Wind and Structures, Vol. 8, No. 6 (2005) 389-405

DOI: http://dx.doi.org/10.12989/was.2005.8.6.389

Meteorological basis for wind loads calculation in Croatia

Alica Bajić†

Research and Atmospheric Modelling Department, Meteorological and Hydrological Service of Croatia, Grič 3, HR-10000 Zagreb, Croatia

Bernardin Peroš‡

Faculty of Civil Engineering, University of Split, Matice Hrvatske 15, HR-21000 Split, Croatia

(Received January 16, 2003, Accepted October 24, 2005)

Abstract. The results of reference wind speed calculation in Croatia as a base for the revision of the Croatian standards for wind loads upon structures are presented. Wind speed averaged over 10 minutes, at 10 m height, in a flat, open terrain, with a 50-year mean return period is given for 27 meteorological stations in Croatia. It is shown that the greatest part of Croatia is covered with expected reference wind speeds up to 25 m/s. Exceptions are stations with specific anemometer location open to the *bura* wind which is accelerated due to the channelling effects of local orography and the nearby mountain passes where the expected reference wind speed ranges between 38 m/s and 55 m/s. The methodology for unifying all available information from wind measurements regardless of the averaging period is discussed by analysing wind speed variability at the meteorological station in Hvar.

Keywords: extreme speed; standards; wind load.

1. Introduction

The availability of precise data on the basic wind speed becomes important when evaluating the actions and effects of wind on structures. The evolution of the international codification scene, particularly the European one, provides a strong motivation for the formulation of an adequate base for the development of national wind maps. In countries with very complex wind regimes, such as Croatia, this is a challenging task. The wind regime in Croatia is influenced by the Alps to the northwest, the Dinaric Mountain along the Adriatic coast, the Adriatic Sea and the Panonian plain to the northeast. Thus, with such complex terrain it is not easy to obtain a representative wind database.

An extensive research programme has been carried out earlier to investigate the wind loads upon slender steel structures, especially along the Adriatic coast, during strong and turbulent *bura* (Peroš 1998, Peroš and Boko 2000, Peroš and Boko 2000a). The results show that the existing standards

† M. Sc-ing., Corresponding Author, E-mail: bajic@cirus.dhz.hr
‡ Professor, E-mail: bernardin.peros@gradst.hr

for loads and safety are not adequate for engineering practice, and that an updating of the Croatian wind map is necessary. The first steps of a comprehensive analysis of reference wind speeds has been carried out during the last few years based on available wind data records until the end of 2002. (Bajić, *et al.* 2001, Bajić and Peroš 2001, Bajić 2004).

The aim of this paper is to present a summary of the results of the mentioned study and to discuss the possibilities of reference wind speed calculation with regard to existent wind measurements and the complex wind regime of Croatia. The paper is divided into five parts dealing with:

- available wind measurements,
- description of the wind regime in Croatia,
- reference wind speed calculation,
- relation between hourly and 10-minute average wind speeds,
- comments and conclusions.

2. Data

Wind speed and direction measurements in Croatia are carried out mostly at meteorological stations as part of the activities of the Meteorological and Hydrological Service of Croatia. Some anemometers have been installed by other companies (mostly Croatian Electricity) but their data acquisition, correction and archiving is done by the National Meteorological Service. Data have been checked for errors and homogeneity (measured in uniform conditions).

The following analyses are based on the available measurement of the average wind speed over 10 minutes (recommended as the base for wind load calculations) performed by 27 stations. Table 1 shows a list of these stations indicating for each one the order number n, the time interval t_1-t_2 of available data, the latitude φ, longitude λ, the altitude h_s above sea level, the description of the site (*C=city, H=hilly zone, I=island, L=coast, M=mountain, P=plain*), the height h_a of the anemometer above the ground and the percentage of missing data *MD*. Fig. 1 illustrates the geographic

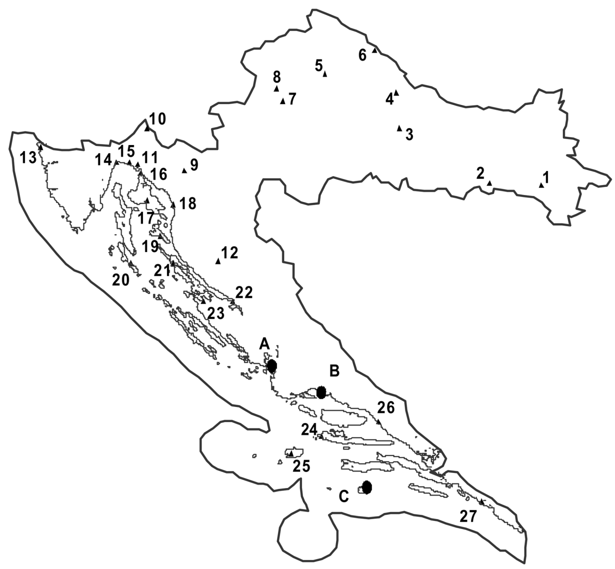

Fig. 1 Location of the meteorological stations numbered as in Table 1 and Table 8

Table 1 Basic data for the meteorological stations used

n	Station	$Ds.$	φ	λ	h_s (m)	h_a (m)	t_1-t_2	MD (%)
1	Gradište	P	45° 09'	18° 42'	97	10	1995-2002	19.6
2	Slavonski Brod	C,P	45° 10'	18° 10'	107	12	1995-2002	14.1
3	Daruvar	C,P	45° 36'	17° 14'	161	12	1999-2002	4.1
4	Bilogora	H	45° 53'	17° 12'	262	15	1995-2002	18.5
5	Čakovec*	P	46° 19'	16° 28'	170	14	1995-2002	33.5
6	Gotalovo	P	46° 13'	16° 59'	122	10	1997-2002	5.6
7	Zagreb-Maksimir	C,P	45° 49'	16° 02'	128	10	1999-2002	6.0
8	Puntijarka*	M	45° 55'	15° 58'	988	28	1995-2002	56.7
9	Ogulin*	C,H	45° 16'	15° 14'	328	10	1995-2002	23.6
10	Parg	M	45° 36'	14° 38'	863	10	1998-2002	9.8
11	Melina*	H	45° 19'	14° 32'	190	10	1995-2002	32.6
12	Gospić	C,H	44° 33'	15° 22'	564	10	1998-2002	15.9
13	Umag	C,L	45° 27'	13° 32'	10	10	1999-2002	6.9
14	Opatija*	C,L	45° 20'	14° 19'	5	15	1997-2002	21.9
15	Rijeka*	C,L	45° 20'	14° 27'	120	10	1996-2002	23.6
16	Krk Bridge	L	45° 15'	14° 34'	57	3	1996-2002	1.3
17	Punat*	C,L	45° 02'	14° 38'	30	10	1999-2002	37.8
18	Senj	C,L	45° 00'	14° 54'	26	10	1995-2002	0.8
19	Rab*	C,I,L	44° 45'	14° 46'	24	13	1995-2002	28.7
20	Mali Lošinj	C,I,L	44° 32'	14° 28'	53	10	1995-2002	3.4
21	Novalja	I,L,P	44° 32'	14° 54'	20	10	1995-2002	0.2
22	Maslenica Bridge	L	44° 14'	15° 31'	90	3	1998-2002	17.0
23	Zadar	C,L	44° 14'	15° 13'	5	13	1995-2002	19.5
24	Hvar	C,L,I	43° 10'	16° 07'	20	15	1995-2002	14.9
25	Hum-Vis*	H,I	43° 02'	16° 07'	587	10.5	1996-2002	22.0
26	Makarska	C,L	43° 17'	17° 01'	52	11	1995-2002	19.1
27	Dubrovnik	C,L	42° 39'	18° 05'	52	10	1995-2002	13.1

n-order number, $Ds.$-station description, φ-latitude, λ-longitude, h_s-altitude above sea level, h_a-height of anemometer, t_1–t_2-time interval of available data, MD-percentage of missing data, *-indication for stations with more than 20% missing data

distribution of the recording stations.

As could be seen the availability of 10-minute wind speed data in Croatia is not adequate. We have only 27 stations with measurement periods of 4 – 8 years. In addition, the number of missing data exceeds 20% at some locations (indicated with * in Table 1). An additional problem is the spatial distribution of the wind measurement stations. The number of stations along the middle and southern Adriatic and on the islands is not adequate for obtaining a correct spatial distribution of wind speed in such complex terrain with pronounced local winds. Nevertheless, the analysis of all available data gives the main characteristics of reference wind speed at locations with wind measurements and makes a solid base for further studies.

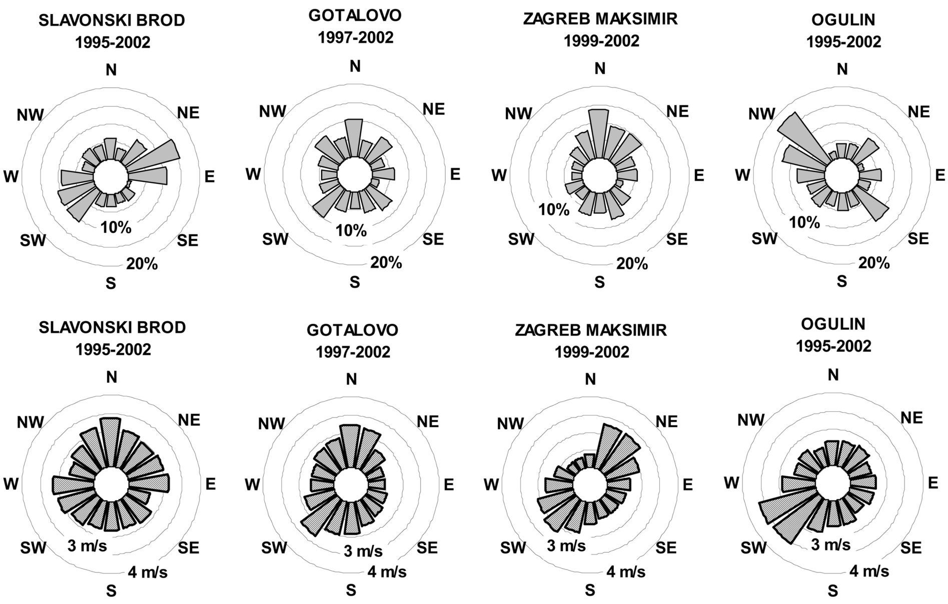

Fig. 2 Relative frequency of wind direction (top) and average wind speed for each wind direction (bottom) for the meteorological stations located in the continental part of Croatia

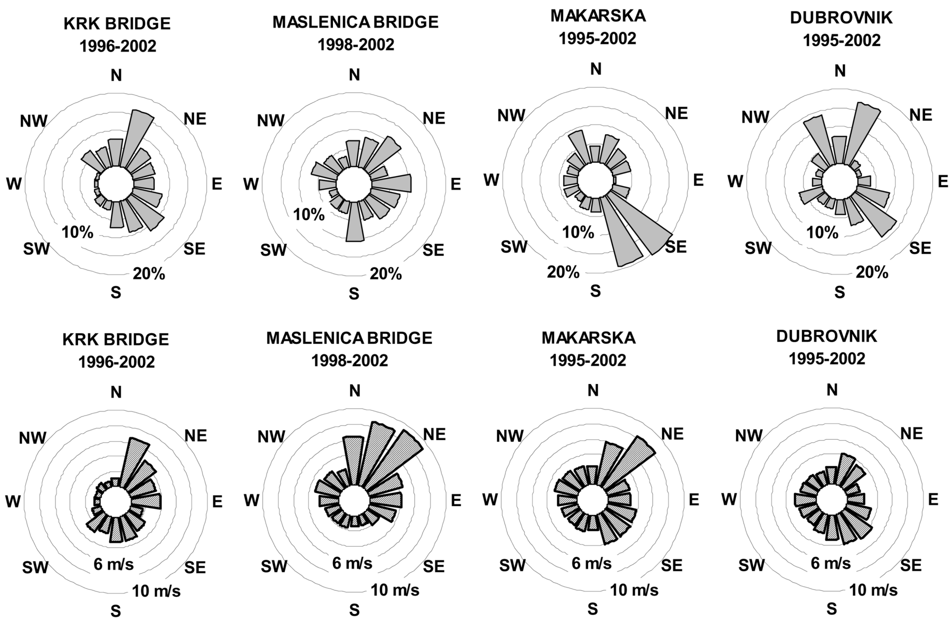

Fig. 3 Relative frequency of wind direction (top) and average wind speed for each wind direction (bottom) for the meteorological stations located on the Croatian coast

3. The wind regime in Croatia

The wind regime in Croatia is influenced by the Alps to the northwest, the Dinaric Mountains along the Adriatic coast, the Adriatic Sea and the Panonian plain to the northeast. Consequently, two main geographic areas with different wind regimes can be distinguished. The continental part is characterised by predominantly weak winds (average wind speeds < 4 m/s) most frequently from the NW-NE directions. Wind circulation connected with the Genoa cyclogenesis (which is frequent during the cold part of the year) causes warm and humid air to penetrate this region from the SW with the greatest mean wind speeds (4 – 5 m/s in average), especially in central continental part represented with the Ogulin station (Fig. 2).

The Adriatic coast and islands are mostly under the influence of the strong *bura* (NE) wind with gusts at times exceeding 50 m/s and average speed greater than 8 m/s (Fig. 3). The *bura* onset is

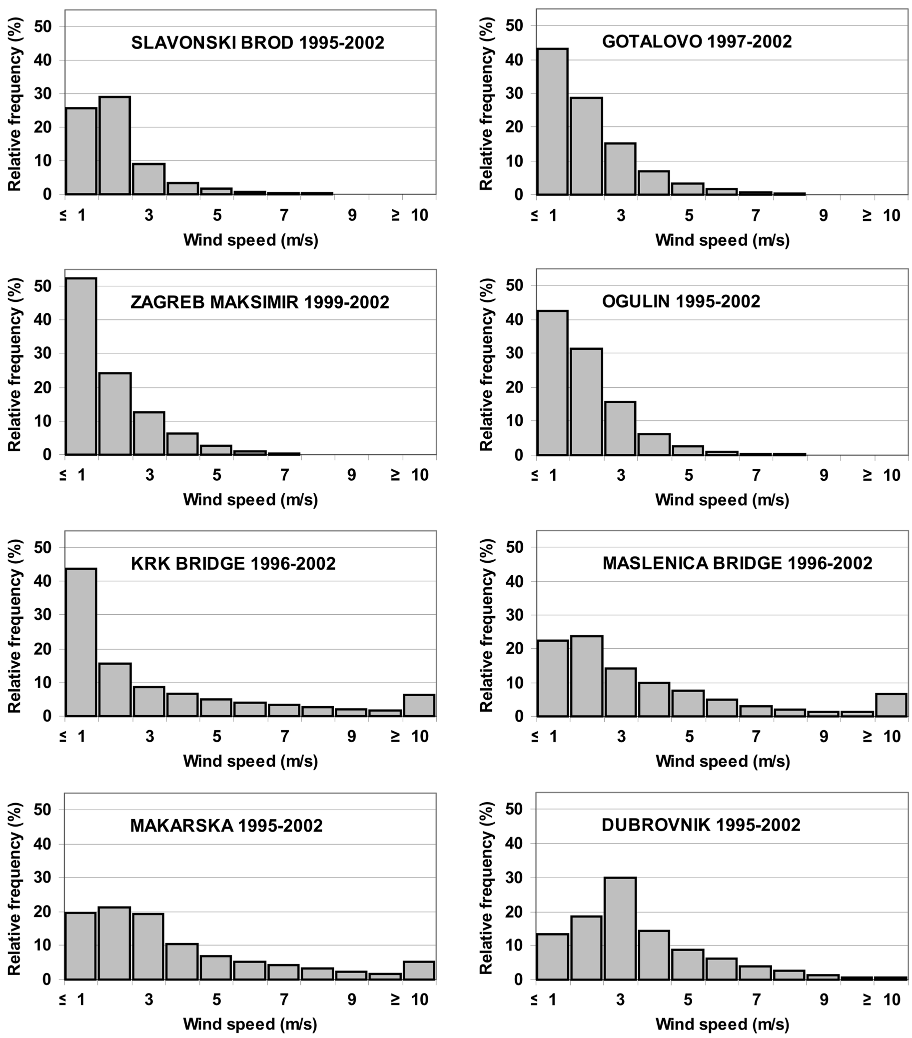

Fig. 4 Wind speed distributions at the selected meteorological stations

always associated with a cold air outbreak either following a deep tropospheric front or appearing some time after the front passage when cold air arrives from the low-level blocking on the northern side of the Alps representing, therefore, the orographic deflection of air around the Alps (Bajić 1988, Jurčec 1989). Frontal passages along the Adriatic coast and the weakening of cyclone activities in the Genoa Bay are accompanied by a strengthening of the SE wind (*jugo*) in the coastal part of Croatia. These situations are very frequent during the whole year that makes *jugo* the most frequent wind along the Adriatic coast (Fig. 3).

Wind speeds (10-minute averages) in the continental part of the country are most frequently below 5 m/s (Fig. 4). The maximum 10-minute wind speed (V_{10min}) ranges between 9.7 m/s in

Table 2 Maximum measured 10-minutes wind speeds (V_{10min}) and maximum measured wind gusts (V_{max}) at meteorological stations given in Table 1

n	Station	V_{max} (m/s)	V_{10min} (m/s)
1	Gradište	23.9	14.7
2	Slavonski Brod	26.8	15.1
3	Daruvar	28.4	12.1
4	Bilogora	42.3	22.0
5	Čakovec*	24.7	15.0
6	Gotalovo	21.3	12.5
7	Zagreb-Maksimir	22.4	10.4
8	Puntijarka*	34.8	16.6
9	Ogulin*	26.4	13.4
10	Parg	28.2	13.1
11	Melina*	52.3	23.7
12	Gospić	26.0	14.9
13	Umag	31.4	17.8
14	Opatija*	21.7	13.8
15	Rijeka*	27.0	12.5
16	Krk Bridge	58.9	35.1
17	Punat*	25.8	15.5
18	Senj	33.0	17.6
19	Rab*	42.7	20.5
20	Mali Lošinj	35.0	18.7
21	Novalja	39.9	24.0
22	Maslenica Bridge	69.0	43.5
23	Zadar	35.3	30.8
24	Hvar	43.8	29.9
25	Hum-Vis*	38.8	28.3
26	Makarska	59.0	32.8
27	Dubrovnik	29.7	17.2

*- indication for stations with more than 20% missing data.

Oborovo and 22.0 m/s in Bilogora. At the same time, the maximum wind gusts (V_{max}) reach from 16.4 m/s in Oborovo to 33.5 m/s in Bilogora (Table 2). The wind directions of extreme winds in this part of Croatia are mostly W-NW-N (related to frontal passages from the northwest).

On the contrary, the extreme winds along the coast and islands are predominately from NE-NNE (*bura*) or ESE-SE (*jugo*) (Bajić 1989, Vučetić 1993). The highest wind speeds have been measured at the locations of Maslenica Bridge, Krk Bridge and Makarska (Table 2 and Fig. 4). They are the consequence of specific locations open to *bura* accelerated by the channelling effects of local orography and the nearby mountain passes. The maximum V_{10min} ever measured in Croatia was 43.5 m/s (V_{max}=69.0 m/s) from NNE recorded at the Maslenica Bridge on 21 December 1998. A slightly lower wind gust of 65.5 m/s was measured on 16 December 2001. The time series of wind speed during the mentioned situations illustrate the huge wind speed variability and gustiness quite common for *bura* (Fig. 5).

4. Reference wind speeds

According "Eurocode 1" (1994) reference speed is the value of the maximum wind speed averaged over

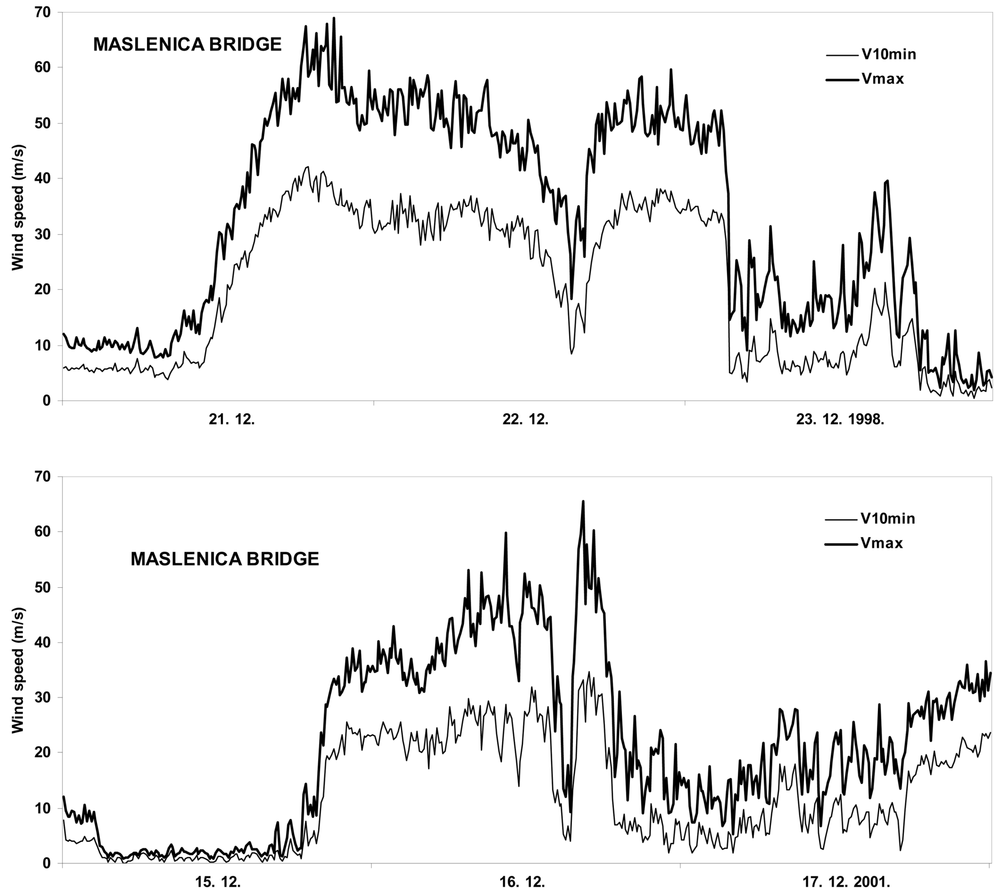

Fig. 5 Time series of 10-minute wind speed (V_{10min}) and maximum wind gust (V_{max}) at Maslenica Bridge on 21-23 December 1998 and 15-17 December 2001

10 minutes recorded by an ideal anemometer placed at a height of 10 m at a location being indefinitely flat, uniformly open, with roughness coefficients 0.05 m and with a mean return period of 50 years (V_T).

The first step in calculating the reference wind speeds is adjustment of measured wind speeds to 10 m above a flat and uniformly open terrain. Suitable models of roughness and topography (described in the European Wind Atlas by Troen and Petersen 1989) have been implemented for each station in order to do such an adjustment.

Long series of observations are generally necessary for the determination of the distribution of extreme values as the annual wind speed maximum. Cook (1985) suggests at least 20 years of data for reliable results (i.e., 20 extremes for analysis), and states that the method should not be employed with fewer than 10 years. For both statistical and meteorological reasons, it is certainly the case that longer records will produce more accurate estimates of wind extremes. Statistically, since the standard error is inversely proportional to the sample size, larger samples imply smaller standard errors. Meteorologically, it is clearly desirable to encompass the full range of variability in extremes and where low frequency variability exists, this may require a long time series. Yet we have only a few years of data available (1995-2002). Although only a few years of observation are available, structures have to be designed in regard to wind loads and it is therefore necessary to obtain the best available information on referent wind speeds.

One of the questions that results from the availability of short data records is how representative is the available observation period of the long-term wind climate. Some insight into the representativeness of the used data will be given by analysing the hourly averaged wind speed data for the period 1987-2002. The analysis has been done for two locations: Zgareb-Maksimir, in the continental part of Croatia, and Šibenik, in coastal part (Fig. 6 and 7). The time

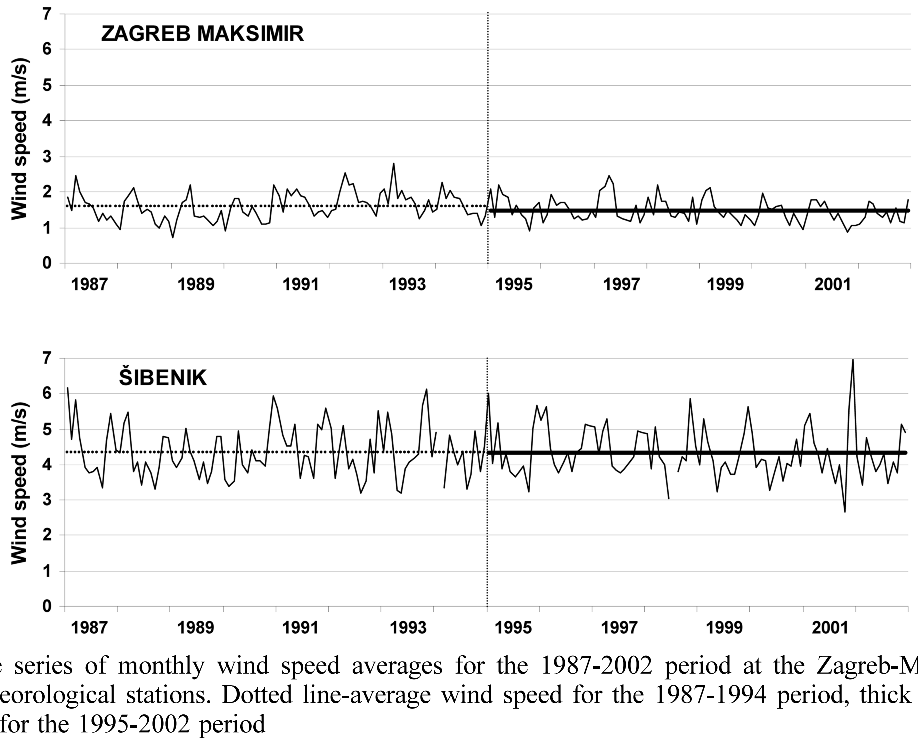

Fig. 6 Time series of monthly wind speed averages for the 1987-2002 period at the Zagreb-Maksimir and Šibenik meteorological stations. Dotted line-average wind speed for the 1987-1994 period, thick line-average wind speed for the 1995-2002 period

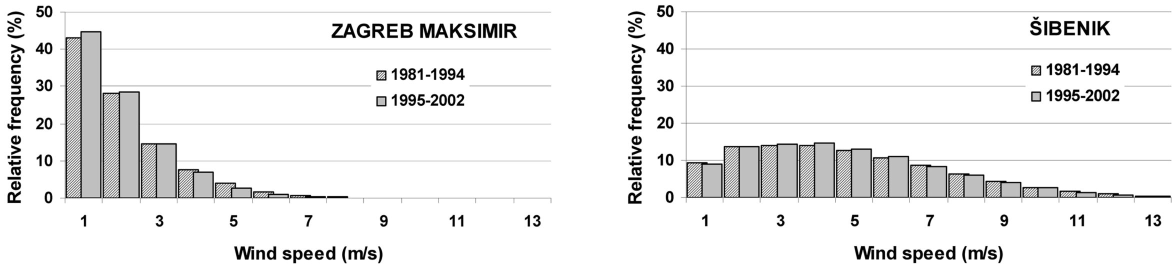

Fig. 7 Wind speed distributions for the 1987-1994 and 1995-2002 periods at Zagreb-Maksimir and Šibenik

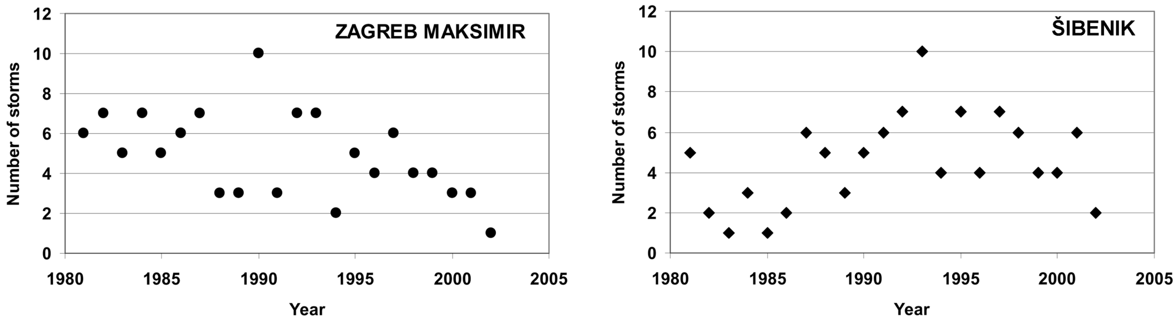

Fig. 8 The number of windstorms in the 1981-2002 data period at the Zagreb Maksimir and Šibenik meteorological stations

series of monthly averaged wind speeds and wind speed distributions for two 8 years periods: A) 1987-1994 and B) 1995-2002 show no statistically significant changes in wind distribution. The mean wind speed at the Zagreb station is 1.60 m/s for period A and slightly less (1.48 m/s) for period B. At the coastal station, the mean wind speeds for both periods are almost the same (0.05 m/s difference). Consequently, we could say that the data period 1995-2002 does not differed significantly from the earlier one. However, if only the strong wind climate is considered, 8 years observation period contain a huge amount of randomness. The number of observed windstorms in the data period 1981-2002 illustrates randomness (Fig. 8). The number of storms varied between 1 and 10 at both considered stations. A similar randomness is obtained if the maximum wind gusts in each year are displayed (Fig. 9). The maximum wind gust lies between 19.3 m/s and 27.2 m/s at Zagreb Maksimir and between 27.5 m/s and 41.0 m/s at Šibenik. Therefore, the data of 8 years have to be accepted as not completely representative and referent wind speeds have to be estimated with appropriate confidence avoiding an underestimation. Consequently we will introduce an adjusting factor of 1.10 for the wind speed to cover the uncertainty from the very short observation period.

To resolve the problem of the short data period, a number of strategies have been developed in calculating the reference wind speed (Palutikof, *et al.* 1999). The classical extreme value theory describes how, for sufficiently long sequences of independent and identically distributed random variables the maxima of sample size n, for large n, can be fitted to one of three basic families. These three families were combined into a single distribution (Jenkinson 1955) universally known as the general extreme value (GEV) distribution. The principal drawback of the classical GEV

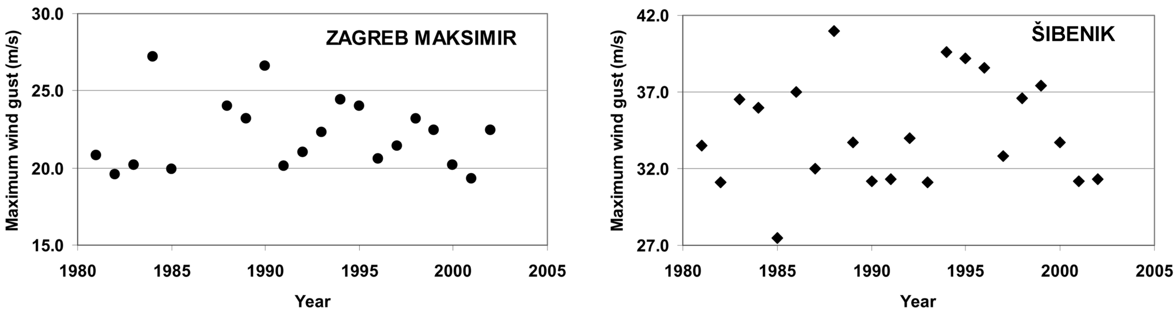

Fig. 9 The maximum wind gusts observed in the 1981-2002 data period at the Zagreb Maksimir and Šibenik meteorological stations

method is that only one value is selected usually per one year. This reduces the data available for analysis so that the data set must be long. To increase the number of cases for analysis, an alternative approach is used in this paper:

Peak-over-threshold (POT) maxima (Simiu and Hecket 1996), extracted from sample data series to produce a series of extreme values above the chosen threshold, have been used with the generalized Pareto distribution (GPD) (Holmes and Moriarty 1999).

For the extreme value theory to be applied successfully, the extremes must be independent and identically distributed. For the POT samples, if no steps are taken to maintain independence, the probability of extracting dependent samples becomes very high because of a strong serial correlation in wind data. A minimum separation distance of two days is employed to ensure independence.

Like the GEV distribution, the GPD has a shape parameter (k) and a scale parameter (α). The maxima of samples of events from the GPD distribution are GEV distributed and have a shape parameter equal to the shape parameter of the parent GPD.

The cumulative distribution function for the GPD is:

$$F(V) = 1 - \left[1 - \frac{k}{\alpha}(V - V_0)\right]^{1/k} \tag{1}$$

where V is the maximum 10-minute wind speed recalculated for a 10-m height above the ground and terrain with a roughness coefficient of 0.05, V_0 is the selected threshold, and $(V - V_0)$ is exceedance. For $k = 0$, the GPD is just an exponential distribution:

$$F(V) = 1 - \exp\left[-\frac{(V - V_0)}{\alpha}\right] \tag{2}$$

In order to calculate the quantiles, it is necessary to estimate the crossing rate of the threshold. If the exceedance process is assumed to be Poisson with rate $L(L - n/M)$ where n is the total number of exceedances over the selected threshold V_0, and M is the number of years of record, then, for the quantile V_T with a return period T, the referent wind speed in our case is (Abild, *et al*. 1992):

$$V_T = V_0 + \frac{\alpha}{k}[1 - (LT)^{-k}] \qquad k \neq 0 \tag{3}$$

$$V_T = V_0 + \alpha \ln(LT) \qquad k=0 \tag{4}$$

A numerical estimation of the distribution parameter can be done using 1) the probability weighted moments method (PWM) (Wang 1991) and 2) the conditional mean exceedance plot (CME). Using the PWM method only the first two estimators are required:

$$b_0 = \bar{V} \tag{5}$$

$$b_1 = \sum_{j=1}^{n-1} \frac{(n-j)V_j}{n(n-1)} \tag{6}$$

then the estimates of k and α are given by:

$$\hat{k} = \frac{b_0}{2b_1 - b_0} - 2 \tag{7}$$

$$\hat{\alpha} = (1+\hat{k})b_0 \tag{8}$$

and are valid within the range $-0.5<k<0.5$.

The conditional mean exceedance method is the expected amount by which a value exceeds threshold V_0, under condition that the threshold be attained. If the exceedance data are fitted into the GDP model and $k<1$, $V_0>0$ and $(\alpha+V_0 k)>0$ then the CME plot (the mean excess over threshold as a function of threshold) should follow a line with intercept $\alpha/(1-k)$ and slope $k/(1-k)$ (Davison and Smith 1990). The linearity of the CME plot can thus be used as an indicator of the appropriateness of the GPD model, and parameters α and k can be estimated from the CME plot (example is given in Fig. 10).

The distribution parameters α and k estimated for the representative continental (Slavonski Brod) and coastal (Novalja) location using the PWM and CME methods (Table 3) show no significant difference. This is especially the case for the continental location where wind speed variability is less pronounced than in the coast and islands.

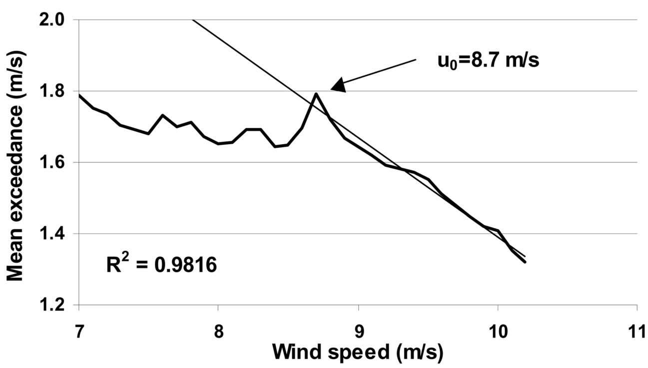

Fig. 10 Example of CME plot

Table 3 Threshold wind speeds (V_0), number of data (N), distribution parameters α and k and referent wind speeds (V_T) obtained using CME and PWM methods at the Slavonski Brod and Novalja meteorological stations for the 1995-2002 data period

			CME			PWM		
Station	V_0 (m/s)	N	α	k	V_T (m/s)	α	k	V_T (m/s)
Slavonski Brod	9.5	56	2.055	0.189	17.0	2.067	0.187	17.0
Novalja	12.3	67	3.616	0.174	26.2	3.756	0.175	26.7

Table 4 Threshold wind speeds (V_0), number of data (N), distribution parameters α and k, referent wind speeds (V_T) and and referent wind speed corrected for the uncertainty from the short observation period (V_{Tcor}) at the 27 meteorological stations given in Table 1

n	Station	V_0 (m/s)	N	α	k	V_T (m/s)	V_{Tcor} (m/s)
1	Gradište	8.5	75	2.305	0.182	17.2	18.9
2	Slavonski Brod	9.5	56	2.055	0.189	17.0	18.7
3	Daruvar	7.4	68	2.941	0.193	17.1	18.8
4	Bilogora	11.3	63	3.176	0.159	23.9	26.3
5	Čakovec*	8.7	68	2.029	0.174	16.4	18.0
6	Gotalovo	8.3	51	1.687	0.167	14.8	16.3
7	Zagreb-Maksimir	7.4	48	2.079	0.188	14.7	16.2
8	Puntijarka*	9.7	62	2.820	0.185	20.1	22.1
9	Ogulin*	7.7	56	2.476	0.190	16.7	18.4
10	Parg	7.1	52	2.885	0.158	18.4	20.2
11	Melina*	16.5	55	3.228	0.193	28.1	30.9
12	Gospić	7.5	64	2.619	0.171	17.6	19.4
13	Umag	9.6	63	2.692	0.182	19.5	21.5
14	Opatija*	8.1	74	2.661	0.174	18.3	20.1
15	Rijeka*	7.8	62	3.105	0.156	19.2	21.1
16	Krk Bridge	19.6	50	5.053	0.192	37.7	41.5
17	Punat*	10.6	53	2.109	0.179	18.4	20.2
18	Senj	13.4	48	2.946	0.198	23.7	26.1
19	Rab*	11.9	64	3.146	0.185	23.6	26.0
20	Mali Lošinj	10.8	52	2.920	0.188	21.4	23.5
21	Novalja	12.3	67	3.616	0.174	26.2	28.8
22	Maslenica Bridge	25.2	57	6.394	0.171	49.5	54.5
23	Zadar	11.2	71	3.314	0.183	24.1	26.5
24	Hvar	12.8	62	4.383	0.160	30.2	33.2
25	Hum-Vis*	14.9	58	4.257	0.193	30.2	33.2
26	Makarska	18.9	62	4.158	0.190	34.0	37.4
27	Dubrovnik	10.7	73	3.183	0.188	21.7	23.9

Since the CME model gives not only the method for estimation of the distribution parameters but also the linearity of plot indicates the appropriateness of using the GPD model, we decided to use the CME model for further calculations. The linearity of the CME plots for all 27 stations is statistically significant, which makes the use of the GPD method acceptable.

The threshold value is chosen from the CME plot as the value at which the linearity on the plot starts to be evident. Additionally, the obtained threshold values are in agreement with the known wind climates at the locations considered.

Obtained threshold wind speeds and distribution parameters α and k, together with resulting reference wind speeds are given in Table 4. It could be seen that parameter k ranges between 0.158 at Parg and 0.198 at Senj, which is in the theoretically allowed range. For $k > 0$ the predicted extreme wind speeds tend to a limiting value at high return periods. There is no noticable difference in k between the continental and coastal stations. The scale parameter α varies from 1.687 to 2.941 for stations in continental part of Croatia and from 2.109 to 6.394 for coastal stations as a consequence of greater measured wind speeds.

Finally, the obtained reference wind speeds corrected for the uncertainty from the short observation period given in Table 4 indicate that in the continental part of Croatia we can expect reference wind speed not greater than 20 m/s (with exception of higher positioned stations like Bilogora, Puntijarka and Parg). The situation is more complex for the coastal area and islands. The greatest part of that region is covered with referent speeds up to 35 m/s. Exceptions are the already mentioned stations with specific nearby orographic characteristics. It is important to stress that the reference speeds at stations located in cities should be taken with circumspection. It is reasonable to expect greater speeds in surrounding areas with no obstacles.

Ballio, *et al*. (1999) separate five factors that best categorise the site for which referent speed has to be calculated: local roughness, geographical position, distance from the coast, altitude and direction of extreme prevailing winds. Although Italy and Croatia have some similar wind regime characteristics (caused by synoptic scale processes and their location on the Mediterranean), specific orography (steep Dinaric Alps with their passes and valleys that separate the hinterland from the very narrow coastal region) makes the situation in Croatia more complex and difficult for zoning. The distance from the sea can not be generally taken as a factor for grouping the stations, since we have stations equally far from the sea (Dubrovnik, Novalja and Makarska for example) with quite different measured and consequently estimated reference speeds. To know how the altitude factor influences wind speed we need to have more measurements at higher altitudes.

Finally, we can conclude that the complexity of the wind regime in Croatia manifests itself in the big differences in reference speeds. However, these results should be taken with having in mind the following weaknesses of the input data sets: a short measurement period and a number of missing data. Special consideration should be given to the insufficient spatial coverage with wind measurement stations. Since the meteorological station network in Croatia includes an additional 3 stations in the mid-Adriatic region with hourly averaged wind speeds measured in time periods longer than 10 years, it will be useful to incorporate these data into the reference wind speed distribution. One of the possible methods for this incorporation is proposed in next section.

5. Relation between hourly and 10-minute averaged wind speeds

The methodology for unifying all available information from wind measurements regardless of

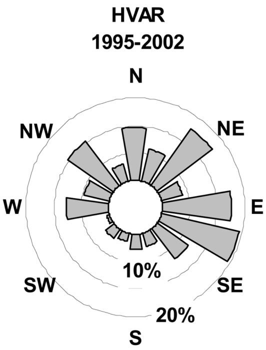

Fig. 11 Relative frequencies of wind direction at the Hvar meteorological station for the 1995-2002 period

Table 5 Statistical characteristics of hourly averaged (V_h), 10-minute averaged (V_{10min}) wind speeds and wind gusts (V_{max}) at the Hvar meteorological station for the 1995-2002 data period

		V_h (m/s)			V_{10min} (m/s)			V_{max} (m/s)		
Direction	N	avg.	std.	max.	avg.	std.	max.	avg.	std.	max.
N	5768	2.02	1.06	25.4	2.44	1.27	29.9	4.46	2.53	34.1
NNE	3524	1.70	0.96	9.10	2.12	1.08	10.8	3.84	2.34	19.9
NE	7448	2.67	1.74	12.0	3.23	1.92	13.9	6.3	4.14	26.4
ENE	2378	2.48	1.55	11.5	3.01	1.75	13.1	5.44	3.48	24.3
E	7500	3.97	2.14	20.6	4.47	2.28	21.7	7.57	3.97	33.1
ESE	8642	5.14	2.50	22.6	5.69	2.62	25.6	8.92	4.22	41.8
SE	4021	3.17	2.06	18.9	3.61	2.21	22.5	5.81	3.67	36.0
SSE	1368	2.34	1.64	21.6	2.69	1.82	27.4	4.46	2.95	38.8
S	1556	2.26	1.65	11.7	2.64	1.80	12.1	4.66	3.14	21.0
SSW	821	2.31	1.72	12.0	2.74	1.94	14.6	4.66	3.21	21.3
SW	1088	1.97	1.36	8.60	2.42	1.53	11.6	4.10	2.65	21.6
WSW	3113	1.60	0.87	5.6	2.01	1.02	6.2	3.66	1.73	12.1
W	4535	2.69	1.11	13.6	3.09	1.16	14.9	5.4	2.24	23.8
WNW	2796	2.36	1.28	23.8	2.79	1.44	26.6	5.25	2.68	43.8
NW	5974	1.92	0.85	14.4	2.28	0.95	16.9	4.46	1.93	29.5
NNW	1883	1.51	0.92	13.9	1.88	1.05	14.9	3.61	2.04	27.5

avg.-average, std.- standard deviation, max.-maximum value

the averaging period will be discussed by analysing wind speed variability at the Hvar meteorological station. Hvar is situated on the Adriatic island of Hvar with *bura* and *jugo* as dominant wind directions (Fig. 11). The highest hourly ($V_h = 25.4$ m/s) and 10-minute wind speed ($V_{10min} = 29.9$ m/s) is measured for N wind (Table 5). The wind speed variation coefficient of hourly wind speed (standard deviation/mean) exceeds 65%, which is an indication of the

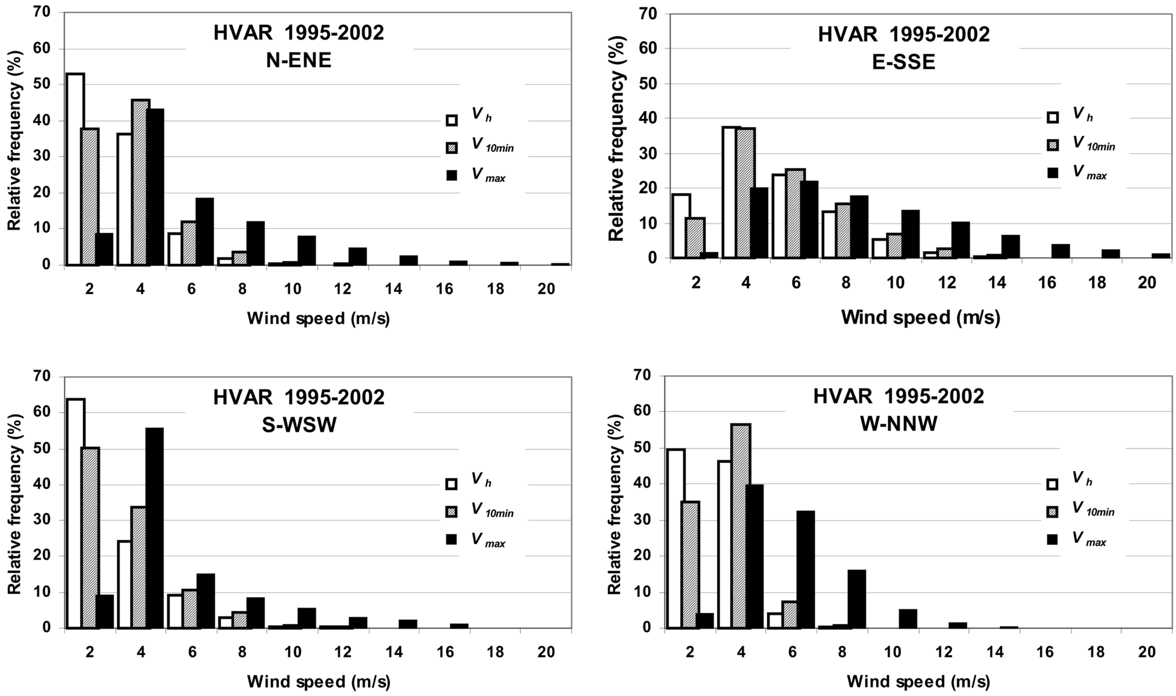

Fig. 12 Distributions of hourly averaged (V_h), 10-minute averaged ($V_{10\mathrm{min}}$) wind speeds and wind gusts ($V_{\max}$) at the Hvar meteorological station for 4 characteristic wind direction groups

Table 6 Regression equations coefficients (a and b) and correlation coefficients (R^2) between $V_{10\mathrm{min}}$, V_h and $V_{\max}$ wind speeds for 4 characteristic wind direction groups at the Hvar meteorological station for the 1995-2002 period

		$V_{10\mathrm{min}}=a\cdot V_h+b$			$V_{\max}=a\cdot V_h+b$			$V_{\max}=a\cdot V_{10\mathrm{min}}+b$		
Direc.	N	a	b	R^2	a	b	R^2	a	b	R^2
N-ENE	19118	1.098	0.266	0.944	2.167	0.261	0.827	1.984	-0.291	0.884
E-SSE	21531	1.048	0.298	0.978	1.670	0.597	0.928	1.598	0.102	0.954
S-WSW	3778	1.089	0.223	0.960	1.806	0.562	0.901	1.664	0.177	0.946
W-NNW	15188	1.055	0.267	0.936	1.800	0.855	0.769	1.731	0.334	0.846

considerable variability of the NE (*bura*) wind. The wind speed distributions given in Fig. 12 shows that the maximum wind gusts exceed 17 m/s in more than 1% for only N-ENE (*bura*) and E-SSE winds (*jugo*).

As can be seen from Fig. 12, the distributions of hourly and 10-minute averaged wind speeds are very similar except for the shift to greater values of $V_{10\mathrm{min}}$. The correlation coefficients and linear correlation equations given in Table 6 indicate statistically significant (at significance level 0.05) correlations among V_h, $V_{10\mathrm{min}}$ and $V_{\max}$ for all characteristic directions.

Thus, knowing V_h and $V_{\max}$ (as we do at meteorological stations with long-term data records) and the correlation between V_h and $V_{10\mathrm{min}}$, we can estimate the 10-minute speeds needed for reference wind speed calculation. So, the procedure for including all available data into the reference wind

Table 7 Basic data for stations with hourly measured wind speeds in mid-Adriatic. The legend is the same as for Table 1

n	Station	*Ds.*	φ	λ	h_s (m)	h_a (m)	$t_1 - t_2$	V_{max} (m/s)	V_h (m/s)
A	Šibenik	C	43° 44'	15° 55'	77	9	1981-2002	41.0	17.8
B	Split-Marjan	C,H	43° 31'	16° 26''	122	12	1981-2002	45.4	25.9
C	Lastovo	C,I,H	42° 46'	16° 54'	186	15	1981-1999	43.0	26.9

V_{max}-maximum measured wind gusts, V_h-maximum measured hourly wind speed

Table 8 Threshold wind speeds (V_0), number of data (N), distribution parameters α and k, referent wind speeds (V_T) and referent wind speed corrected for the uncertainty from the short observation period (V_{Tcor}) for the stations given in Table 7

n	Station	V_0 (m/s)	N	α	k	V_T (m/s)	V_{Tcor} (m/s)
A	Šibenik	12.1	72	5.981	0.243	31.6	34.8
B	Split Marjan	13.1	65	5.602	0.230	31.7	34.9
C	Lastovo	14.4	77	5.237	0.256	30.9	34.0

map could be following: a) V_h, V_{10min} and V_{max} correlation analysis for stations with 10-minute data records, b) estimation of 10-minute wind speeds at stations with hourly data, c) reference speed calculation.

Using the correlation equations obtained for Hvar (Table 6) and having hourly data from 3 additional mid-Adriatic stations (Table 7) (Šibenik, Split-Marjan and Lastovo-indicated as stations A, B and C in Fig. 1) we performed the procedure and finally got the reference wind speeds at those three locations (Table 8). The calculated reference wind speeds are well matched with those at neighbouring stations and make the background for wind load zoning more consistent.

6. Conclusions

The complexity of the wind regime in Croatia makes the wind mapping of Croatia very difficult. The task is even more complicated due to the insufficient number of measurements and short time periods with wind data. Nevertheless, the estimated reference speeds clearly differ in the continental and coastal part of Croatia. Inland, reference speeds reach values up to 25 m/s. The greatest values can be expected during *bura* along the Adriatic Sea. The channelling effects of the local orography strengthen the wind and at some locations cause reference speeds greater than 35 m/s. The data show that distance from the sea can not be taken as a simple factor for wind zoning.

Zoning of the high altitude region could not be performed due to lack of data at high altitude locations. Available data do not show any wind speed increase with height that could be generally valid.

So, there is a clear necessity for better spatial coverage with data. Incorporating hourly measured data into the reference speed calculation provides a more reliable background for the wind load zoning of Croatia.

Special emphasis should be given to *bura* as the most frequent wind on the coast, which, as a highly turbulent wind, produces more wind load upon structures than other winds.

Acknowledgements

This paper represents one segment of the research carried out within the scientific research project "Dynamic action of wind upon structures" (083134) financed by the Ministry of Science and Technology of the Republic of Croatia and the Telecommunication Centre in Split, Croatia.

References

Abild, J. *et al*. (1992), "The climate of extreme winds at the Great belt, Denmark", *J. Wind Eng. Ind. Aerodyn.*, **41-44**, 521-532.

Bajić, A. (1988), "The strongest bora event during ALPEX-SOP", *Rasprave (Papers)* **23**, 1-13.

Bajić, A. (1989), "Severe bora on the Northern Adriatic. Part I: Statistical analysis", *Rasprave (Papers)* **24**, 1-9.

Bajić, A., *et al*. (2001), "Wind load-a meteorological basis for Croatian Standards", *Gradevinar*, **53**(8), 495-506 (in Croatian).

Bajić A. and Peroš, B. (2001), "Referent wind velocity-influence of averaging period", *Gradevinar*, **53**(9), 555-562 (in Croatian).

Ballio, G., Lagomarsino, S., Piccardo, G. and Solari, G. (1999), "Probabilistic analysis of Italian extreme winds: Reference velocity and return criteria", *Wind and Struct.*, **2**(1), 51/68.

Coles, S.G. and Walshaw, D. (1994), "Directional modelling of extreme wind speeds", *Appl. Stat*., **43**, 139-157.

Cook, N.J. (1985), "The designers guide to wind loading of building structures. Part 1: Background, damage survey, wind data and structural classification", *Building Research Establishment*, Garston and Butterworths, London, 371 pp.

Davison, S.C. and Smith, R.L. (1990), "Models of exceedances over high thresholds", *J. Royal Statistical Soc.*, *Series B*, **52**, 339-442.

"Eurocode 1": "Basis of design and actions on structures, Part 2-4: Wind actions" (1994), ENV 1991-2-4, European Committee for Standardization.

Holmes, J.D. and Moriarty, W.W. (1999), "Application of the generalized Pareto distribution to extreme value analysis in wind engineering", *J. Wind Eng. Ind. Aerodyn.,* **83**, 1-10.

Jenkinson, A.F. (1955), "The frequency distribution of the annual maximum (or minimum) values of meteorological elements", *Quart. J. R. Met. Soc*., **87**, 158-171.

Jurčec, V. (1989), "Severe Adriatic Bora storms in relation to synoptic developments", *Rasprave (Papers)*, **24**, 11-21.

Koračin, D. (1982), "Spectral analysis of Bura wind gust factor at Rijeka airport", *Zbornik Meteoroloških i hidroloških radova*, **8**, 55-62 (in Croatian).

Palutikof, J.P. (1999) "A review of methods to calculate extreme wind speeds", *Meteorol. Appl.*, **6**, 119-132.

Peroš, B. (1994), "Modelling of the Bora effects upon the lower layer", *Eng. Modelling*, **7**, 3-4, 81-95.

Peroš, B. (1998), "Constructional steel design for structures with a dominant wind Bora load", *J. Constructional Steel Research*, **46**(1-3), Paper Number 146.

Peroš, B. and I. Boko (2000), "Reliability of steel bridges exposed to the Bora wind action", *International Conference on Steel Structures of the 2000s*, Istanbul, 51-56.

Peroš B. and I. Boko (2000a), "Investigations of the effects of the Bora wind load upon transmission line pylons", *3rd International Congress of the Croatian Society for Mechanics*, *Proceedings*, 587-594.

Simiu, E. and Heckert, N.A. (1996) "Extreme wind distribution tails: a 'peak-over-threshold' approach", *J. Struct. Eng*., **122**, 539-547.

Troen, I. and Petersen, E.L. (1983), "European wind atlas", *Commission of the European Communities*, 631.

Vučetić, V. (1993), "Severe Bora on Mid-Adriatic", *Hrvatski meteorološki časopis*, **28**, 19-36.
Wang, Q.J. (1991), "The POT model described by the generalized Pareto distribution with Poisson arrival rate", *J. Hydrol.*, **129**, 263-280.

GS