast but also for other dynamically similar places around the world thus making the *bura* research globally applicable, (e.g., Jurčec, 1981).

For example, *bura* affects lives of people and may create significant problems to traffic and engineering structures (e.g., Kozmar et al., 2014, 2015). Due to *bura*, ferry traffic among the coastal ports and the islands usually stops, major roads and highways remain closed for traffic for several days. *Bura* can cause vehicles to roll over or slide away from the road, blow off roofs and building facades. It can damage cable-stayed bridges as well. For example, the Dubrovnik cable-stayed bridge was considerably damaged in several severe *bura* episodes in 2005 and 2006. Wind turbines cannot operate during strong *bura* events because they experience structural loading considerably different than the wind turbines in other areas without *bura*. *Bura* blows down the trees, causing larger areas or even entire counties to lose electricity due to collapsing poles. There are not many records of building collapsing due to the severe *bura* wind because buildings in coastal Croatia are generally low-rise and made of concrete that makes them not very prone to wind effects. In the summer, wildfires are significantly enhanced when *bura* blows. For these reasons, further research is still needed to fully elucidate *bura* characteristics in a form useful to engineers studying wind loads on structures. Therefore, an analysis of vertical wind profiles, time series of turbulence intensity, Reynolds shear stress, turbulence length scales, power spectral density and other relevant parameters was carried out and the results were compared to international standards. Furthermore, velocity power spectra and thermal stratification of the low-level atmosphere during *bura* was analysed.

2. Methodology

The measured data considered in this study were obtained from April 2010 until June 2011 at the meteorological tower on the Pometeno brdo (43° 36' 28.9'' N and 16° 28' 37.4'' E) in the hinterland of Split, Croatia on the lee side of the central Dinaric Alps. This rather long measurement period allows us to make quite robust and reliable conclusions. Northern, eastern and vertical wind velocity components as well as the ultrasonic temperature were measured using ultrasonic anemometers at the sampling frequency of 5 Hz. That frequency was at the time the finest sampling rate ever applied to study *bura* turbulence characteristics. Anemometers were mounted on a 60 m high meteorological tower at 10, 22 and 40 m heights placed along the main *bura* direction. The vegetation surrounding the measurement site is mostly shrubs and bushes lower than 3 m and this area is known for frequent and strong *bura* occurrences (e.g., Makjanić, 1978; Jurčec, 1981).

Prior to the analysis of the measured data, it is necessary to check the data quality and remove the outliers (e.g., Pandžić, 2002). The suspicious data that were removed (rather small amount, less than approximately 0.004% of the total dataset), were afterwards replaced with linearly interpolated ones, and *bura* episodes were accordingly selected. A data set is considered as one *bura* episode if the wind direction is from the northeast with negative longitudinal and lateral wind velocity components and if these conditions lasted continuously for a minimum of three hours.

During 18 months, the period in which the measurements were carried out, there were in total 296 *bura* episodes that lasted from a few hours up to 127 hours. In total, 119 *bura* episodes lasting longer than ten hours were selected and analysed. As expected, the wintertime *bura* episodes generally last longer and have larger mean and maximum wind velocities than the summertime episodes, in agreement with Enger and Grisogono (1998).

Initial calculations and analyses were based on one summer *bura* episode that lasted a total of 62 h between 24 and 27 July 2010 (Magjarević et al., 2011). During this period, the wind was relatively strong and long-lasting with mean hourly values of wind velocities above 15 ms^{-1}. To check whether the trends obtained for this summer episode are valid for other 118 analysed *bura* episodes, the same analyses were performed for each individual *bura* occurrence. The studied parameters include thermal stratification, the mean *bura* wind velocity, turbulence intensity, Reynolds shear stress, turbulence length scales and velocity power spectra.

To investigate the applicability of the power- and logarithmic laws on *bura* mean wind velocity profiles, a suitable coordinate system was adopted with the x-axis aligned along the mean wind direction. Therefore, the original data for the two horizontal velocity components were adjusted to this new coordinate system.

To test the data sensitivity to the choice of the time averaging period, the time-averaged wind velocity for the summertime *bura* episode was calculated using moving average with four different time averaging periods. Periods of 5 min, 8 min, 17 min and 20 min were selected because it appears that, for this particular episode, the quasi-periodic *bura* pulsations occur at the time period of about 8 min and the time period of 17 ± 3 min represents a suitable turbulence averaging scale – the scale that separates turbulence from the mean flows at large scales (Magjarević et al., 2011). The analysis for the remaining 118 *bura* episodes was accordingly performed using moving average with the time averaging period of 17 min.

Thermal stratification is commonly described using the dimensionless stability parameter (e.g., Stull, 1988). Positive implies statically stable, negative implies statically unstable and equal to zero implies statically neutral thermal stratification.

In the past, the power law proposed by Hellman (1916) proved to represent well the mean wind velocity profile throughout the entire atmospheric boundary layer, while the logarithmic law (e.g., Thuillier and Lappe, 1964) is considered valid within the surface layer. While it is hypothesized that a typical *bura* surface layer is almost always near a neutral stratification, it is reasonable to ignore the thermal stability correction term in the logarithmic law and use the simplified expression in further analysis.

The applicability of the power law on the *bura* wind velocity profile is analysed by calculating the power-law exponent, α, and subsequently fitting the power law to the mean wind velocity profile that comprises of measured data at three studied heights. In particular, the time-averaged mean wind velocities in the x-direction at three levels are normalized using the time-averaged mean wind velocity in the x-direction at 40 m height. To test the logarithmic law suitability for the mean *bura* wind velocity profile, friction velocity, u_*, and aerodynamic surface roughness length, z_0, were calculated in two different ways, i.e., by data adjustment to the logarithmic law, and by directly applying the logarithmic law to a layer between 10 m and 40 m (Lepri et al., 2014, 2015). Turbulence intensity is defined as the root-mean-square of the fluctuating velocity components normalized with the time-averaged wind velocity (e.g., Simiu and Scanlan, 1996). Reynolds shear stress was calculated by using the fluctuating velocity correlations. The integral length scales of turbulence in the x-direction related to u', v', w' fluctuations were calculated using autocorrelation functions and assuming the validity of the Taylor frozen turbulence hypothesis (e.g., ESDU 74030, 1976). To remove the long-wave meandering from the time history prior to calculating *bu-*

ra turbulence parameters, the moving average was removed from the velocity time history because this long-wave meandering is not considered to be a part of *bura* turbulence. The power spectral density of longitudinal, lateral and vertical *bura* velocity fluctuations on all three height levels were calculated using the fast Fourier transform (FFT) (e.g., Stull, 1988). The results obtained for turbulence intensity, Reynolds shear stress, turbulence length scales and power spectrum densities were compared with values recommended in major international wind engineering standards and codes.

3. Results and concluding remarks

Due to strong mechanical mixing, *bura* is near-neutral thermally stratified. The differences in day to night trends are negligible for all parameters considered in this study (Lepri et al., 2017).

Trends in the power-law exponent, α, friction velocity, u_*, and aerodynamic surface roughness length, z_0, were studied dependent on the mean *bura* wind velocity. For the first time, it was established that the observed profiles of the mean wind velocity along the dominant *bura* direction agree well with the power law and logarithmic law approximations. The logarithmic law and the power law fit the measured data better when performing the analysis using the median rather than using the arithmetic mean wind velocity due to a drifting of the mean aerodynamic surface roughness length during the recording time. This indicates that a more robust median may be a more suitable parameter to determine the aerodynamic surface roughness length than the arithmetic mean value. For the friction velocity, the arithmetic mean proved to be independent of the time-averaging period length, while for the power-law exponent neither the arithmetic mean nor the median are influenced by the time-averaging period.

Another interesting feature is a decrease in α and z_0 and an increase in u_* with increasing *bura* mean wind velocity, and vice versa. This indicates an urban-like velocity profile for smaller wind velocities and a rural-like velocity profile for larger wind velocities, which is due to a stronger increase in absolute velocity at each of the heights observed as compared to the respective velocity gradient (difference in mean wind velocity among two different heights), (Lepri et al., 2014). Variations in velocity profiles at the same site during different wind periods are important to be noted because in the engineering community it has been commonly adopted that the aerodynamic characteristics at a particular site remain the same during various wind regimes.

For the first time, Reynolds shear stress during *bura* is assessed directly from suitable data sets. The observed values for turbulence intensity and Reynolds shear stress remain within the same range during the time record if the mean wind velocities exceed 5 ms^{-1}. When the mean wind velocities are lower than 5 ms^{-1}, the spread of these respective values increases considerably. This means that the wind velocity of 5 ms^{-1} may be considered as the critical velocity for *bura*. Turbulence intensity, unlike Reynolds shear stress, agrees well with the values recommended in international standards for the respective terrain type. 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, all in agreement with characteristics of the typical atmospheric boundary layer. Longitudinal turbulence length scales generally agree well with the values recommended in international standards for the respective terrain type, while turbulence length scales related to the lateral and vertical velocity fluctuations are much larger than the standard values. The choice of the time-averaging period proved not to influence the observed trends, while the median and arithmetic mean values are nearly the same for all three parameters.

Spectral distribution of *bura* turbulence kinetic energy differs from ESDU 85020 (1985) in a way that it is distributed across a wider range of frequencies compared to ESDU 85020 (1985). *Bura* spectrum is flatter, without a distinct peak, and there is a strong energy content at high frequencies.

To understand the real importance of the *bura* wind characterization from the engineering point of view, further work is still required with respect to *bura* turbulence for other terrain types, seasons and elevations from the ground, as well as the extreme value distributions in comparison with cyclonic events.

SADRŽAJ
CONTENTS

Hrv. meteor. časopis	Vol. 56	p. 1-216	ZAGREB	2023