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WIND DIRECTION FREQUENCY ANALYSIS FOR THE *JUGO* WIND IN THE ADRIATIC

Analiza čestina smjera vjetra za vrijeme juga na Jadranu

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Abstract: The strong wind blowing from the south-eastern quadrant over the Adriatic Sea region is known as *jugo*, in the eastern coastal area customarily also called scirocco. The *jugo* wind type has been separated from the five-year hourly wind data (1976–1980) for three stations (Pula, Split and Dubrovnik), by introducing a criterion with conditions a wind vector should satisfy during a *jugo* event. The stations are situated on the northern, middle and southern part of the eastern (Croatian) Adriatic coast. All *jugo* events consisting of hourly mean wind velocities ≥ 0.3 ms^{-1}, and subsets of *jugo* events, referred to as stronger *jugo*, consisting of hourly mean wind velocities ≥ 3 ms^{-1}, were analysed.
The results show that wind from the SE quadrant (6 wind directions), independent of any wind type criterion, accounts for 33% to 40% of all the five-year wind data (16 wind directions) with percentages growing from the north toward the south, along the Croatian part of the Adriatic coast. All *jugo* events contribute from 19% to 27%, going from the north toward the south. Stronger *jugo* contributes only 6% to 20% going in the same direction along the coast. Increased seasonal frequencies of *jugo* events were obtained in spring for Pula, and in both winter and spring for Split and Dubrovnik. The mathematical approximation of the *jugo* wind roses by means of mixture distribution resulted in two components in each of the seasonal wind roses. The shape and contribution of these components change from season to season and from station to station. Two components for the *jugo* wind roses approximation calls to mind the known, but yet unproved empirical statement about the existence of a cyclonic and an anticyclonic *jugo* wind type.

Key words: *jugo* wind, scirocco in the Adriatic, statistical mixture distribution, wind rose analysis

Sažetak: Jak vjetar, koji puše u Jadranu iz SE kvadranta, poznat je u istočno-jadranskom području pod imenom jugo, kao i pod imenom *široko*. Podaci o tom vjetru za tri postaje (Pula, Split i Dubrovnik) izdvojeni su iz petogodišnjeg niza srednjih satnih vrijednosti vjetra (1976–1980), primjenom ovdje uvedenog kriterija s uvjetima za vektor vjetra za vrijeme juga. Tako su dobivene ruže smjera vjetra za jugo za tri postaje, smještene u sjevernom, srednjem i južnom području hrvatske obale Jadrana. Analizirani su podaci jugo događaja svih brzina ≥ 0.3 ms^{-1}, kao i podskupovi jugo događaja brzina ≥ 3 ms^{-1}, ovdje nazvani jače jugo.
Rezultati pokazuju da vjetar iz SE kvadranta (6 smjerova vjetra), neovisno o kriteriju za neki tip vjetra, sadrži od 33% do 40% svih podataka satnih vrijednosti o vjetru (16 smjerova), idući od sjevera prema jugu duž hrvatske obale Jadrana. Vjetar iz SE kvadranta, koji

udovoljava uvjetima za sve jugo događaje sadrži od 19% do 27% svih podataka idući od sjevera prema jugu, a pojavu jačeg juga čine od 6% do 20% svih podataka idući duž obale u istom smjeru. Godišnje doba najvećih čestina s pojavom svih jugo događaja u Puli je proljeće, a u Splitu i Dubrovniku i zima i proljeće. Matematičkom aproksimacijom ruža jugo vjetra pomoću miješane razdiobe, dobivene su funkcije aproksimacije sastavljene od dviju komponenata. Udjeli i oblici tih komponenata mijenjaju se različito, ovisno o postaji i o godišnjoj dobi. Dobivanje dviju komponenata u postupku aproksimacije upućuje na još uvijek nedovoljno ispitano gledište o postojanju ciklonalnog i anticiklonalnog tipa juga.

Ključne riječi: jugo, široko na Jadranu, statistička miješana razdioba, analiza ruža vjetra

1. INTRODUCTION

Jugo is the Croatian name[1] for one of the three dominant Adriatic wind types *bura*, *jugo* and *etezija*. The *jugo* type belongs to the family of south-easterly winds known in the Mediterranean under the common name of *scirocco*. It is considered that the *jugo* wind is associated with warm and humid weather. According to some recent studies, an opinion exists that the *jugo* develops under a specific synoptic situation in the Adriatic, which may differ from the general weather conditions under which the *scirocco* normally develops (Jurčec *et al.*, 1996). The subject of this paper is reduced to the analysis of the wind vector properties during *jugo* events, not taking into account other meteorological parameters.

Compared to the interest shown for other pronounced wind types in the Adriatic, not equal attention has been paid by Croatian meteorologists to the *jugo* type, until recently. The oldest instructive description of *jugo* events in the Adriatic (named *scirocco* in that work), and the accompanying weather characteristics, was published at the beginning of the 20th century (Kesslitz and Roessler, 1904; Kesslitz, 1914). Some additional, but still descriptive details about this type of wind in the Adriatic were presented a few decades later (Marki, 1924, 1950). These authors described two subtypes of the *jugo* wind, which they called the cyclonic and anticyclonic type of *jugo* and such statement was accepted by some of later authors as well. The biggest attention, including a weather data analysis, was paid to the *jugo* events associated primarily with cyclonic activity over the Adriatic region. Several articles published around the middle of the 20th century described the *jugo* within a general description of pronounced Adriatic wind types (Makjanić, 1978; Stipaničić, 1969 and Stipanović, 1972), using classical or standard statistical parameters (wind roses, mean, maximal and minimal values and values of standard deviation of scalar wind velocity). Newer results and conclusions related to the *jugo* (published in the seventies and later) were based on the long-term wind data collected at climatological terms (7, 14, 21 h). Systematic and detailed presentations of *jugo* events, based for the first time on hourly wind data over a five-year period, applying again classical statistical methods, can be find in Trošić's papers (1983, 1984 and 1985). Combined statistical methods (Hrabak-Tumpa *et al.*, 1996; Poje, 1992 and Vukičević, 1991), applied to severe *jugo* wind data only, gave further climatological information about the extreme properties of the *jugo* wind. Thermodynamic models (Brzović, 1999; Brzović and Strelec-Mahović, 1999; Jurčec and Vukičević, 1996 and Jurčec *et al.*, 1996) successfully described several case studies of severe *jugo* associated with heavy precipitation, especially after the introduction of orographycal effects (Dinaric and Apennine Alps) to dynamical processes in the lower troposphere over the Adriatic. It might be interesting to mention that there are over 20 different local names (Poje, 1995) relating to *jugo* intensity and associated weather characteristics, used by fishermen, sailors and in everyday people's talk across the Croatian coastal region.

Trošić's Adriatic wind data study separates the *jugo* from the five-year hourly wind data set by introducing a criterion which takes into consideration the wind vector properties (Trošić, 1983, 1985).

The separated data set contains all the *jugo* events related to the low, moderate, strong and severe *jugo* velocity categories (according

1 pronounced as yugo in English; in Croatian "jug" means "south".

to the Beaufort scale). The empirical frequency distributions for the *jugo* wind directions interval or the *jugo* wind roses for three stations (Pula, Split and Dubrovnik) were obtained. These three stations, situated in the northern, middle and southern part of the Croatian coast, illustrated roughly the *jugo* events regime in these parts of the eastern Adriatic coastal belt.

This paper describes some additional climatological characteristics of the *jugo*, derived from the mentioned *jugo* wind roses, as a contribution to the already known climatological facts. In addition, it presents the results of a mathematical approximation of the *jugo* wind roses by means of mixture distribution, which has been applied to several other surface and high-level wind roses (e.g. Essenwanger, 1976; Lisac and Zelenko, 1984, 1985 and Zelenko and Lisac, 1994).

2. THE KNOWN CHARACTERISTICS OF *JUGO*

From the previously listed articles, the following characteristics of the adriatic *jugo* can be extracted:

- The *jugo* (SE quadrant), as well as the *bura* (NE quadrant), are the most pronounced winds over the eastern Adriatic coastal region, especially during the cold part of the year, when both types can reach stormy velocities that are not significantly different. The *jugo* blows along the Adriatic, between, and parallel to, the Dinaric and Apennine mountain chains and the *bura* blows perpendicular to the Dinaric Alps over the eastern Adriatic coast.
- Both the *jugo* and *bura* winds can blow over the Adriatic either simultaneously (e.g. the *bura* over the northern part of the eastern Adriatic coast, the *jugo* over its middle or southern part) or consecutively at the same place. When the *jugo* appears in the northern Adriatic (Pula), there is a high probability that it will blow along the whole eastern coast, with the exception of a small northern part (Senj and the Kvarner Bay). The cases with the *jugo* prevailing all over the coast are rare.
- The *jugo* blows stronger over the Adriatic open sea and over its southern part. It is also stronger over the eastern than over the western Adriatic coastal belt. It starts and ends with low wind velocities (below 3 ms^{-1}). The duration of a *jugo* event varies from several hours to several days, when its mean hourly wind velocities can reach stormy values (above 30 ms^{-1}).
- Strong *jugo* induces high tides in the Adriatic that occasionally lead to the flooding of the northern Adriatic lowlands.
- Because it blows from the open sea, the *jugo* is mostly associated with warmer temperatures and a higher relative humidity of the air, especially during the cold part the year. This causes inconvenient biological effects, especially on humans (e.g. depressions). On the other hand, in spring or summer, the *jugo* sometimes can bring lower air temperatures, but the air humidity stays still high and people feel uncomfortable or unwell again. Depending on the synoptic situation, the *jugo* may be associated with thick haze and, therefore, reduced visibility, especially when the parent cyclone originates over the North African desert area. The *jugo* may be associated with heavy and persistent precipitation as well, especially in cases of high wind velocities. It has not yet been investigated how much mean air temperature, relative humidity and amount of precipitation during a *jugo* event can deviate, from the overall mean values.
- The *jugo* is a gradient wind and can be of the *cyclonic* type, developing inside a warm sector of the frontal part of a cyclone centred SW, W or NW of the Adriatic Sea or even over the Adriatic itself. There are several domestic names for this subtype of *jugo* wind: *jug*, *julian*, *šilok*, *široko* (the Croatian transcription of the word „scirocco" or „scilocco" the general term for a SE wind in the Mediterranean). This type of SE wind is accompanied by cloudy and precipitation rich weather.
- In the case when an anticyclone or a high pressure ridge and a clear sky prevail over the Balkan peninsula, at the rear part of the pressure pattern, a warm but relatively dry wind (as opposed to the previous type) from the SE quadrant can appear in the Adriatic. This subtype of *jugo* wind is called *anticyclonic jugo* in professional domestic literature and in empirical sources (local people, fishermen and sailors). This *jugo* subtype, carrying less humid air, is accom-

panied by predominantly cloudless or barely cloudy weather, poor in precipitation, as opposed to the weather accompanying the cyclonic type of *jugo*. The domestic names for this *jugo* wind are *suho jugo* (dry *jugo*), *gnjilo jugo* (rotten *jugo*) and *palac* (scorching wind). The anticyclonic *jugo* **type** is less frequent then the former one, but it can last longer and reach even higher velocities.

- The two types of *jugo* can appear on the same station separately, or consecutively one after the other. This consecutive appearance makes it difficult to separate the two types of *jugo* events. They are still only empirically recognised, but their existence has not been scientifically proved by appropriate methods in meteorology.

3. DATA AND METHODS OF ANALYSIS

The five-year (1976–1980) **h**ourly **m**ean **w**ind **v**ector (or **hmwv**) data for three stations on the eastern Adriatic coast (Pula, Split and Dubrovnik) were analysed.

The data from the stations illustrate approximately the wind circumstances over the northern, middle and southern part of the Croatian Adriatic coast (Fig. 1). The time interval was chosen for the data to be according to the instruments installed (R. Fuess universal anemograph) and to the technical procedure applied for data evaluation. Thus the conditions of data homogeneity and comparability were satisfied.

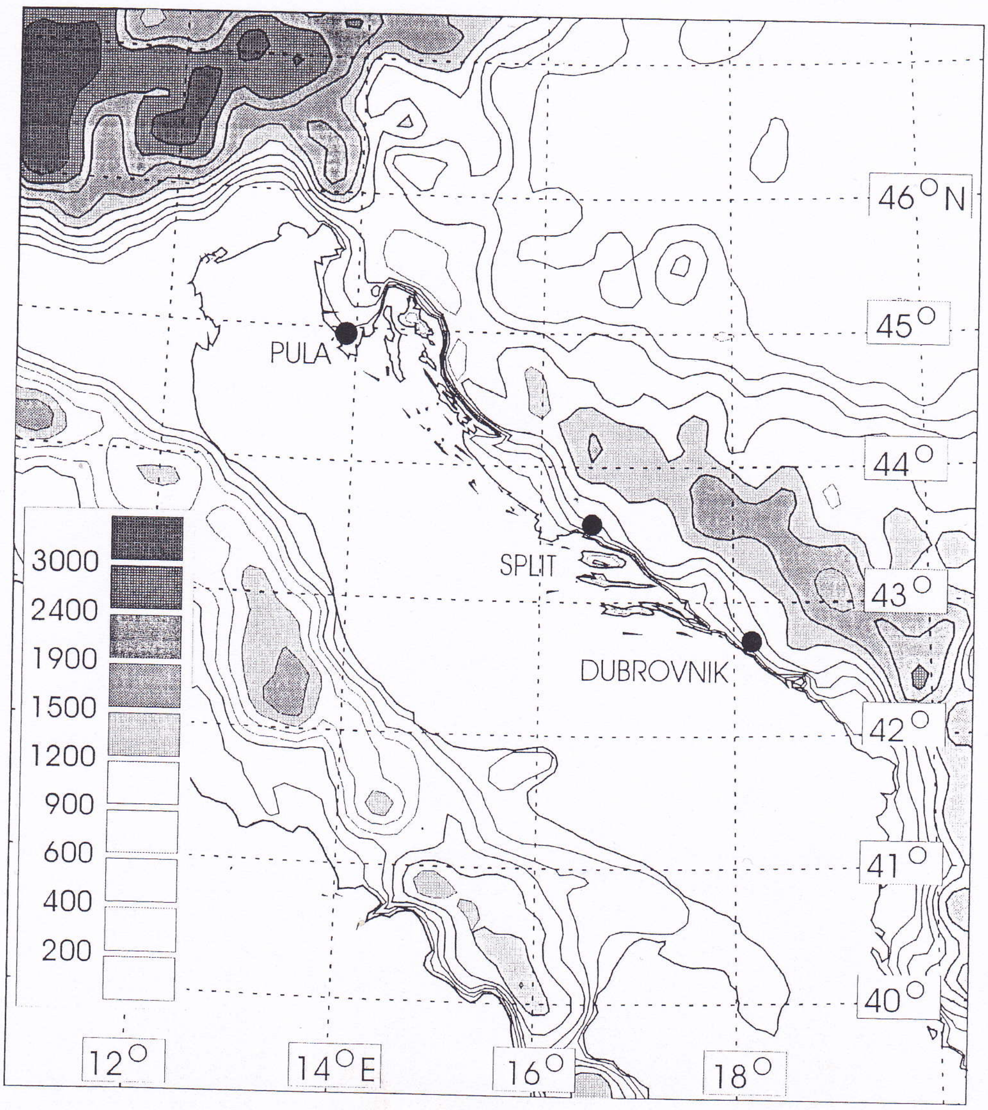


Figure 1. The stations with anemograph data used in the study.

Slika 1. Položaj postaja s anemografom, čiji su podaci analizirani u radu.

Table 1. Basic data for the anemographic stations: φ, λ – geographic coordinates, h – elevation above mean sea level (m), h_a – height of anemograph (m), mean annual and seasonal (SP, SU, FA, WI) wind speed or scalar wind velocity (ms^{-1}) during the period 1976–1980.

Tablica 1. Osnovni podaci anemografskih postaja: φ, λ – geografske koordinate, h – visina postaje iznad srednje razine mora (m), h_a – visina anemografa (m), srednje godišnje i sezonske (SP, SU, FA, WI) brzine vjetra (ms^{-1}) za razdoblje 1976–1980.

Station	φ	λ	h (m)	h_a (m)	Terrain around a station	SP (ms^{-1})	SU (ms^{-1})	FA (ms^{-1})	WI (ms^{-1})	annual (ms^{-1})
Pula-airport	44°54´N	13°55´E	67	10	flat	3.1	2.6	3.0	3.1	2.9
Split-Marjan	43°31´N	16°26´E	123	9.4	hilly	4.2	3.3	4.3	5.1	4.2
Dubrovnik-Ćilipi	42°39´N	18°05´E	157	10	hilly and close to runway	4.1	3.7	4.1	4.9	4.2

The data obtained from Meteorological and Hydrological Service of Croatia in Zagreb

The data were analysed in two phases:

1. Identification of hourly *jugo* data and *jugo* events from the entire **hmwv** data in the five-year interval, at a particular station and determination of the contributions in percentage terms, of several categories of these data sets (see Tab. 2a–c).
2. Approximation of the empirical wind direction frequency distributions of the hourly mean *jugo* vectors (or *jugo* wind roses) for the seasonal sets of data for each of the three stations by theoretical mixture distribution and then an analysis of the obtained parameter values.

3.1. Identification of *jugo* events

A "*jugo* event" has been defined by applying the criterion firstly introduced by Trošić (1983) and presented here with additional details. The wind can be of the "*jugo*" type at a certain hour if the wind data (or **hmwv**) at this hour, immediately before it and during the next hours have determined properties. Accordingly, these properties determine the beginning, the evolution and the end of a sequence of hours with the *jugo* type wind. The obtained sequence of consecutive hours with wind of the *jugo* type (or just the *jugo*) defines a "*jugo* event".

The main characteristics of the *jugo* are those of the **hmwv**.

From a statistical point of view, a particular **hmwv** belongs to a simple event (or outcome) associated with the following four data: (1) location of the station, (2) time (date and hour), (3) hourly mean wind direction, and (4) hourly mean wind velocity. Data (3) and (4) are those of the **hmwv**. In general, they form sequences of hours consecutive in time inside a chosen total time interval, in this case inside a five-year interval.

The criterion for the identification of a *jugo* event:

1. The **hmwv** has to fulfill two necessary conditions during a particular hour with a *jugo*-type wind:

   (a) the hourly mean wind velocity is at least 0.3 ms^{-1}, and

   b) the hourly mean wind direction is within the six-direction interval belonging to the total wind rose of 16 directions. This six-direction interval contains four main directions belonging to the SE quadrant (ESE, SE, SSE, and S) and two boundary directions (E and SSW).

2. A *jugo* event starts at hour t_1:

   (a) if the wind during the previous hour t_0 does not belong to a *jugo* event and

   (b) if during three consecutive hours (t_1, t_2, and t_3) the velocity condition 1(a) is satisfied and the hourly mean wind directions belong to the main directions. Then the wind is of the *jugo* type at hours t_1, t_2, and t_3.

3. After a *jugo* event started, and t_{i-1} is an hour that belongs to this *jugo* event, then the wind during the consecutive hour t_i is of the *jugo* type and the jugo event is prolonged with t_i in either of the following two possibilities:

(a) if at hour t_i the velocity condition 1(a) is satisfied and the wind direction is one of the main directions or

(b) if at hour t_i the velocity condition 1(a) is satisfied and the wind direction is one of the boundary directions, and at the next hour t_{i+1} the velocity condition is satisfied and the wind direction turns back to one of the main directions.

The sequence of the jugo-type **hmwv** forming a *jugo* event has to be prolonged as long as one of the possibilities 3(a) or 3(b) exists.

4. A jugo event ends with hour t_n, ($n \geq 3$) if the wind is of the *jugo* type at this hour and the condition 3. for prolonging the *jugo* event to hour t_{n+1} is not fulfilled.

Notes:

1. Condition 1. a necessary for a simple event to be of the *jugo* type.
2. Condition 2. is sufficient for simple events at hour's t_1, t_2 and t_3 to be of the *jugo* type.
3. The shortest *jugo* event lasts three hours.
4. Condition 3(a) is sufficient for a simple event at hour t_i to be of the *jugo* type.
5. Condition 3(b) is sufficient for simple events at hours t_i and t_{i+1} to be of the *jugo* type. In this case, the *jugo* event has to be prolonged to hours t_i and t_{i+1}.

The following are examples that illustrate *jugo* events of various duration. The examples are presented by directions of **hmwv** in sequences of consecutive hours, using the following symbols:

- **J** is used for the main directions,
- **B** is used for boundary directions,
- **C** is used for a weak wind with an hourly mean velocity below 0.3 ms^{-1}, independently of its direction, and
- **O** is used for a **hmwv** of any direction outside the entire *jugo* interval.

Examples:

(a) A *jugo* event lasting for 3 hours:
O J J J B C, also **C J J J B O**

(b) A *jugo* event lasting for 4 hours:
O J J J J C C

(c) A *jugo* event lasting for 5 hours:
O J J J B J B B, also **O J J J B J C**

(d) A *jugo* event lasting for 7 hours:
O J J J B J J J B B

(e) A *jugo* event lasting for 10 hours:
C J J J B J J J J B J C

(f) Two *jugo* events (the former lasting 3 and the latter 4 hours):
O J J J C B J J J J O.

By applying the criterion for the identification of a *jugo* event, a sequence of *jugo* events has been obtained. The *jugo* events are separated by at least one hour of wind not of *jugo* type. These events form a sequence of all *jugo* event (a *jugo* data set) at a particular station and within a chosen time interval.

According to Beaufort's wind power categories, each **hmwv** of a *jugo* event is included in one of these categories: weak (velocity v below 3 ms^{-1}), moderate (v between 3 and 11 ms^{-1}), strong (v between 11 and 20 ms^{-1}) and severe (v above 20 ms^{-1}). During a *jugo* event, when the hourly mean wind velocity is not lower than the velocity threshold of 3 ms^{-1} it is said that a "stronger *jugo*" blows. Such **hmwv** data define a subset of all *jugo* events, referred in this paper as ***stronger jugo*** (including moderate, strong and severe wind from Beaufort categories). As opposed to the **hmwv** of a *jugo* event, stronger *jugo* may not blow consecutively in time, but may have interruptions in the sequence of hours already within a single *jugo* event, when the wind velocity is below 3 ms^{-1}.

After applying the criterion for the *jugo* and for stronger *jugo*, the total set of five-year **hmwv** data was sorted into 24 subsets (three stations, four seasons and two wind velocity categories) and prepared for further analyses.

3.2. *Jugo* wind roses approximation

The empirical frequency distribution of directions belonging to the hourly wind vectors (the vectors in a plane) can be approximated by a theoretical distribution. This method makes it possible to analyse the wind roses by applying statistical criteria. The details of this theory are explained in Zelenko and Lisac (1994) and only its basic statements are given here.

The approximation of empirical frequencies by theoretical frequencies is carried out by means of mixture distributions, which are defined in the following way:

Let φ_1, ..., φ_n be linearly independent probability density functions (PDF) of directions of a vector in a plane. Then a PDF φ of a distribution of directions α in the plane can be defined as

$$\varphi(\alpha) = u_1\varphi_1(\alpha) + \ldots u_n\varphi_n(\alpha) \tag{1}$$

where u_i are such non-negative constants that satisfy the relation

$$u_1 + u_2 + \ldots + u_n = 1 \tag{1a}$$

The function φ is a *mixture density function* and it defines the mixture distribution of directions in a plane. The $\varphi_i(\alpha)$ are component densities of the distribution $\varphi_i(\alpha)$ and the factors u_i are mixing weights. A component distribution is defined by its component density $\varphi_i(\alpha)$. Its mixing weight u_i is the probability of the component distribution occurrence.

A wind rose presents a discrete distribution, which may have several modes. Another property of the wind rose is a low number of direction classes (12 or 16 mostly), with a large number of observations. A multimodal distribution can be obtained by mixing a few unimodal components. Some simple distributions can be used as components: uniform, wrapped normal and cosine distribution, as well as deformed distributions (Zelenko and Lisac, 1994). In previous statistical wind data analyses (Lisac and Zelenko, 1984, 1985), besides a uniform distribution $\varphi(\alpha) = 1/2\pi$, the wrapped normal distributions have been mostly used. Such a distribution is defined (Perrin, 1928; Mardia, 1978; Breckling, 1989) with two parameters α_i and σ_i by its PDF $\varphi_i(\alpha)$:

$$\varphi_i(\alpha) = \frac{1}{\sigma_i\sqrt{2\pi}} \sum_{k=-\infty}^{+\infty} \exp\{-(\alpha - \alpha_i + 2k\pi)^2 / 2\sigma_i^2\} \tag{2}$$

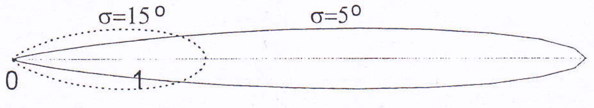


Figure 2. Probability density function of wrapped normal distribution for two σ values.

Slika 2. Funkcija gustoće vjerojatnosti za namotanu normalnu razdiobu za dvije vrijednosti σ.

Figure 2 presents the PDFs of wrapped normal distributions for two values of parameter σ.

The function $\varphi_i(\alpha)$ in eq. (2) could be imagined as arisen from a normal distribution with an expectation angle α_i and dispersion σ_i, wrapped on a circle. The distribution is axially symmetric related to the direction of α_i.

According to the criterion, there are six *jugo* direction classes. Thus, in an approximation there are five independently determined frequencies, while the sixth one is defined by the total number of observations in a data sample. It follows that the approximation can be made by means of one or mostly two statistical distributions, since the two distributions defined by the functions φ_1 and φ_2 both with two yet undefined parameters, have five unknown parameters. Success depends on the choice of the type of the functions φ_1 and φ_2. If a normal distribution in the approximation procedure is chosen, the unknown parameters are α_i and σ_i. The attempt to approximate the *jugo* wind roses by means of only one distribution gave unsatisfactory results, due to the asymmetric shape of all wind roses. A choice of two normal distribution components gave five parameters that should be determined by means of five independent frequencies.

In the expression

$$\varphi(\alpha) = u_1\varphi_1(\alpha) + u_2\varphi_2(\alpha) \tag{3}$$

with two wrapped normal distributions φ_1 and φ_2, the parameters α_1, α_2 and σ_1, σ_2 and u_1 can be determined by the given 5 independent frequencies, but parameter u_2 is already defined by $u_2 = 1 - u_1$ (see eq. 1a). It can be expected that the obtained approximation by means of two normal distributions will represent six satisfactorily accurate empirical frequencies.

The approximation has been made by wrapped normal distributions. Because of the small number of direction classes, as determined by the criterion for a *jugo* wind, the unknown parameters could not be determined by applying common statistical methods, e.g. in the minimum of chi-square method. Therefore, the least square method has been applied and the obtained results practically entirely fit the empirical frequencies. It should be mentioned that in many other seasonal wind data analyses different methods were used. The differences in the resulting parameters obtained by other statistical procedures (e.g. maximum likelihood, minimum chi-square, and least squares) were insignificant. Based on such experience, wrapped normal distributions for the component distributions have been applied.

Common statistical tests to check the quality of approximation could have been applied only if additional information, as some other meteorological parameters associated with *jugo* events, had been taken into account.

4. RESULTS

4.1. Extraction of *jugo* events

The results of the identification and separation of *jugo* events (first phase of the data analysis) are presented in tables 2 and 3.

Table 2 contains the empirical frequencies and average velocities for 6 *jugo* directions and three categories of wind data for Pula, Split and Dubrovnik. The frequency values belonging to these stations, sorted according to annual and seasonal groups of data and wind velocity categories, were the basis for the relative values contained in table 3. The frequencies are equal to the entire five-year total number of data (annual frequencies or *annual* wind roses) and to the five-year totals in a particular season (seasonal frequencies or a *seasonal* wind rose). From these data the wind roses were derived (Fig. 3) and also the frequency approximation in the second phase of the data analysis.

Table 3 contains the annual and seasonal percentage contribution of the above listed data groups, related to the totals N in the five annual and seasonal data groups (16 wind directions) which also equals the entire duration of *jugo* events expressed in number of hours. As already mentioned, the Pula, Split and Dubrovnik stations can be accepted, as they roughly illustrate the *jugo* wind characteristics in the northern, middle and southern part of the Croatian Adriatic coast.

The totals N of the entire annual groups have been rounded to 42500 and the size of the seasonal groups has been rounded to 10600. As

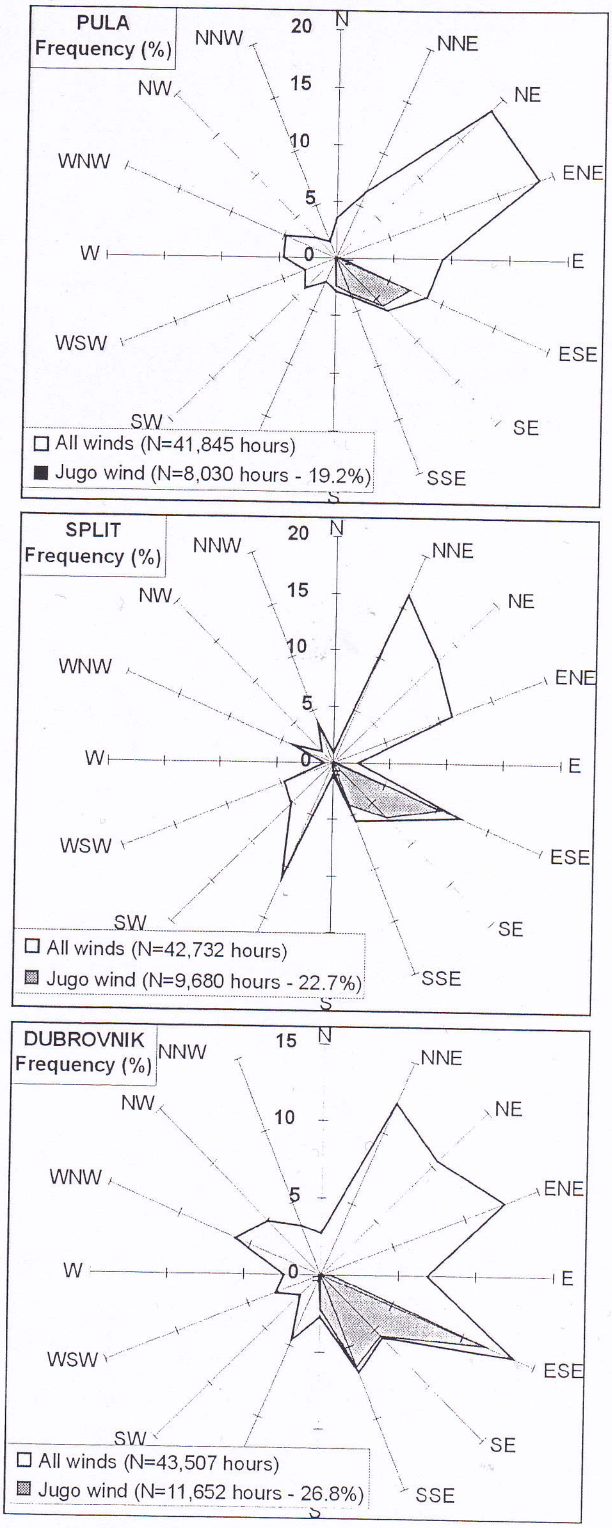


Figure 3. Annual wind roses for the entire data set of the hourly mean wind vector (all 16 directions) and for the extracted *jugo* events obtained by application the criterion for *jugo*, period 1976–1980, stations Pula, Split and Dubrovnik.

Slika 3. Ruže vjetra prema svim podacima srednjih satnih vrijednosti anemograma (svih 16 smjerova) i prema podacima za *jugo* događaje (6 smjerova iz SE kvadranta), razdoblje 1976–1980, postaje Pula, Split i Dubrovnik.

the totals N equal the number of hours, table 3 leads to the following conclusions:

Wind blowing from 6 wind directions, regardless of the *jugo* criterion, accounts for 33% to 40% of the total wind data (16 wind directions), going from north toward south (line (a) in Tab. 3). The percentages are listed in rounded values. These annual data sets expressed in percentages vary less from station to station than from season to season at a particular station (line (a) in the seasonal boxes, Tab. 3).

The percentage contribution of the *jugo* wind to the total wind data set from the three stations generally increases going from north (19%) towards south (27%). This increase is even more expressed for stronger *jugo* (6% and 20%). The rounded average annual number of days with all *jugo* events is: 67 days at Pula, 80 days at Split and 97 days at Dubrovnik, or 22, 62 and 72 days with stronger *jugo*, respectively (lines (b) and (c) in Tab. 3).

Weak *jugo* wind velocities ($0.3 \le v < 3.0$ ms^{-1}) account for 67% of all the *jugo* events at Pula, but only for 23% at Split and 26% at Dubrovnik, taking into account the number of data satisfying the criterion for *jugo*.

According to the data at the Pula airport, weak *jugo* blows mostly over the northern Adriatic. There might be several reasons for such a result. One reason is the elevation of the station, which is lower than the station elevations at Split and Dubrovnik. Another reason for a weakening *jugo* might be the ceasing of the airflow after moving from the open sea to about 10 km into the continent, where the Pula airport station is situated. Jugo events are usually connected with a

Table 2a. Empirical frequencies and mean hourly wind velocities for Pula from the SE quadrant, sorted into data groups: a) all hmwv data, b) *jugo* according to the criterion for *jugo*, hmjv ($v \ge 0.3$ ms^{-1}) and c) stronger *jugo* ($v \ge 3.0$ ms^{-1}). v_a, v_b and v_c denote average wind velocities (ms^{-1}) for the corespondent wind categories. Period: 1976–1980.

Tablica 2a. Empirijske (apsolutne) čestine i srednje satne brzine vjetra za Pulu iz SE kvadranta svrstanih u grupe podataka: a) svi podaci satnih vrijednosti vjetra, b) *jugo* vjetar prema kriteriju za *jugo* ($v \ge 0.3$ ms^{-1}) i c) jači *jugo* ($v \ge 3.0$ ms^{-1}). v_a, v_b and v_c označavaju srednje brzine vjetra (ms^{-1}) za odgovarajuće kategorije vjetra. Razdoblje: 1976–1980.

Wind direction		E	ESE	SE	SSE	S	SSW	Total
Year	a	3833	3610	2630	1507	1210	905	13695
	v_a	3.0	2.7	2.8	2.6	2.3	2.3	2.6
	b	162	2937	2443	1393	1012	83	8030
	v_b	2.7	2.7	2.9	2.6	2.3	2.1	2.5
	c	44	934	938	490	224	10	2640
	v_c	4.4	4.5	4.7	4.3	4.3	3.6	4.3
Spring	a	1204	1173	816	408	301	219	4121
	v_a	3.1	2.8	2.9	2.6	2.2	2.4	2.7
	b	59	988	759	378	246	18	2448
	v_b	2.8	2.7	3.0	2.6	2.3	2.2	2.6
	c	24	342	328	153	54	3	904
	v_c	4.3	4.5	4.6	4.1	4.1	4.0	4.3
Summer	a	1187	1037	790	411	355	331	4111
	v_a	3.0	2.4	2.3	2.2	2.0	2.0	2.3
	b	41	825	734	372	294	35	2301
	v_b	2.3	2.3	2.3	2.2	2.0	1.9	2.2
	c	4	190	198	74	30	3	499
	v_c	3.8	4.0	4.0	3.9	3.7	3.3	3.8
Fall	a	725	811	587	376	253	189	2941
	v_a	2.8	2.7	3.1	2.8	2.4	2.5	2.7
	b	33	665	545	351	214	19	1827
	v_b	3.3	2.8	3.1	2.9	2.5	2.3	2.8
	c	11	259	235	143	63	3	714
	v_c	4.5	4.5	5.0	4.7	4.3	3.6	4.4
Winter	a	717	589	437	312	301	166	2522
	v_a	3.1	2.9	3.2	2.8	2.6	2.5	2.9
	b	29	459	405	292	258	11	1454
	v_b	2.6	3.0	3.3	2.8	2.6	1.9	2.7
	c	5	143	177	120	77	1	523
	v_c	4.6	5.4	5.3	4.5	4.6	3.3	4.6

Table 2b. Same as in table 2a, only for Split.

Tablica 2b. Isto kao u tablici 2a, ali za postaju Split.

Wind direction		E	ESE	SE	SSE	S	SSW	Total
Year	a v_a	923 4.5	5237 6.1	3037 7.8	2368 4.5	483 3.8	4723 2.6	16771 4.9
	b v_b	238 5.0	4485 6.7	2897 8.0	1728 5.3	328 4.6	104 3.2	9680 5.5
	c v_c	94 6.5	3650 7.9	2618 8.7	912 8.4	131 8.6	28 6.6	7433 7.8
Spring	a v_a	244 4.3	1408 5.6	1084 7.8	671 4.2	118 3.6	1337 2.7	4862 4.7
	b v_b	41 4.4	1206 6.1	1040 8.0	506 4.8	84 4.0	33 3.1	2910 5.1
	c v_c	24 6.0	933 7.4	936 8.7	259 7.6	31 7.5	9 6.6	2192 7.3
Summer	a v_a	188 4.1	825 4.8	540 6.3	566 2.9	146 2.1	1591 2.3	3856 3.7
	b v_b	24 6.1	614 5.5	497 6.6	351 3.6	81 2.3	32 2.4	1599 4.4
	c v_c	16 8.0	423 7.2	416 7.5	126 6.5	14 4.2	6 4.3	1001 6.3
Fall	a v_a	217 4.1	1331 6.3	799 7.6	649 4.8	158 5.2	1239 2.6	4393 5.1
	b v_b	34 5.3	1154 6.9	776 7.8	486 5.7	123 6.2	28 4.4	2601 6.0
	c v_c	23 7.0	962 8.0	718 8.3	273 8.8	67 9.6	11 8.3	2054 8.3
Winter	a v_a	274 5.1	1673 7.1	614 9.4	482 6.2	61 4.5	556 3.6	3660 6.0
	b v_b	39 4.9	1511 7.5	584 9.7	385 7.1	40 5.9	11 2.3	2570 6.2
	c v_c	31 5.7	1332 8.3	548 10.2	254 9.8	19 10.4	2 3.8	2186 8.0

Table 2c. Same as in table 2a, only for Dubrovnik.

Tablica 2c. Isto kao u tabilci 2a, ali za postaju Dubrovnik.

Wind direction		E	ESE	SE	SSE	S	SSW	Total
Year	a v_a	3013 2.9	5899 4.0	2482 6.1	2978 5.4	1185 4.1	2014 3.2	17571 4.3
	b v_b	293 3.1	5070 4.3	2380 6.3	2795 5.6	995 4.3	119 3.5	11652 4.5
	c v_c	130 4.8	3331 5.7	2092 6.9	2385 6.3	691 5.5	53 5.1	8682 5.7
Spring	a v_a	644 3.0	1430 3.8	835 6.1	999 5.2	350 3.9	553 3.2	4811 4.2
	b v_b	73 3.4	1225 4.1	795 6.2	947 5.4	296 4.1	36 3.3	3372 4.4
	c v_c	36 5.0	764 5.6	700 6.9	796 6.1	197 5.3	14 5.1	2507 5.7
Summer	a v_a	582 2.5	1031 3.1	403 5.4	675 5.1	358 3.8	710 3.1	3759 3.8
	b v_b	56 2.4	843 3.3	377 5.6	633 5.3	300 4.0	33 3.5	2242 4.0
	c v_c	16 4.1	348 5.3	305 6.6	533 6.0	203 5.0	15 4.8	1420 5.3
Fall	a v_a	821 2.7	1633 3.9	521 6.1	694 5.5	278 4.2	503 3.1	4450 4.2
	b v_b	77 2.8	1412 4.2	498 6.3	648 5.7	251 4.7	32 3.9	2918 4.6
	c v_c	31 4.5	972 5.4	438 6.9	554 6.5	184 5.8	17 5.5	2196 5.8
Winter	a v_a	966 3.1	1805 4.8	723 6.6	610 5.9	199 4.7	248 3.6	4551 4.8
	b v_b	87 3.4	1590 5.1	710 6.7	567 6.1	148 4.8	18 3.1	3120 4.8
	c v_c	47 4.9	1247 6.1	649 7.2	502 6.7	107 6.0	7 4.8	2559 5.9

Table 3. Percentage parts of the average annual and seasonal data sets of wind from the SE quadrant, according to the empirical frequencies presented in tables 2a–c (the duration of a particular data group expressed in days is shawn in brackets). N is the total number of data in a group (equal to the number of hours), excluding the number of calms and missing data. Data groups: a) all **hmwv** data, b) *jugo* according to the criterion for *jugo* (v ≥ 0.3 ms^{-1}) and c) stronger *jugo* (v ≥ 3.0 ms^{-1}). Period 1976–1980, stations Pula, Split and Dubrovnik.

Tablica 3. Procentualni udjeli godišnjih i sezonskih podataka vjetra iz SE kvadranta, prema empirijskim čestinama sadržanim u tablicama 2a–c. (unutar zagrada, trajanje pojedine grupe podataka izraženo u danima). N je ukupni broj podataka sadržanih u grupi (jednako broju sati), koji ne uključuje broj tišina, niti broj nedostajućih podataka. Grupe podataka: a) svi podaci satnih vrijednosti vjetra, b) jugo vjetar prema kriteriju za *jugo* (v ≥ 0.3 ms^{-1}) i c) jači jugo (v ≥ 3.0 ms^{-1}). Razdoblje 1976–1980, postaje Pula, Split i Dubrovnik.

		PULA	SPLIT	DUBROVNIK
Year	a	32.7 (14)	39.2 (16)	40.4 (13)
	b	19.2 (67)	22.7 (80)	26.8 (97)
	c	6.3 (22)	17.4 (62)	20.0 (72)
	N	41845	42732	43507
Spring	a	38.8 (16)	44.3 (17)	43.9 (13)
	b	23.1 (20)	26.5 (24)	30.7 (28)
	c	8.5 (8)	20.0 (18)	22.9 (21)
	N	10619	10987	10968
Summer	a	38.5 (17)	35.1 (20)	34.5 (14)
	b	21.5 (19)	14.5 (13)	20.6 (19)
	c	4.7 (4)	9.1 (9)	13.0 (12)
	N	10688	10993	10903
Fall	a	28.5 (11)	40.4 (16)	41.1 (14)
	b	17.7 (15)	24.0 (22)	27.0 (24)
	c	6.9 (6)	18.9 (17)	20.3 (18)
	N	10336	10857	10827
Winter	a	24.7 (11)	37.0 (11)	42.1 (13)
	b	14.3 (12)	26.0 (21)	28.9 (26)
	c	5.1 (4)	22.1 (18)	23.7 (21)
	N	10202	9895	10809

well-pronounced pressure pattern over the southern part of the Adriatic. One more reason might be the weakening of this pressure pattern after moving north-westward. The stations at Split and Dubrovnik are at higher altitude, but both are situated closer to the coastal line.

The empirical frequencies for all *jugo* events have their highest values in spring at Pula, and both in spring and winter in Split and Dubrovnik with the exception of stronger *jugo* at the latter stations, which develops only in the winter seasons.

Figure 3 shows that the *jugo* wind roses have an asymmetric shape at all three stations:

- The asymmetry in Pula is characterised by pronounced frequencies for the neighbouring ESE and SE directions.
- The wind rose at Split has a similar type of asymmetry, but with a more pronounced mode in the ESE wind direction.
- The wind rose at Dubrovnik has two modes: one is more pronounced in the ESE and the other in the SSE wind direction.

These wind rose shape characteristics for a particular station do not change significantly with the seasons. Their shape might be partly explained by the influence of the surrounding topographical pattern, especially in Split. The narrow Brač Channel, extending between the island of Brač and the continent, channels the airflow blowing from ESE to Split. On the contrary, Pula and Dubrovnik are open to the wind blowing mostly undisturbed from the SE quadrant.

The *jugo* wind roses were obtained by the application of the criterion with four conditions

Table 4. An example for the approximation of an empirical wind rose with the mixture distribution by two wrapped normal components. The upper part contains the parameters (contribution u_i, expectation α_i and dispersion σ_i) and the lower part contains the wind direction classes and corresponding frequencies: empirical, theoretical, squares of their differences, component frequencies and the obtained rms value.

Tablica 4. Primjer rezultata aproksimacije ruže vjetra (empirijske razdiobe čestina) miješanom razdiobom pomoću dvije komponente namotane normalne razdiobe. Gornji dio sadrži parametre (udjel ili težina, očekivanje i disperzija), dok donji dio sadrži klase smjerova i čestine: empirijske, teorijske, kvadrate njihovih razlika, teorijske čestine komponentnih razdioba, te vrijednost korijena iz srednjeg kvadrata odstupanja (rms).

i	weight, u_i	expectation angle, α_i	"standard deviation", σ_i
1	0.738	105.2	2.3
2	0.262	148.2	17.1

Directions	№	Frequency			Component frequencies	
		$(f_{emp})_i$	$(f_{theor})_i$	$[(f_{emp})_i-(f_{theor})_i]^2$	$(f_{theor1})_i$	$(f_{theor2})_i$
0	1	0	0.0	0.000	0.00	0.00
22.5	2	0	0.0	0.000	0.00	0.00
45.0	3	0	0.0	0.000	0.00	0.00
67.5	4	0	0.0	0.002	0.00	0.04
90.0	5	36	33.5	6.123	28.05	5.47
112.5	6	764	765.3	1.638	629.73	135.55
135.0	7	700	701.5	2.130	0.00	701.46
157.5	8	796	796.6	0.360	0.00	796.60
180.0	9	197	199.4	5.991	0.00	199.45
202.5	10	14	10.5	11.981	0.00	10.54
225.0	11	0	0.1	0.012	0.00	0.11
247.5	12	0	0.0	0.000	0.00	0.00
270.0	13	0	0.0	0.000	0.00	0.00
292.5	14	0	0.0	0.000	0.00	0.00
315.0	15	0	0.0	0.000	0.00	0.00
337.5	16	0	0.0	0.000	0.00	0.00

Root of the mean of squared deviations **(rms)** = 2.169

for a *jugo* event, described in the previous chapter.

4.2. Results of the *jugo* wind roses approximation

The approximation of the *jugo* wind roses by mixture distributions, consisting of two wrapped normal distributions, was made for seasonal groups of data only. The average annual data, as well as the entire five-year data sets containing the annual run of the wind vector, make the empirical frequency distribution complex in structure and not suitable for such an analysis. On the other hand, a particular seasonal wind rose, free of the annual signal, was simpler in structure and easier to analyse as well. There were 24 seasonal frequency groups in total, i.e. 8 for each station, four representing the total number of hours of all *jugo* events and the other four representing the totals of stronger *jugo*.

As already mentioned, approximation with only one wrapped normal distribution has not proved successful in any of the available frequency distributions, while approximation with two theoretical component distributions was successful in all cases. An example of the main and secondary results in the mathematical procedure is presented in table 4. Its upper part contains the main results (distribution parameters u_i, α_i and σ_i). The lower part of the same table contains the empirical and theoretical frequencies (secondary results), the square of their differences and the component frequencies, including the root mean

Table 5. Maximal values for: a) *rms* (root mean squares of deviations), b) for squared deviations and c) for the relative share of empirical frequencies from SSW direction.

Tablica 5. Najveće vrijednosti korijena iz a) srednjeg kvadrata odstupanja (*rms*), b) kvadratnog odstupanja i c) relativnog udjela empirijskih frekvencija iz SSW smjera.

a) Maximal *rms* values

Station	all *jugo*	stronger *jugo*
Pula	0.274	0.121
Split	12.155	7.431
Dubrovnik	5.159	2.169

b) Maximal contribution, coming from SSW direction always

Station	all *jugo*	stronger *jugo*
Pula	negligible	negligible
Split	0.831	0.912
Dubrovnik	0.749	0.772

c) Maximal percentage contribution of the empirical SSW frequency to stronger *jugo* subsample size

Station	spring	summer	fall	winter
Pula	negligible			
Split	0.4%	0.6%	0.5%	0.1%
Dubrovnik	0.6%	negligible	0.6%	0.3%

square value (*rms*) as a rough test of approximation accuracy.

A comparison of the obtained *rms* values shows that the lowest values (higher approximation accuracy) were obtained for Pula and the highest *rms* values for Split. The obtained maximal *rms* values are listed in table 5a.

The maximal contributions to the rms came from the empirical SSW frequencies (α = 202.5°) in almost all seasonal data. The maximal squared deviation values corresponding to *rms* are shown in table 5b. On the other hand, the SSW wind direction is at the southern edge of the direction interval defining *jugo* events (boundary direction in the criterion). The corresponding empirical frequency is usually low, except in the data for Pula, but the approximation for that station was always successful. The low empirical frequencies for SSW, obtained for Split and Dubrovnik, make negligible their relative contribution to the total number N of seasonal data. This is clearly shown by the percentages in table 5c. The relative value for stronger *jugo* in spring at Dubrovnik, for example, has been obtained as $f_i/N=14/2.507=0.6\%$ (data contained in Tab. 2c).

The main results, represented in parameters of component distributions for all seasonal data, are listed in table 6 (all *jugo* events) and table 7 (stronger *jugo*).

The precision in the parameters calculation procedure presented in tables 6 and 7 has been investigated. One of the parameters has been changed from its optimal value and an auxiliary optimum has been searched for the other four variable parameters. The difference between the initial and changed parameter values showed that, for example, changes in u_i value in the third decimal place could influence the expectations α_i by tenths of degrees. Such experience resulted in the decision about the number of parameter decimals presented in the tables 6 and 7.

The differences in parameter values for component distributions are represented in table 8, where the parameter values are sorted into categories according to their values in tables 6 and 7.

The components have been named by their value of expectation α_i, being inside a particular wind direction interval (Tab. 8a). The shape of a particular component is given by its value for σ_i (Tab. 8b). If the contribution given by the u_i value differs less than 0.1, the components are taken as equal in their contribution or weight.

The procedure of approximation of the *jugo* wind roses gave two component distributions in all 24 seasonal wind roses. There were a pair of ESE and SE components in 13 out of 24 seasonal wind roses (8 in Split and 5 in Dubrovnik), a pair of ESE with SSE components in 10 out of 24 seasonal wind roses (7 in Pula and 3 in Dubrovnik) and just one wind rose with SE and SSE components obtained for Pula (stronger *jugo* in winter). The components differ from station to station and their mean annual run, presented in changes from season to season, can be described by means of parameter categories (Tab. 8) in more detail as follows:

- **Pula.** The two components ESE and SSE came together in 7 out of 8 wind roses. Only in the winter data for stronger *jugo* the SE

Table 6. Parameters of component distributions, obtained by approximation procedure of the seasonal *jugo* wind roses (all *jugo* events) for three stations.

Tablica 6. Parametri komponentnih razdiobi, dobiveni u postupku aproksimiranja sezonskih jugo ruža vjetra za sve jugo događaje i za tri postaje.

Component number	PULA			SPLIT			DUBROVNIK		
				spring					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.721	121.2	10.9	0.420	118.1	7.8	0.330	108.7	4.7
2	0.279	164.9	13.7	0.580	139.6	18.3	0.670	149.2	18.4
	N=2448		rms=0.216	N=2910		rms=12.155	N=3372		rms=5.159
				summer					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.678	122.3	10.8	0.334	115.7	7.2	0.372	103.8	1.7
2	0.322	166.7	14.7	0.666	142.4	19.8	0.628	155.5	18.7
	N=2301		rms=0.274	N=1599		rms=11.445	N=2242		rms=2.700
				fall					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.640	121.3	10.5	0.428	117.3	6.6	0.468	108.6	4.5
2	0.360	163.2	14.9	0.572	142.2	20.2	0.532	151.2	19.4
	N=1827		rms=0.264	N=2601		rms=7.822	N=2918		rms=1.554
				winter					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.616	122.5	11.5	0.569	112.5	5.8	0.429	109.6	4.5
2	0.384	168.3	11.2	0.431	141.9	15.3	0.571	141.6	20.5
	N=1454		rms=0.093	N=2570		rms=4.632	N=3120		rms=2.557

Table 7. Same as in table 6, only for *stronger jugo*.

Tablica 7. Isto kao u tablici 6, ali za jači jugo.

Component number	PULA			SPLIT			DUBROVNIK		
				spring					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.716	122.0	11.6	0.607	121.3	8.9	0.262	105.2	2.3
2	0.284	157.3	14.9	0.393	139.2	16.7	0.738	148.2	17.1
	N=904		rms=0.116	N=2192		rms=3.655	N=2507		rms=2.169
				summer					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.693	122.7	9.3	0.532	120.3	9.2	0.251	113.2	7.0
2	0.307	154.8	17.7	0.468	137.4	16.9	0.749	155.2	16.5
	N=499		rms=0.116	N=1001		rms=2.558	N=1420		rms=0.233
				fall					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.663	122.0	10.4	0.595	119.9	7.8	0.450	113.3	6.4
2	0.337	160.5	13.8	0.405	142.1	19.9	0.550	151.8	17.4
	N=714		rms=0.118	N=2054		rms=2.760	N=2196		rms=1.415
				winter					
i	u_i	α_i	σ_i	u_i	α_i	σ_i	u_i	α_i	σ_i
1	0.631	125.2	10.9	0.508	110.9	16.3	0.433	112.5	5.9
2	0.369	166.4	9.8	0.492	135.6	4.2	0.567	142.7	18.3
	N=523		rms=0.121	N=2186		rms=1.626	N=2559		rms=0.579

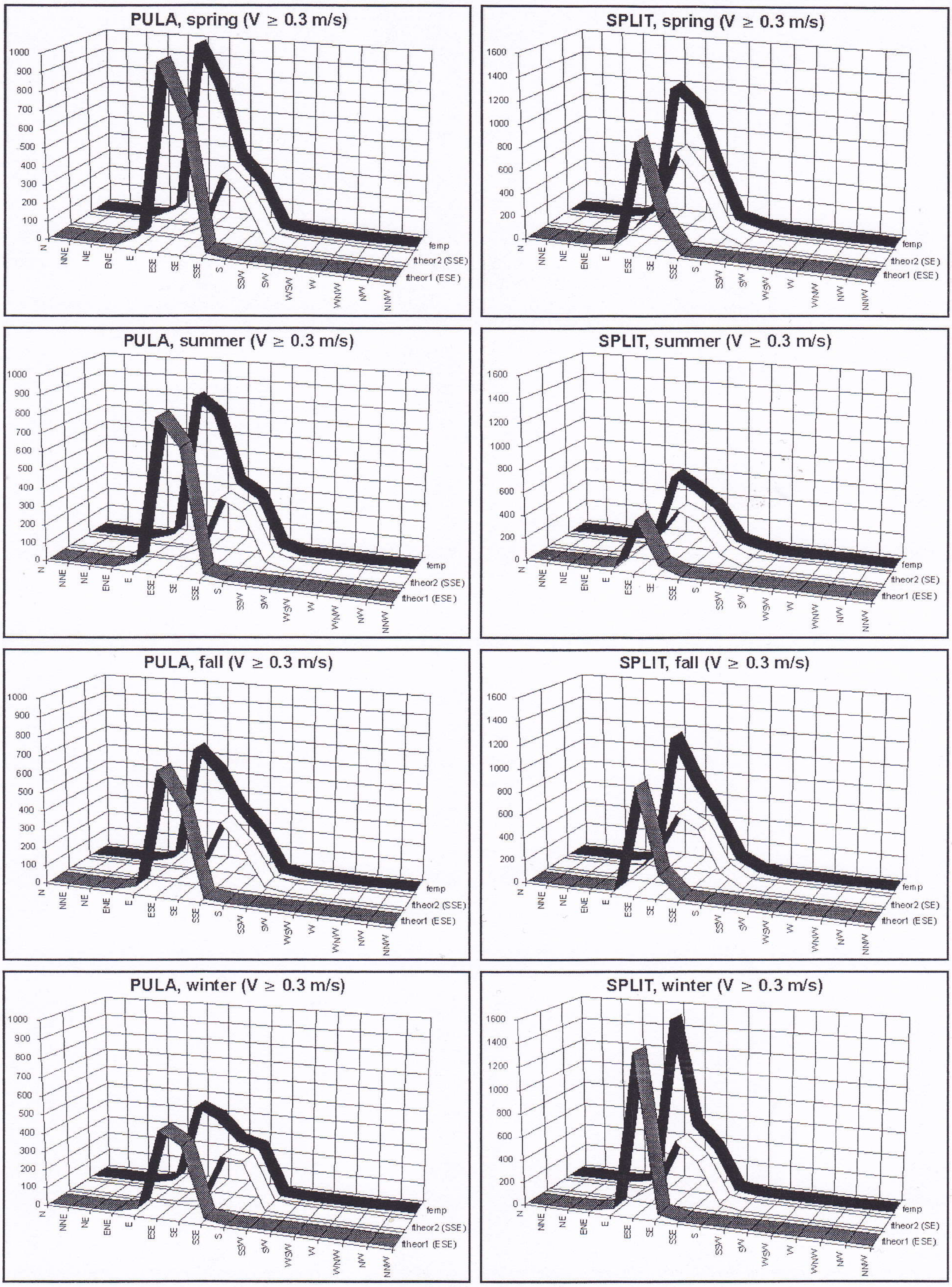
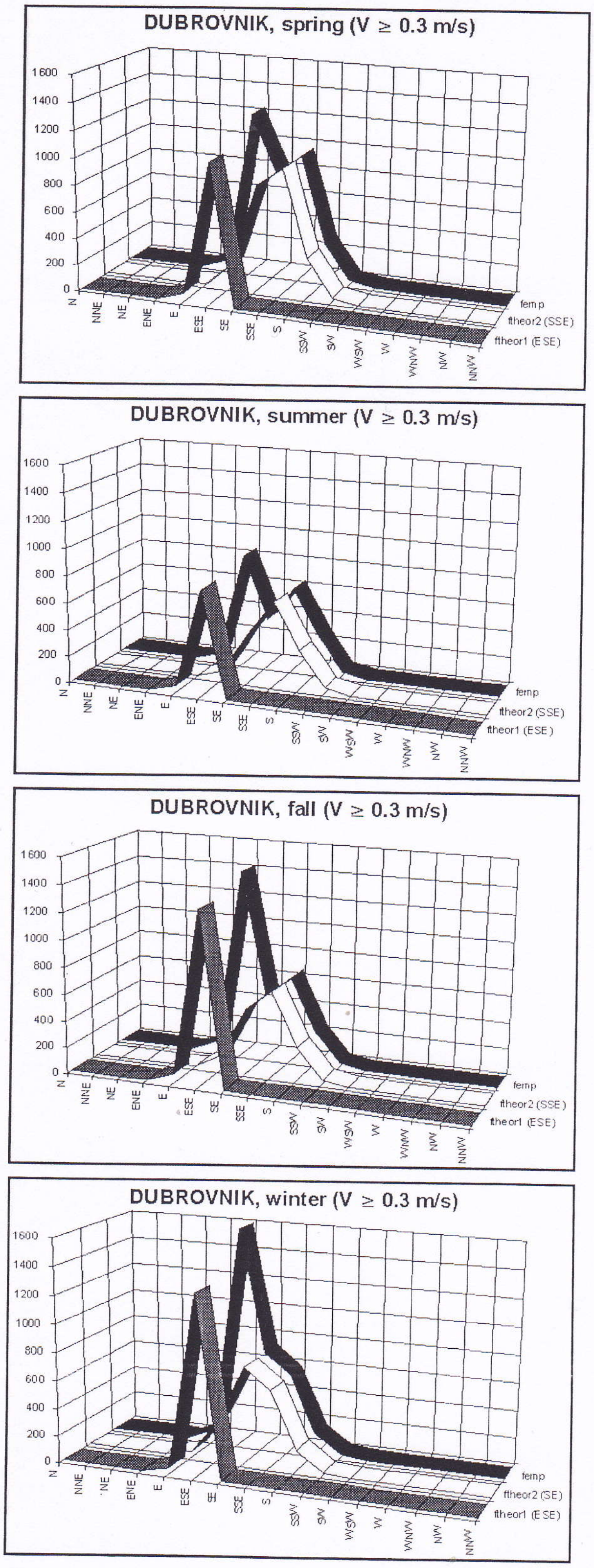


Figure 4. Graphical presentation of the results for the parameters contained in table 6: empirical frequencies (f_{emp}) and component distributions (f_{theor1} and f_{theor2}) for all *jugo* events which approximate the given empirical distribution.

Slika 4. Grafički prikaz razdiobe čestina empirijskih (f_{emp}) i komponentnih razdioba (f_{theor1} i f_{theor2}), koje aproksimiraju empirijske razdiobe za sve jugo događaje, prema rezultatima za parametre iz tablice 6.



Continuation of figure 4.

Nastavak slike 4.

with SSE component was obtained, but the associated α_i had a value at the limit range between the SE and ESE α interval. The contribution u_i of all ESE and of the single

Table 8. Categories for parameters α_i i σ_i.

Tablica 8. Kategorije parametara α_i i σ_i.

a)

The component name according to the i value	i interval
E or 90° 11.25°	78.75° to 101.25°
ESE or 112.5° 11.25°	101.25° to 123.75°
SE or 135° 11.25°	123.75° to 146.25°
SSE or 157.5° 11.25°	145.25° to 168.75°
S or 180° 11.25°	168.75° to 191.25°
SSW or 202.5° 11.25°	191.25° to 213.75°

b)

	i	
rounded value	interval	category
7°	2°–12°	narrow
17°	13°–22°	broad

SE component prevails compared to the SSE contribution in all 8 wind roses, with a maximal value around 0.72 in spring for both categories of *jugo* velocities. The ESE component has a very pronounced frequency peak at its α_i value, because the σ_i value being less than 12 most of the time. As opposed to ESE, the SSE component is broad, with a less expressed maximal frequency, with σ values being above 13 most of the time. The properties of the SSE component seem to be almost independent of seasons.

- **Split.** The approximation resulted in ESE and SE components appearing in all 8 seasonal wind roses. The number of data for a particular season is almost double compared with Pula. The contributions u_i of both components are pretty close, being between 0.4 and 0.6 in 7 out of 8 wind roses. The exception is the wind rose for all *jugo* events in summer, when the SE component prevails with its contribution value of 0.7. The ESE component is even narrower in all wind roses, compared to the ESE component in Pula, with a pronounced frequency peak at σ values above 13.
- **Dubrovnik.** An ESE with SE component was obtained in 2 out of 8 seasonal wind roses and an ESE with SSE component in the 6 remaining wind roses. The number of data in each season is about 20% above the

number of data in Split. The contributions of the two components do not differ significantly (u_i values 0.4 to 0.6), but the ESE component persists in remaining almost constantly below the SE component. The ESE component is significantly narrower than either the SE or SSE component. In three out of four seasons, the σ_i values relate as 5 to 18. A seasonally variable σ makes the shape of the ESE component seasonally variable too (in spite of keeping the σ values below 7) even more than the shapes of the SE or SSE component.

Figure 4 presents the main numerical results from table 6. The presentation of the results from table 7 does not differ significantly from the one presented in figure 4, and, therefore, it has not been shown here. In general the two components can be described as follows:

One component has its α_i inside the ESE angle interval and keeps a narrow shape because of a low σ_i value in all seasonal wind roses, being not significantly influenced by seasons or wind velocity. The ESE component contribution prevails in Pula all over the year, it contributes almost equally as the other component in Split, but it is below the other component contribution in Dubrovnik.

The other component has its α_i inside the SSE angle interval in all Pula seasonal wind roses and in 6 out of 8 wind roses in Dubrovnik. The SSE component has usually a higher σ_i value, especially in all seasonal wind roses at Dubrovnik. The SSE component shows a higher seasonal variation than the ESE component. This is valid for all three stations.

5. SUMMARY AND CONCLUSIONS

A criterion for the identification the *jugo* wind has been introduced to separate *jugo* events from the five-year period (1976–1980) of hourly mean wind data independently collected at three stations on the eastern (Croatian) Adriatic coast (Pula, Split and Dubrovnik). The criterion related to the hourly mean wind vectors data makes it possible to determine the start, the duration and the end of a *jugo* event. Two *jugo* data categories were analysed: one includes the hourly mean wind velocities equal to and above 0.3 ms^{-1} (all *jugo* events) and the other category includes velocities equal to and above 3 ms^{-1} (stronger *jugo*). The final results and conclusions are as follows:

- The hourly mean wind from the SE quadrant (6 direction classes) independent of any wind type, accounts for 33% to 40% of the entire wind data set (including 16 direction classes), going from north to south along the eastern Adriatic coast.
- The contribution of *jugo* events to the entire wind data set also increases going from north (19%) to south (27%). The increase is even more pronounced for stronger *jugo* (6% to 20%). Expressed as the average annual number of days, the contributions of the mentioned groups of data are 67 days with all *jugo* events at Pula, 80 days in Split and 97 days in Dubrovnik, or 22, 62 and 72 days with stronger *jugo*, respectively.
- Weak wind velocities ($0.3 \leq v \leq 2.9$ ms^{-1}) account for 67% of the *jugo* wind data in Pula, but only for 23% in Split and 26% in Dubrovnik, out of the number of data with all *jugo* events.
- The approximation of the seasonal *jugo* wind roses by means of mixture distribution gave a satisfactory result when using two wrapped normal component distributions with a minimum of the root of mean squared deviations as a measure of the validity of the approximation. For each station, 8 seasonal wind roses were approximated (4 for all *jugo* events and 4 for stronger *jugo*). Altogether, there were 24 seasonal wind roses. The approximation results for all *jugo* events and for stronger *jugo* did not differ significantly at all three stations.
- All 24 *jugo* wind roses were approximated with a pair of components. In 13 seasonal wind roses (8 in Split and 5 in Dubrovnik) the approximation procedure resulted in ESE and SE components. In 10 seasonal wind roses a pair of ESE and SSE components was obtained (7 in Pula and 3 in Dubrovnik). Only for one wind rose a pair of SE and SSE component was obtained (Pula, winter, stronger *jugo*).
- The ESE component contribution prevails in Pula all over the year, it contributes almost equally as the other component in Split, but it is below the other component contribution in Dubrovnik. The shape of the ESE component is not seasonally dependent, like the other SSE component, be-

cause of its σ value having a pronounced seasonal variation.

Obtaining two components for the *jugo* wind roses by the approximation procedure using mixture distribution calls to mind the known empirical statement about the existence of two types of *jugo* events i.e. the cyclonic and the anticyclonic type. Meanwhile, it can not be said yet that these results prove this statement. Two types of *jugo* events according to empirical statements are associated to different types of pressure patterns over the region of the Adriatic Sea and its surroundings and to different types of weather conditions, as mentioned in articles published already at the beginning of the 20th century. The question might be answered if other meteorological parameters are correlated to each of these analysed *jugo* events. In other words, the synoptic situation, temperature, humidity and precipitation conditions should be taken into account, to see if a model for each of the *jugo* event types could be obtained.

REFERENCES

Breckling, J., 1989: The Analyses of directional time series: Applications to wind speed and direction. Springer Verlag, Berlin, Heidelberg, N.Y., 238 str.

Brzović, N., 1999: Factors affecting the Adriatic cyclone and associated windstorms. *Contributions to Atmospheric Physics*, **72**, No 1, 51–65.

Brzović, N. and N. Strelec-Mahović, 1999: Cyclonic activity and severe *jugo* in the Adriatic. *Physics and Chemistry of the Earth*, (B), **24**, No.6, 653–657.

Essenwanger, O., 1976: Applied Statistics in Atmospheric Science. Part A: Frequencies and Curve Fitting, Elsevier Publ. Co., 412 str.

Hrabak-Tumpa, G., M. Mileta i J. Bukovina, 1996: Olujno jugo i bura na području Palagruže i Lastova. *Zbornik radova: Palagruža, Biser Jadrana*, 28–30 lipnja 1995, Split, 259–264.

Jurčec, V. i V. Vukičević, 1996: Olujno *jugo* na Palagruži. *Zbornik radova: Palagruža, Biser Jadrana*, 28–30 lipnja 1995, Split, 251–258.

Jurčec, V., B. Ivančan-Picek, V. Tutiš and V. Vukičević, 1996: Severe Adriatic jugo wind. *Meteor. Zeitschrift* N.F. **5**, H2, 67–75.

Kesslitz, W, 1914: Über die Windverhaeltnisse in der Adria. *Meteor. Zeitschrift* **May/1914**, 248–250.

Kesslitz, W. und K. Roessler, 1904: Grundzüge der maritimen Meteorologie. Für den Unterricht an den k.u.k. Marine-Akademie, Pola und Fiume, 51–54, 162–167.

Lisac, I. and B. Zelenko, 1984: Airflow type characteristics determined statistically from the wind rose. *Zbornik meteor. i hidrol. radova*, **11**, 67–70.

Lisac, I. and B. Zelenko, 1985: Advantages and disadvantages of statistical wind rose analysis. *International Dr. F. Sauberer Gedächtnis-symposium*. Universitt für Bodenkultur, Wien, 161–163.

Makjanić, B., 1978: Bura i jugo. Prilozi poznavanju vremena i klime SFRJ, **5**, Savezni hidrometeorološki zavod, Beograd, 1–56.

Mardia, K. V., 1978: Statistics of directional data. Nauka, Moscow, 240 str. (in Russian).

Marki, E., 1924: Klimatske prilike Dalmacije. Splitska društvena tiskara, Split, 22 str.

Marki, E., 1950: Vrijeme, upute za poznavanje i prognozu vremena bez upotrebe instrumenata. Poglavlje: Južina, Pomorstvo, Split, 109–113.

Perrin, F., 1928: Etude mathématique du mouvement brownien de rotation. *Ann. Scient. Ec. Norm. Sup.*, **45**, 1–58.

Poje, D., 1992: Wind persistence in Croatia. *International Journal of Climatology*, **12**, 569–586.

Poje, D., 1995: O nazivu vjetrova na Jadranu. *Hrvatski meteorološki časopis*, **30**, 55–62.

Poje, D., 2001: Variations in bora weather type, *Weather* (in print).

Stipaničić, V., 1969: Južni vjetrovi uz našu obalu. *Vijesti PMS*, **1/2**, 6–7.

Stipanović. V., 1972: Vjetar u Splitu sa posebnim naglaskom na jake i olujne vjetrove. *Hidrografski godišnjak 1971*, 71–81.

Trošić, Ž., 1983: Statističke karakteristike juga na Jadranskom moru. *Magistarski rad*, PMF, Sveučilište u Zagrebu, 111 str.

Trošić, Ž., 1984: The indirect calculation of the *jugo* wind maxima on Adria. *Vijesti PMS*, **1–2**, 17–18.

Trošić, Ž., 1985: Some statistical characteristics of the *jugo* wind on the Adriatic Sea. *Vijesti PMS*, **1–2**, 16–22.

Vukičević, V., 1991: Statistička analiza olujnog juga u Splitu. *Vijesti PMS*, **37**, 7–18.

Zelenko, B. and I. Lisac, 1994: On the statistical wind rose analysis. *Theor. Appl. Climat.*, **48**, 209–214.