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Weibull distribution of bora and sirocco winds in the northern Adriatic Sea

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Wind data measured at three off-shore stations in the northern part of the Adriatic Sea were considered: the Coastal oceanographic station Piran buoy (COSP), the PALOMA tower (the Gulf of Trieste) and the A. ALTA platform (Venice). Annual wind roses for all stations and additional seasonal wind roses for COSP are presented. The Weibull distribution function was applied to wind speed frequency distribution for winds from all directions and separately for bora and sirocco winds. Wind speed frequency distributions for bora winds measured at COSP and PALOMA are bimodal. One peak of this distribution of speeds belongs to nocturnal land breezes and another to bora winds. The peak separation method based on the difference in potential temperature of the atmospheric boundary layer (ABL) between two land stations (Udine and Zagreb) enabled the successful separation of the peaks of bora and land breeze winds. The frequency distribution of the wind speeds changed to the usual unimodal distribution when only those episodes were considered in which the potential temperature of ABL above Udine is higher than that above Zagreb.

Keywords: wind, wind rose, Weibull distribution, northern Adriatic Sea, potential temperature

1. Introduction

Coastal meteorological stations do not always represent the wind field over the sea because of the complex topography surrounding the northern part of a small Adriatic basin that influences directions of the winds on a very small scale. Therefore, oceanographic stations located at the sea are more appropriate for observing the undisturbed wind field above the sea. The new oceanographic station Piran is on the sea, not far from the coast (thus it is called »coastal«), but due to its exposed location it nevertheless gives rather reliable information about winds over the sea at the southwestern part of the Gulf of Trieste.

Typical winds above the Adriatic Sea are the northeasterly bora (from Greek *Boreas*, *burja* in Slovenian and *bura* in Croatian), blowing perpendicular to the Adriatic Sea axis, and the southeasterly sirocco winds (called *jugo* in Slovenia and Croatia), that blow along the Adriatic axis (Penzar et al., 2001). Their directions, however, differ along the Adriatic Sea coast due to its relief (Pasarić et al., 2007). Numerous studies on the causes and nature of the bora have been conducted. It's intensity and presence along the eastern coast of the Adriatic Sea (Penzar et al., 2001) have been investigated and studies of gust frequency, maximal wind speed and the duration of the bora have also been made (Pristov et al., 1989). Petkovšek and Paradiž (1976) made the first wind roses for some places with the bora in Slovenia – Ajdovščina, Postojna and Koper. In the same work they also showed a clear-cut connection between the strong bora and temperature differences between inland and the coastal area. An invasion of cold air from NE–E direction fills up the Pannonian basin while at the same time the air over the Adriatic is normally potentially still warmer. When the cold air passes the mountains the air accelerates along the steep southwestern slopes – this is the bora wind. The traditional explanation is that bora is a fall wind in case the windward temperature is cold enough so that when the air reaches the lowlands or coast, the dynamic warming is insufficient to raise the air temperature above that of the environment. The intensity and duration of Adriatic bora depend not only on a cold air supply over the Dinaric Alps but also on the lee side effects due to the mesoscale cyclone in the Adriatic sea (Brzović, 1999). The dynamic explanation of bora was revised, after intensive measurement campaign in ALPEX (Smith, 1987), after numerical modelling (Klemp and Durran, 1987), and some additional conceptual models (Smith and Sun, 1987) and so some recent studies have revealed that some boras have downslope windstorm or hydraulic jump structure (Gohm et al., 2007; Grubišić, 2004; Klaić et al., 2003). Its gustiness was traditionally explained by quasi-periodic spills of the cold air masses over the mountain ridge, while some new investigations connect the gustiness to the upper-tropospheric jet and tropopause behaviour (Belušić et al., 2004), to shear instabilities (Belušić and Klaić, 2004), to (quasi-periodic) Kelvin-Helmholtz instability and to the formation of the mountain-wave-induced rotor (Belušić et al., 2007).

Adriatic sirocco (hereinafter referred to as sirocco) considered in present work is only a part of the Mediterannean sirocco. It is moist and warm wind without gusts generally present on the front side of the eastward moving cyclonic activity in case of cyclonic sirocco (Pasarić and Orlić, 2004; Penzar et al., 2001; Poje, 1992). Less frequent anticyclonic sirocco is forced by high pressure field above the Mediterranean (Jurčec et al., 1996). Severe sirocco events can cause heavy precipitation in the northern part of the Adriatic area and sea level rise with flooding of the northern Adriatic lowlands (Brzović, 1999; Brzović and Strelec-Mahović, 1999).

The frequency distribution of the wind speed is of importance for the technology of wind energy (Burton et al., 2001; Seguro and Lambert, 2000; Wolstenholme, 1999), where the Weibull distribution (Weibull, 1951) of wind speed is frequently applied. Condradsen et al. (1984) made a review of the methods found in statistical literature for the purpose of estimation of the Weibull distribution parameters. Authors made a general conclusion that maximum likelihood estimators should be used due to their large sample efficiency. They suggest that wind speeds below the threshold value should be grouped together before estimation of the Weibull parameters to avoid bimodal wind speed distributions with a high probability of calm. In the work of Lavagnini et al. (1996) the regional wind climatology for Italian coastal stations along the western coast of the Adriatic Sea is given in the form of Weibull distribution parameters. They also calculated Weibull parameters for the offshore platform station in front of the Venice lagoon. In the work of Petkovšek and Paradiž (1976) we find the wind speed frequency distribution of bora gusts, the shape of which is similar to Weibull's.

Poje (1996) in his paper showed that the frequency distribution of the annual wind data at the coastal stations in Croatia with mountain-coastal type (Senj, Karlobag, Plomin,…) can have two or three overlapping peaks. He separated peaks to subsets using program Peakfit, which separates frequency curve with more peaks to two or more overlapping individual curves using Levenberg-Marquardt algorithm. Best results were accomplished using Weibull and Gamma function curves. In another paper Poje (1995) analyzed ten-year hourly wind data measured at Split-Marjan meteorological station for the months January and July to determine the main statistical characteristics of the most frequent NNE–NE winds. Poje used some statistical program for group separations on the wind speed distribution and had found that in most cases wind speed data from NE quadrant can be divided to two or even three subgroups. Therefore he separated winds from these directions to two main subgroups bora and burin (»a form of weak or moderate bora«) on the basis of duration and the nature of the wind speed.

A comparison of the wind properties measured above the sea at locations near the eastern and western coasts of the northern Adriatic Sea (NAS) has not been done yet. Yoshimura and Tamiya (1976) compared gust nature in Ajdovščina (Slovenia) and Trieste (Italy), but only land measurements were considered.

Yoshino (1976) mentioned that a strong bora reaches a distance of 50–60 km off the coast to the open sea, but in the Venice lagoons the strength of bora gusts achieves 60–70 % of the gust strength measured in Trieste. Recently Dorman et al. (2007) showed that when a distinctive bora pith exists in the Gulf of Trieste the wind strength is almost the same at the other side of the northern Adriatic (near Venice).

This study is focused on the analysis of the wind data from the coastal oceanographic station Piran (COSP). Seasonal and annual wind rose diagrams and the Weibull distribution coefficients of wind speed frequencies are presented. The distribution of the most frequent winds, bora and sirocco, will also be shown. A comparison of analyzed wind data of COSP with the analyzed data of two other maritime stations in the NAS is presented.

2. Methods

2.1. The data and wind rose diagrams

Three offshore stations in the NAS are the »Coastal oceanographic station Piran« of NIB-MBS (COSP), the »Paloma« tower of ARPA FVG-OSMER and the »Acqua Alta« Oceanographic Platform of CNR-ISMAR. The positions of these offshore stations are presented in Figure 1 while the stations' characteristics and time intervals of available data are collected in Table 1. The wind data contain average wind speed and direction information half-hourly for COSP and hourly for Paloma and Acqua Alta. Half-hourly values from COSP are averages computed over a time interval of 10 minutes preceding that time until 21.5.2003, after which a new anemometer was installed at COSP and averages over a time interval of 30 minutes are computed for a certain value. The A.Alta hourly value is an average of 5 minute intervals preceding the hour and the Paloma hourly value is the average computed over a time interval of 10 minutes preceding the hour.

Firstly, the essential analysis of wind data is made to determine the typical seasonal and annual wind directions and intensities at COSP, which are presented with wind rose diagrams. Wind directions are distributed in 36 direction sectors 10° wide. For each direction sector the frequency distribution of wind speeds is made, where the first speed class is reserved for calms – winds with speeds below 0.5 m/s. The next speed class is between 0.5 m/s – 2 m/s. All other speed classes are 2 m/s wide and range up to 16 m/s. Wind rose diagrams were made using the software tool Lakes Environmental WRPLOT View ver. 5.0.1. Seasonal wind rose diagrams for the COSP station are made for the following seasons: winter – December, January, February; spring – March, April, May; summer – June, July, August; autumn – September, October, November. Secondly, annual wind rose diagrams for the other two stations reveal differences in typical wind directions above the northern Adriatic Sea.

We define here as candidates for bora all winds that blow from approximately northeastern directions and for sirocco all winds that blow from approximately southeastern directions (details are given in Table 2). Furthermore, frequency distribution histograms are made for all winds and separately for the bora and sirocco. These are the basis for the regression with the Weibull

Table 1. List of stations with form descriptions, geographical co-ordinates, measuring frequencies and data periods.

Station	Form	Latitude	Longitude	Frequency [h]	Ha [m]	Interval
COSP Piran	buoy	45° 33' N	13° 33' E	1/2	2.8	2001–2004
PALOMA Trieste	tower	45° 37' N	13° 34' E	1	5	2003–2004
A.ALTA Venice	platform	45° 19' N	12° 31' E	1	15	2002–2004

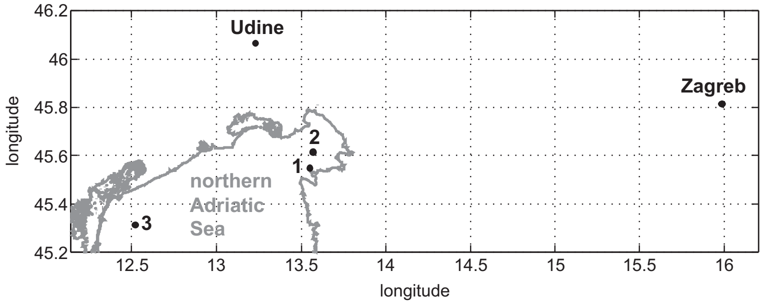

Figure 1. Map of the northern Adriatic Sea with the locations of offshore measuring stations (1 – COSP Piran, 2 – PALOMA Trieste, 3 – A. ALTA Venice). Zagreb and Udine are locations of the radiosoundings.

distribution described below. Wind speeds for this purpose are distributed in classes of 1 m/s.

2.2. The Weibull distribution

Seasonal and annual variations of wind speed can be described with distribution functions. Stewart and Essenwanger (1978) showed that the Weibull distribution function (Weibull, 1951) provides a good analytical approximation for frequency distribution of wind speeds near the surface. The probability density function of the Weibull distribution is defined as

$$f(x) = \frac{\delta}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\delta-1} \exp\left[-\left(\frac{x-\gamma}{\beta}\right)^{\delta}\right] \mathit{for}\ x \geq \gamma, \tag{1}$$

where $\delta > 0$ is the shape parameter, $\beta > 0$ the scale parameter and γ is the location parameter of the distribution. The scale and location parameters have the dimension of the variable (m/s); the shape parameter is dimensionless. In the case of $\gamma = 0$ we get a two parametric version of the distribution. The parameter β is in relationship with the mean value of the wind speed as follows (Wolstenholme, 1999)

$$\bar{x} = \beta \cdot \Gamma\left(1 + \frac{1}{\delta}\right) \tag{2}$$

where Γ represents the Gamma function. The Weibull distribution of wind speeds over a year is a consequence of a high level of coincidental variations. Important are also seasonal variations: at moderate latitudes winter months are in general much windier than summer months. At coastal stations sea--land breeze plays additional role, especially during summer. So in some cases we get two peaks in the frequency distribution of wind speed – the bimodal probability density function of the Weibull distribution that is described with the equation (Wolstenholme, 1999)

$$\begin{aligned} f_b(x) = {} & w\frac{\delta_1}{\beta_1}\left(\frac{x-\gamma_1}{\beta_1}\right)^{\delta_1-1}\exp\left[-\left(\frac{x-\gamma_1}{\beta_1}\right)^{\delta_1}\right]+ \\ & +(1-w)\frac{\delta_2}{\beta_2}\left(\frac{x-\gamma_2}{\beta_2}\right)^{\delta_2-1}\exp\left[-\left(\frac{x-\gamma_2}{\beta_2}\right)^{\delta_2}\right] \quad \mathit{for}\ x \geq \gamma_1, \gamma_2 \end{aligned} \tag{3}$$

where δ_i, β_i and γ_i are parameters for each peak in density and w is a weight coefficient.

The above mentioned distribution is used as a model function for the regression analysis of wind speed distribution. For this analysis a frequency distribution of the wind speed data with speed classes 1 m/s wide is made for winds from a chosen range of wind directions. Then a model curve is fitted to this distribution. Both, 2- and 3-parametric models were applied for unimodal distributions and 5- and 7-parametrics for obvious bimodal distributions of wind speeds. The mean absolute error is defined as

$$Err = \sum_{i=1}^{N}(x_i - f_i)^2, \tag{4}$$

where x_i and f_i stand for measured data and modelled result respectively. This measure shows which model better fits the data.

2.3. Separation of peaks

Some histograms for winds from the northeast sector of directions reveal a bimodal frequency distribution of wind speeds. It is expected that one peak belongs to the typical bora wind and the other to the wind driven by the land breeze. We tried to isolate bora wind events by looking at the difference in temperature in the lower layers of the atmosphere. The radiosounding data are found to be the most appropriate for the study of temperature differences. For the horizontal temperature gradient over the northwest Adriatic are the radiosounding data from Zagreb and Udine the most representive for gradient estimation (Figure 1).

The radiosounding data we used is available at the website[1]. The mean mixed layer potential temperature (MMLPT) – the average potential temperature in the lowest 500 m of air – was applied in further analysis. Selection of the subset of the wind data is related to the horizontal gradient of the poten-

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[1] http://weather.uwyo.edu/upperair/europe.html

tial temperature between inland and the coast – criterion for the »proper« bora is when the MMLPT above Zagreb is lower than that above Udine. A simple criteria for separation between land breeze and bora is thus defined with

$$MMLPT_{Zagreb} - MMLPT_{Udine} = \begin{cases} \geq 0; & sea\ breeze \\ < 0; & bora \end{cases}. \tag{5}$$

We separated wind data with the above criteria. The information about the horizontal gradient of potential temperature is available every 12 hours while the wind data from COSP are retrieved every half hour and hourly from other stations. For every radiosounding data the wind data in the time window of 6 hours before and after time of the radiosounding is considered.

3. Results

3.1. Wind rose diagrams

The prevalent wind in the northern Adriatic area is the bora which blows from the NE–E area as can be seen on annual wind rose diagrams for all three offshore stations (Figure 2). The second most frequent wind measured at COSP is the sirocco as expected, blowing from the S–SE direction. At the other two stations the sirocco is not present so explicitly – besides the bora there are almost uniform distributions of wind directions, except at the Paloma station, where a peak of northern wind is present. Our attention is concentrated on bora and sirocco winds therefore we analyzed direction intervals and portions of these winds at a certain station. These intervals are presented in Table 2 which also contains a portion of calms that are not presented on the diagrams. From Table 2 one reads a relatively high percentage of calms at the Paloma

Table 2. Direction intervals and percentage of calm for each location.

	COSP Piran	Paloma Trieste	A. Alta Venice
directions of bora [°]	45.0–78.8	67.5–90.0	45.0–67.5
directions of sirocco [°]	135.0–180.0	135.0–180.0	135.0–180.0
calm [%]	1.33	8.33	1.55

Table 3. Mean wind velocity and portion of bora and sirocco winds for all 3 stations from whole sets of data.

	COSP Piran		Paloma Trieste		A.Alta Venice	
direction	bora	sirocco	bora	sirocco	bora	sirocco
mean velocity [m/s]	7.3	3.6	9.3	3.5	7.8	4.2
% of bora/sirocco of all winds	26	18	22	5	21	12

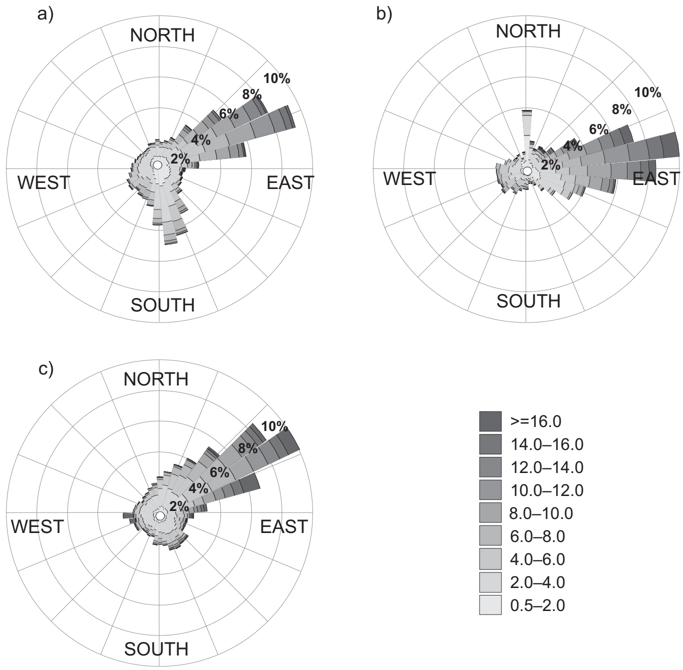

Figure 2. Annual wind rose diagrams for offshore stations – (a) COSP, (b) Paloma, (c) A. Alta; values in legend are m/s.

station which may be related to instrumental error or high anemometer threshold.

As already mentioned special attention is given to COSP winds where we analyzed wind data seasonally. In every season of the year bora and sirocco winds prevail (Figure 3) and the bora prevails over the sirocco except during the summer period, yet it still has the highest frequency also during these seasons. The bora is the weakest and least frequent during spring and summer. On the other hand the southwestern wind plays an important part in spring and summer winds.

3.2. Weibull distribution

Similar distributions of the wind speeds of the bora at Paloma in the center of the Gulf of Trieste and at its southern side at the entrance to this gulf near COSP can be found. This is the bimodal distribution of wind speed and it appears in both cases (Figure 4 and Figure 5). It is suspected that the first weaker peak is related to nightly land breeze while the second represents the bora. Positions of the first peak at COSP and Paloma are the same: at 2–3 m/s. The positions of the second peak are also close to one another. At COSP the

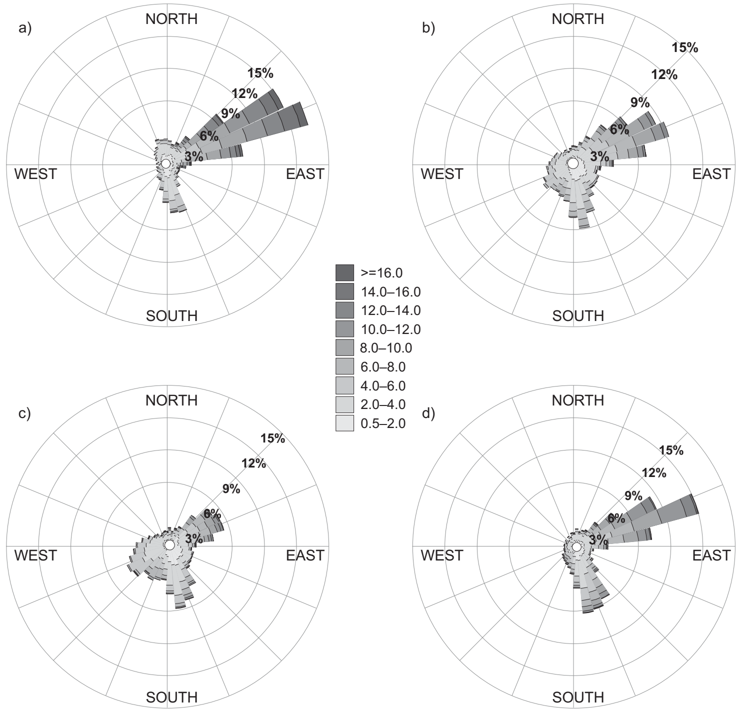

Figure 3. Seasonal wind rose diagrams for COSP – (a) winter, (b) spring, (c) summer, (d) autumn; values in legend are in m/s.

second peak is sharp and is located at 7–8 m/s. At Paloma the peak is wider and is located at speeds 8–11 m/s. In the area of Venice the direction of the bora coincides with the direction of the daily sea breeze therefore the unimodal distribution was expected there. We can see (Figure 6) that only one peak exists at 4–5 m/s. Distributions of wind speeds for all winds from all di-

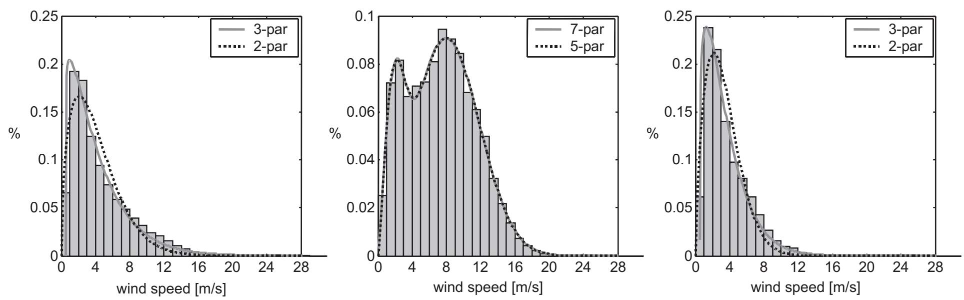

Figure 4. Wind speed frequency distribution for COSP station with fitted curves for 3 cases: all winds (left), bora wind (center) and sirocco wind (right).

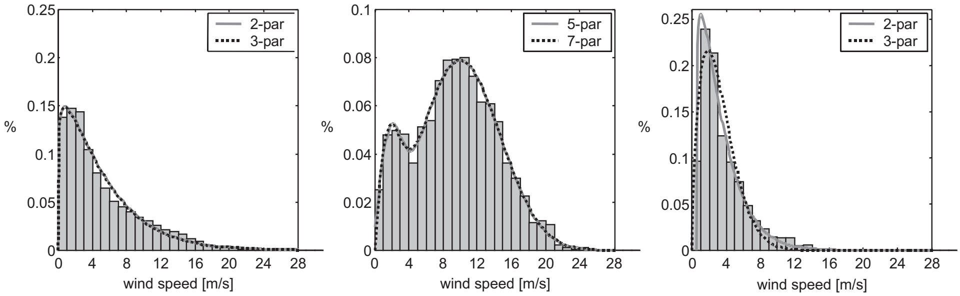

Figure 5. Same as Figure 4 except for Paloma station.

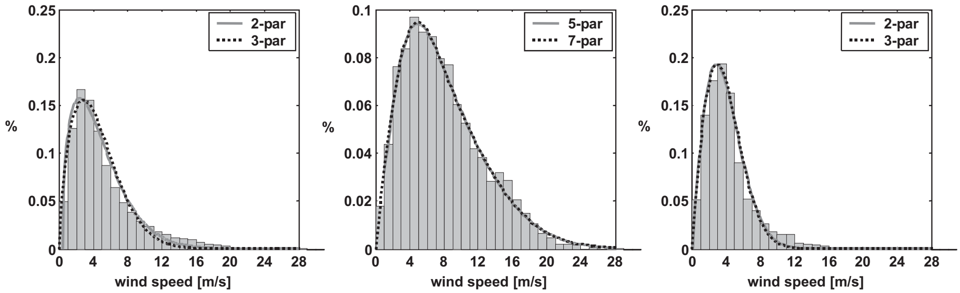

Figure 6. Same as Figure 4 except for A. Alta station.

rections and for the sirocco only are unimodal for all three stations. Two and three parametric Weibull functions (unimodal distribution) were used for fitting all the wind data and the data of the sirocco wind, while for the bora five and seven parametric functions (bimodal distribution) were applied. It turns

Table 4. Weibull parameters for COSP station.

COSP	all winds		sirocco		bora	
	2par	3par	2par	3par	5par	7par
w	–	–	–	–	0.179	0.168
β_1	4.485	3.928	3.687	3.136	2.499	2.544
δ_1	1.490	1.106	1.688	1.223	2.140	2.280
β_2	–	–	–	–	9.550	9.780
δ_2	–	–	–	–	2.642	2.672
γ_1	–	0.500	–	0.499	–	–0.091
γ_2	–	–	–	–	–	–0.280
Err	0.0056	0.0007	0.0073	0.0008	0.0001	0.0001

Table 5. Weibull parameters for Paloma station

Paloma	all winds		sirocco		bora	
	2par	3par	2par	3par	5par	7par
w	–	–	–	–	0.130	0.128
β_1	5.298	5.317	3.523	3.020	2.447	2.866
δ_1	1.127	1.116	1.598	1.153	1.904	2.327
β_2	–	–	–	–	11.835	12.034
δ_2	–	–	–	–	2.701	2.746
γ_1	–	0.089	–	0.500	–	–0.478
γ_2	–	–	–	–	–	–0.234
Err	0.0010	0.0010	0.0055	0.0009	0.0003	0.0002

out that there is no significant difference in the »goodness of fit« (the »Err« quantity in tables 4–7) between two or three and five or seven parametric fitting models. Estimated Weibull parameters are presented in tables 4, 5 and 6.

After separating the bimodal distributions to bora and to the land breeze wind according to the difference in the MMLPT between Zagreb and Udine the pure unimodal distributions for the bora in COSP and Paloma (close to Piran and Trieste) were obtained. This indicates the usefulness of the applied criterion. Figure 7 shows the distribution of selected data for »real« bora. This method also seems to separate the land breeze from the bora in Venice quite successfully, irrespective of the same wind directions. Coefficients of the Weibull distribution of the selected wind data from the direction of the bora are presented in Table 7.

Table 6. Weibull parameters for A. Alta station

A. Alta	all winds		sirocco		bora	
	2par	3par	2par	3par	5par	7par
w	–	–	–	–	0.175	0.147
β_1	4.951	4.666	4.333	4.214	5.343	4.535
δ_1	1.656	1.408	1.927	1.835	2.232	1.920
β_2	–	–	–	–	9.709	9.844
δ_2	–	–	–	–	1.803	1.811
γ_1	–	0.445	–	0.151	–	1.029
γ_2	–	–	–	–	–	–0.338
Err	0.0023	0.0014	0.0018	0.0018	0.0003	0.0003

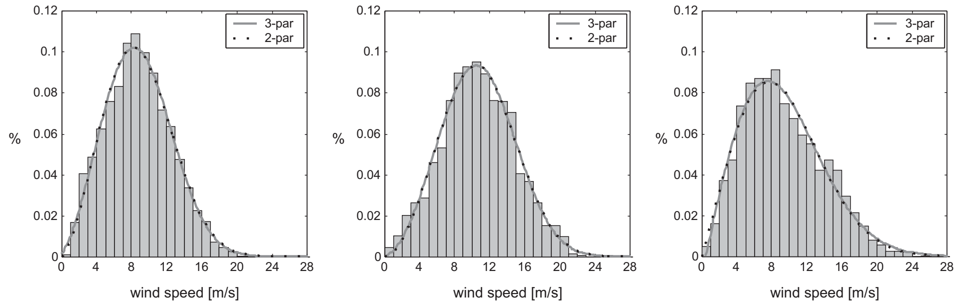

Figure 7. Wind speed distribution with fitted curves for bora wind for all 3 stations after selection of the wind data for winds blowing from the direction of the bora.

Table 7. Weibull parameters for the bora.

	COSP Piran		PALOMA Trieste		ACQUA ALTA Venice	
	2par	3par	2par	3par	2par	3par
β	9.565	10.422	12.121	12.363	10.433	10.000
δ	2.401	2.675	2.871	2.938	2.112	1.998
γ	–	–0.952	–	–0.266	–	0.489
Err	0.0005	0.0003	0.0005	0.0005	0.0007	0.0006

4. Conclusions

The bora wind is the prevalent wind at all three stations. Seasonal wind rose diagrams for the COSP station show that the bora prevails throughout the year except during the summer period when the sirocco prevails. The sirocco blows in every season, while the bora is weakest and less frequent during spring and summer.

Wind speed frequency distribution indicates that the most frequent winds are those with velocities 1–2 m/s at the COSP and PALOMA stations and 2–3 m/s at A.ALTA station. Fitting a Weibull distribution to the wind speed frequency distribution at A.ALTA station shows very similar Weibull parameters to the Lavagnini et al. (1996) estimate. It also must not be forgotten that statistical analysis of the wind data from non-overlapping time intervals as in our case could lead to different estimates of Weibull parameters. It would be interesting to make a comparison of Weibull coefficients estimated on longer and same data period for all three stations with coefficients estimated in this paper.

Wind speed frequency distribution of bora winds shows bimodal distribution at COSP and PALOMA while there the distribution of sirocco winds is unimodal. At A.ALTA both distributions for the bora and sirocco are unimodal. The separation method, which applied the proper difference in potential temperature of the atmospheric boundary layer enabled the successful separation of peaks of the bora and sea breeze winds. For all three stations only about 80 % of measured winds from the northeast directions are related to the bora, while about 20 % are related to the sea-land breeze. Two or three parametric Weibull distribution functions gave insignificant differences in the goodness of fit for filtered data. Separating the Venice data was also successful, although already the original data have a unimodal distribution.

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References

Belušić, D. and Klaić, Z.B. (2004): Estimation of Bora wind gusts using a limited area model, *Tellus A*, **56**, 296–307.

Belušić, D., Pasarić, M. and Orlić, M. (2004): Quasi-periodic bora gusts related to the structure of the troposphere, *Q. J. Roy. Meteor. Soc.*, **130**, 1103–1121.

Belušić, D., Žagar, M. and Grisogono, B. (2007): Numerical simulation of pulsations in the bora wind, *Q. J. Roy. Meteor. Soc.*, **133**, 1371–1388.

Brzović, N. (1999): Factors affecting the Adriatic cyclone and associated windstorms, *Contrib. Atmos. Phys.*, **72**, 51–65.

Brzović, N. and Strelec Mahović, N. (1999): Cyclonic activity and severe jugo in the Adriatic, *Phys. Chem. Earth (B)*, **24**, 653–657.

Burton, T.D., Sharp, D., Jenkins, N. and Bossanyi, E. (2001): *Wind energy handbook*. John Wiley & Sons, Ltd., West Sussex,

Conradsen, K., Nielsen, B. and Prahm, L.P. (1984): Review of Weibull statistics for estimation of wind speed distributions, *J. Appl. Meteorol.*, **23**, 1173–1183.

Dorman, C.E., Carniel, S., Cavaleri, L., Sclavo, M., Chiggiato, J., Doyle, J., Haack, T., Pullen, J., Grbec, B., Vilibic, I., Janekovic, I., Lee, C.M., Malacic, V., Orlic, M., Paschini, E., Russo, A. and Signell, R.P.: (2007): February 2003 marine atmospheric conditions and the bora over the northern Adriatic, *J. Geophys. Res.-Oceans*, **112** (C3), 1–21.

Essenwanger, O.M. (1976): Applied statistics in atmospheric science, Part A. Frequences and curve fitting. Elsevier Scientific Publishing Company, 424 pp.

Gohm, A., Mayr, G.J. and Giez, A. (2007): On the onset of bora and the formation of rotors and jumps near a mountain gap, *Q. J. Roy. Meteor. Soc.*, **133**, 1–25.

Grubišić, V. (2004): Bora-driven potential vorticity banners over the Adriatic, *Q. J.Roy. Meteor. Soc.*, **130**, 2571–2603.

Jurčec, V., Ivančan-Picek, B., Tutiš, V. and Vukičevič, V. (1996): Severe Adriatic jugo wind, *Meteorol. Z.*, **5**, 67–75.

Klaić, Z.B., Belušić, D., Grubišić, V., Gabela, L. and Čoso, L. (2003): Mesoscale airflow structure over the northern Croatian coast during MAP IOP 15 – a major bora event, *Geofizika*, **20**, 23–61.

Klemp, J.B. and Durran, D.R. (1987): Numerical modelling of bora winds, *Meteorol. Atmos. Phys.*, **36**, 215–227.

Lavagnini, A., Martorelli, S. and Cavaleri, L. (1996): The wind climatology of the Adriatic Sea deduced from coastal stations, *Il Nuovo Cimento C*, **19**, 37–50.

Pasarić, Z., Belušić, D. and Klaić, Z.B. (2007): Orographic influences on the Adriatic sirocco wind, *Ann. Geophys.*, **25**, 1263–1267.

Pasarić, M. and Orlić, M. (2004): Meteorological forcing of the Adriatic: present vs. projected climate conditions, *Geofizika*, **21**, 69–87.

Penzar, B., Penzar, I. and Orlić, M. (2001): *Vrijeme i klima hrvatskog Jadrana*. Nakladna kuća »Dr. Feletar«, Zagreb,

Petkovšek, Z. and Paradiž, B. (1976): *Bora in the Slovenian coastal region*. University of Tokyo Press, Tokyo,

Poje, D. (1995): Bura (bora) and burin at Split, *Hrv. meteorološki časopis*, **30**, 1–19.

Poje, D. (1996): Distribution functions and the estimation of wind power, *Hrv. meteorološki časopis*, **31**, 1–13.

Poje, D. (1992): Wind persistence in Croatia, *Int. J. Climatol.*, **12**, 569–586.

Pristov, N., Petkovšek, Z. and Zaveršek, J. (1989): Some characteristics of bora and its beginnings in Slovenia, *Razprave – Papers DMS*, **30**, 37–52.

Seguro, J.V. and Lambert, T.W. (2000): Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis, *Wind Eng. Ind. Aerod.*, **85**, 75–84.

Smith, R.B. (1987): Aerial observations of the Yugoslavian bora, *J. Atmos. Sci.*, **44**, 269–297.

Smith, R.B. and Sun, J.-L. (1987): Generalized hydraulic solutions pertaining to severe downslope winds, *J. Atmos. Sci.*, **44**, 2934–2939.

Stewart, D.A. and Essenwanger, O.M. (1978): Frequency distribution of wind speed near the surface, *J. Appl. Meteorol.*, **17**, 1633–1642.

Weibull, W. (1951): A statistical distribution function of wide applicability, *J. Appl. Mech.*, 293–297.

Wolstenholme, L.C. (1999): *Reliability modelling: A statistical aproach*. Chapman & Hall/CRC, 272 pp.

Yoshimura, M. and Tamiya, H. (1976): Some climatological aspects of bora on the northern part of the Adriatic Sea. University of Tokyo Press, Tokyo

Yoshino, M.M. (1976): *Local wind Bora*. University of Tokyo Press, Tokyo, 289 pp.

Appendix

Regression with the Weibull function

The Matlab routine lsqcurvefit is applied for regression. The routine is based on the Levenberg-Marquardt algorithm and it requires initial values for searched parameters. The third parameter γ is initialized to 0 in the 3-parametric case. Out of the histogram an approximate position of the extremes could be read which helps in the initialization of the other two parameters. The other way of initialization is related to analytical derivation of the extreme of the density function

$$\begin{aligned}
&\frac{df(x)}{dx}=\frac{\delta}{\beta^2}\left(\frac{x}{\beta}\right)^{\delta-2}\cdot\left[(\delta-1)-\delta\left(\frac{x}{\beta}\right)^{\delta}\right]\cdot\exp\left[-\left(\frac{x}{\beta}\right)^{\delta}\right]=0\\
&x_1=0 \qquad\qquad (6)\\
&x_2=\beta\left(1-\frac{1}{\delta}\right)^{1/\delta}=x_E
\end{aligned}$$

The first solution for extreme is trivial and the second is important for us. Parameter β can be eliminated by dividing x_E from eq. (6) with the mean value of x defined with eq. (2). The following fraction is a constant:

$$\frac{x_E}{\bar{x}} = \frac{\beta \cdot \sqrt[\delta]{1-\frac{1}{\delta}}}{\beta \cdot \Gamma\left(1+\frac{1}{\delta}\right)} = const. = \alpha \,, \tag{7}$$

where Γ stands for the Gamma function. The mean value of x can also be evaluated from the data so only parameter δ remains unknown.

A logarithm of the last equation (7) yields the following expression for δ

$$\delta = \left(1 - \exp\left[\delta \cdot \left(\ln\alpha + \ln\left[\Gamma\left(1+\frac{1}{\delta}\right)\right]\right)\right]\right)^{-1}, \tag{8}$$

which can be solved iteratively. The most frequent value of parameter δ is 2 (Essenwanger, 1976). So this value is used as the initial value for the iteration. When δ is calculated, β could be evaluated either with equation (2) or (6). This completes the procedure for the initial values of three parameters needed for curve fitting.

In the case of bimodal Weibull distribution we need 5 or 7 initial values, depending on the use of parameter γ. In the first place we separated peaks and worked with them separately to get initial values of parameters δ_1, β_1 and δ_2, β_2, as described above for the unimodal distribution. Again, initial γ_1 and γ_2 were set to 0 in the case of 5 parametric distribution. Then we needed to determine the initial value for weight coefficient w. Here we used the graphical procedure described by Essewanger (1976). He plotted normalized cumulative distribution of data in a logarithmic scale on x axis. A cross-section of a tangent to the data curve with a parallel to y axis gives an initial value for w. The main advantage of the method we used to evaluate Weibull distribution coefficients is its simplicity and good fitting results. In the case of bimodal distribution some improvements in determining initial weight coefficients could be done for use on study of several cases (e.g. for several stations).

SAŽETAK

Weibullova distribucija bure i juga na sjevernom Jadranu

Maja Jeromel, Vlado Malačič i Jože Rakovec

Obrađeni su podaci na tri morske postaje na sjevernom Jadranu: oceanografskoj plutači Obalne oceanografske postaje Piran (COSP), tornju Paloma u Tršćanskom zaljevu i na platformi A.ALTA ispred Venecije. Predstavljene su godišnje ruže vjetrova za sve tri postaje i dodatno sezonske ruže vjetrova za COSP. Weibullova distribucijska funkcija bila je primijenjena na razdiobu čestine brzine vjetra za vjetrove iz svih smjerova i posebno za buru i sirocco. Razdioba čestina brzine vjetra izmjerenog na COSP i PALOMA iz smjerova bure pokazala se kao bimodalna. Jedan vrh u toj distribuciji pripada dnevno-noćnoj cirkulaciji zraka, a drugi buri. Uspješna metoda separacije vrhova temelji se na razlici u potencijalnoj temperaturi zraka u atmosferskom graničnom sloju (AGS) iznad Udina i Zagreba. Razdioba čestina brzine vjetra postaje unimodalna kada se promatraju samo one epizode vjetra kad je potencijalna temperatura AGS iznad Udina viša od potencijalne temperature iznad Zagreba.

Ključne riječi: vjetar, ruža vjetrova, Weibullova razdioba, sjeverni Jadran, potencijalna temperatura

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