Theor Appl Climatol (2018) 131:1273–1284
DOI 10.1007/s00704-017-2044-6

ORIGINAL PAPER

Seasonal prevailing surface winds in Northern Serbia

Ivana Tošić[1] · **Milivoj B. Gavrilov**[2] · **Slobodan B. Marković**[2] · **Albert Ruman**[3] · **Suzana Putniković**[1]

Received: 9 June 2016 / Accepted: 16 January 2017 / Published online: 2 February 2017

Abstract Seasonal prevailing surface winds are analyzed in the territory of Northern Serbia, using observational data from 12 meteorological stations over several decades. In accordance with the general definition of prevailing wind, two special definitions of this term are used. The seasonal wind roses in 16 directions at each station are analyzed. This study shows that the prevailing winds in Northern Serbia have northwestern and southeastern directions. Circulation weather types over Serbia are presented in order to determine the connections between the synoptic circulations and prevailing surface winds. Three controlling pressure centers, i.e., the Mediterranean cyclone, Siberian high, and the Azores anticyclone, appear as the most important large-scale factors that influence the creation of the prevailing winds over Northern Serbia. Beside the synoptic cause of the prevailing winds, it is noted that the orography of the eastern Balkans has a major influence on the winds from the second quadrant. It was found that the frequencies of circulation weather types are in agreement with those of the prevailing winds over Northern Serbia.

1 Introduction

The term "prevailing wind" is usually used when describing the permanent winds of the Ferrel circulation cells on the surface that blow from west to east in the northern hemisphere, which are known as prevailing westerlies or westerlies (e.g., Palmén and Newton 1969), and also from west to east in the middle latitudes of the southern hemisphere (although circulation in atmospheric systems is of opposite sign on the hemispheres). In this case, the term "prevailing" is used to mark winds that blow near the surface in the global space in an approximately constant direction. Also, permanent easterly winds blow near the surface of the Hadley circulation cells, which are known as the trade winds. Unlike winds in the Ferrel cells, trade winds are not prefaced with the term "prevailing", but have prevailing characteristics. In this case, surface winds[1] blow from approximately constant directions, as a result of the general circulation of the atmosphere (e.g., Holton 1972). These winds are more permanent over the ocean, because the influence of the water on their deformation is very small. Above the ocean, surface friction is minimal and the friction layer is at its thinnest (e.g., Stull 1988). These winds are significantly modified above the continents, and they are often unrecognizable because they are under the influence of different processes on the land, such as terrain orography, surface composition, plant cover, and thermal conditions.

Ward (1919) presented maps of the prevailing winds in January and July over the USA. He explained the causes of wind, which gave rise to the modern concept explored in this paper. Recent research of prevailing winds has included regional areas from polar regions (e.g., Stegall and Zhang 2012) to tropical regions (e.g., Mahongo et al. 2011); there are other studies that have been extended to the upper wind on the highest layers of the atmosphere (e.g., Prakash and Roper 1981).

✉ Ivana Tošić
itosic@ff.bg.ac.rs

1 University of Belgrade-Faculty of Physics, Institute of Meteorology, Dobračina 16, Belgrade 11000, Serbia

2 Faculty of Sciences, Chair of Physical Geography, University of Novi Sad, Trg Dositeja Obradovića 3, Novi Sad 21000, Serbia

3 Republic Hydrometeorological Service of Serbia, Kneza Višeslava, Belgrade 66, Serbia

[1] Surface wind is the wind blowing near the Earth's surface. It is measured by an anemometer (speed) or wind vane (wind direction) at a standard height of 10 m above ground in an area where the distance between the instrument and any obstruction is at least 10 times the height of the obstruction.

Some workers have established the high correlation between wind patterns and large-scale atmospheric conditions. Pandžić and Likso (2005) recognized synoptic-scale atmospheric conditions over the northern Atlantic European region as the primary factor for the creation of wind field patterns along the eastern Adriatic coast. Jiménez et al. (2009) performed a classification of daily surface wind fields over the Comunidad Foral de Navarra (CFN) region (northeastern Iberian Peninsula) into wind pattern types. They associated eight pressure patterns with the surface wind patterns (WPs) in order to understand the forcing mechanism of the different WPs. A characterization of surface winds over the Iberian Peninsula (IP) was made by Lorente-Plazas et al. (2015). They explained the wind behavior of various regions, characterized by the wind rose and wind speed histogram, as the response of each region to the main circulation types affecting the IP.

In Serbia, there are almost no publications analyzing prevailing winds, but there are some studies on the subject of wind. One of the first published articles about wind in Serbia was Küttner (1940) and relates to the local wind, the Koshava. After that, there was a series of publications on the Koshava wind; for example Milosavljević (1950), Vukmirović (1985), Unkašević et al. (1998, 1999, 2007), Unkašević and Tošić (2006), and Romanić et al. (2015, 2016). In addition to publications on the Koshava wind, further studies can be found about winds over Serbia generally (Dobrilović 1960; Sokolović et al. 1984; Gburčik et al. 2006). In addition, there are other studies that investigate winds in nearby regions (e.g., Poje 1992; Klaić et al. 2009).

The aim of this work is to analyze the seasonal prevailing winds in Northern Serbia over a time period of 60 years, and to assess the impact of synoptic circulation types on the winds' behavior. Northern Serbia is very suitable for the study of prevailing winds, because this area is mostly flat, the obstacles for the air flow are minimal, the boundary layer is very thin, surface friction is very small, and all these factors minimally modify the local winds. Research about prevailing winds should complete information about the climate of Northern Serbia (Vojvodina) previously published by Gavrilov et al. (2011) about hail, Hrnjak et al. (2014) about aridity, Tošić et al. (2014) about precipitation, and Gavrilov et al. (2015, 2016a) about temperatures. The remainder of this paper is organized as follows: Section 2 presents a description of the research area, the data are described in Section 3, the methodology is defined in Section 4, the obtained results are presented in Section 5, Section 6 will present a discussion of the findings, and conclusions are given in Section 7.

2 Target region

The target region that is the subject of this study, Northern Serbia, is shown in Fig. 1. This region is located in the southeastern part of the Carpathian (Pannonian) Basin and covers a territory that includes the province of Vojvodina (Serbia), plains on both banks of the Sava river, and both banks of the Danube from Belgrade downstream to its exit from Serbia. The most distinctive landforms of this region are four

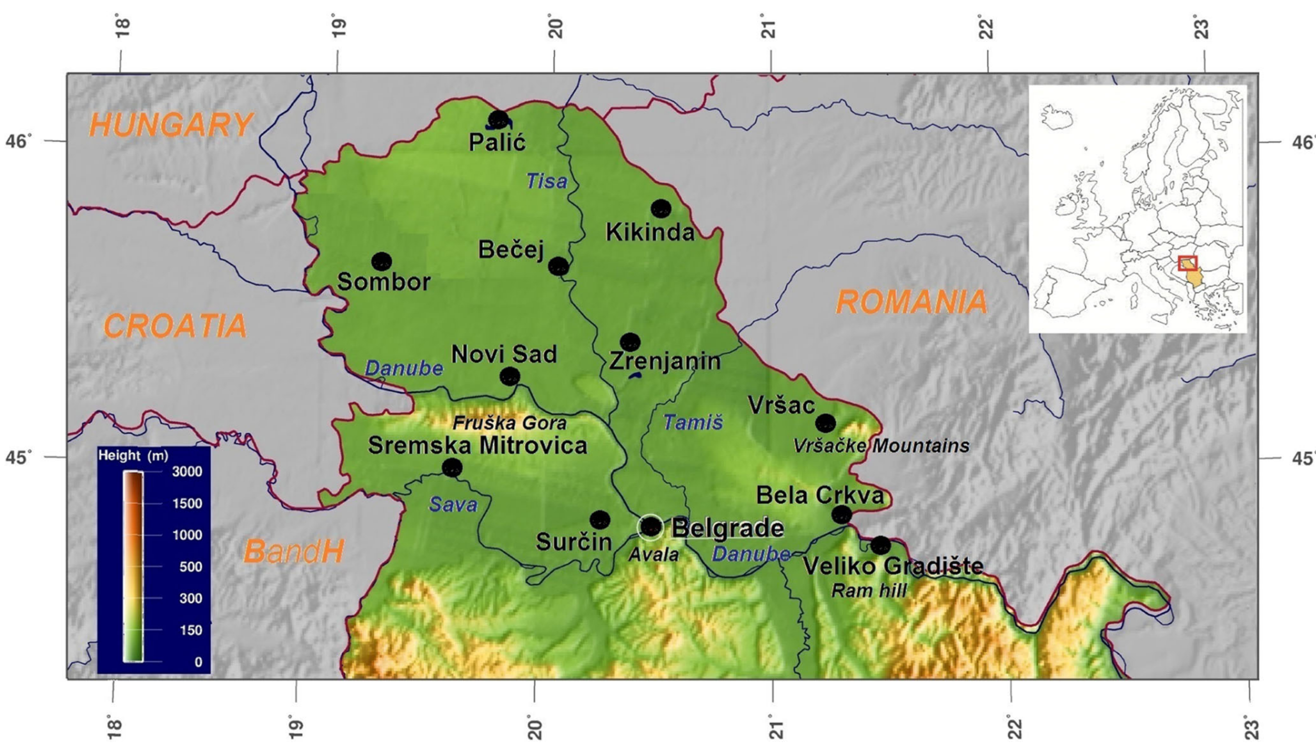


Fig. 1 Northern Serbia with geographical position, orography, and location of meteorological stations (http://www.ginkgomaps.com/maps_serbia.html)

mountains: Vršačke Mountains (641 m) in the southeast, Fruška Gora (539 m) in the southwest, Avala (511 m) in the south, and Ram Hill (282 m) in the southeast. These mountains make up a small part of the surface area, while the rest of the region is flat and crisscrossed by the rivers Danube, Sava, Tisa, and Tamiš.

As the local terrain obstacles for the air flow are weak in the area of Northern Serbia, wind features should reflect the characteristics of large-scale atmospheric circulation stronger than the local terrain influence. Thus, it is expected that the area is appropriate for exploring prevailing local winds. On the other hand, local impacts on the winds' appearance will be more easily identified because there are only three clearly separated orographic barriers, while the other impacts can be considered negligible.

It has long been considered that the target region of interest is under the influence of undulations of the polar front. When the polar front comes into this area over the Atlantic, and Western and Central Europe without retention in the Alps, in Northern Serbia, there are incursions of cold fronts from the north/northwest, which reduce the surface temperature, bringing precipitation and northwesterly winds (e.g., Radinović 1981). If the Polar front is retained in the Alps area, cyclonic developments usually start in the West Mediterranean Basin, mostly in the Gulf of Genoa. These processes mainly lead to the movement of warm fronts into Northern Serbia. These incursions usually precede winds from the southern quadrants, which are stronger if a larger pressure difference exists between the Mediterranean cyclone and the anticyclone over the European part of Russia. These processes have long been described (Gburčik 1960; Radinović 1962; Trigo et al. 2002; Horvath et al. 2008). Occasionally, this area comes under the influence of the ridges of the Azores/Atlantic or the Siberian anticyclone. In this case, stable weather usually occurs without precipitation (Putniković et al. 2016), mainly calm with very high temperatures in summer and very low temperatures in winter (Unkašević and Tošić 2013).

3 Data

We analyze daily anemograph wind data recorded at the climatological term at 7, 14, and 21 local time (LT) from 12 meteorological stations in Northern Serbia in accordance with the World Meteorological Organization (1979). These stations are operated by the Republic Hydrometeorological Service of Serbia (http://www.hidmet.gov.rs/). The locations of the stations are shown in Fig. 1; their main characteristics are given in Table 1. Ten of these stations are located at altitudes of less than 100 m above sea level (a.s.l.), while the remaining two stations are at altitudes of 102 and 132 m a.s.l. Eleven stations are located in very representative places for observing the surface wind, out of urban areas with the anemograph at an altitude of 10 m absolute ground level (a.g.l.). The anemograph in Belgrade is at an altitude of 24 m a.g.l., in order to reduce the impact of urban facilities on observation wind. Wind data were measured by anemographs of two types: Fuess and Lambrecht. The data contained measurement error inherent in these instruments, which were previously calibrated in an accredited meteorological laboratory. A quality control check of hourly wind direction and hourly wind speed was passed. The missing hourly data were interpolated only from the neighboring hourly data at the same station.

In order to obtain the prevailing wind, we used two wind datasets: wind direction in degrees and wind speed in ms^{-1}. For both wind datasets, a time series of maximum length periods was used, from the beginning to the end year of the observation wind (Table 1). At 11 stations, the periods of observation are longer than 50 years. Although at one station, wind measurements had been performed for shorter periods (20 years in Bela Crkva), we thought it appropriate to include this station in the analysis in order to cover as much territory as possible. As shown in Table 1, datasets were completed for all terms at nine stations over the entire period, while at the three other stations, the missing data were less than 4%. The

Table 1 List of meteorological stations with abbreviations (Ab), latitude, longitude and altitude, period of observation, and missing data

No	Ab	Station	Latitude	Longitude	Altitude (m)	Period	Missing data (%)
1	BE	Bečej	45° 37′	20° 02′	84	1949–2009	0.0
2	BC	Bela Crkva	44° 54′	21° 25′	90	1995–2014	0.0
3	KI	Kikinda	45° 51′	20° 28′	81	1949–2014	0.0
4	BG	Belgrade	44° 48′	20° 28′	132	1939–2014	0.0
5	NS	Novi Sad	45° 20′	19° 51′	86	1949–2014	0.0
6	PA	Palić	46° 06′	19° 46′	102	1949–2013	3.1
7	SO	Sombor	45° 46′	19° 09′	87	1965–2014	4.0
8	SM	Sremska Mitrovica	44° 58′	19° 38′	82	1949–2001	1.9
9	SU	Surčin	44° 47′	20° 16′	73	1966–1997	0.0
10	VG	Veliko Gradište	44° 45′	21° 31′	82	1965–2014	0.0
11	VR	Vršac	45° 07′	21° 18′	83	1965–2014	0.0
12	ZR	Zrenjanin	45° 24′	20° 21′	80	1966–2014	0.0

missing values were not estimated, since the goal of this study was the climatological analysis of the prevailing winds in Northern Serbia.

To obtain the circulation weather types (CWT), daily values of the sea level pressure (SLP) for the period 1961–2010 were retrieved from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al. 1996). In order to obtain a view of the synoptic situation defined by each CWT, the location between 32.5–52.5° N and 5–35° E was selected, because this position best describes the weather types over Serbia (Putniković et al. 2016).

4 Methods

In this study, two research steps were applied. In the first step, after considering the general definition of prevailing wind, special definitions for this term were derived, and are explained in the following two paragraphs. These definitions have helped to determine the prevailing winds in Northern Serbia quantitatively. In the second step, we assessed the influence of the synoptic conditions on wind climatology using the characterization of the atmospheric circulation over Serbia proposed by Putniković et al. (2016).

Although the term "prevailing wind" has an implicitly clear meaning, it does not have a quantitative definition, despite the very long history of use of this term. Therefore, for the purposes of this study, the following definition of the term from the Glossary (Huschke 2000) will be used: "Prevailing wind direction or prevailing wind is most frequently observed during a given period. The periods most frequently used are the observational day, month, season, and year. Methods for determination vary from a simple count of periodic observations to the computation of a wind rose."

In accordance with the previous general definition of prevailing wind, here we will use two specific definitions of this term. In the first definition, the maximum value of the frequency of the observed wind direction in one of the four quadrants, which is obtained by calculating the sum of all frequencies in quadrant, is considered to be *the primary prevailing wind per quadrant* (PPQ). The second largest value is considered as *the secondary prevailing wind per quadrant* (SPQ). The four quadrants are defined in degrees, as follows: I (0–90°), II (90–180°), III (180–270°), and IV (270–360°). In the second definition, the maximum value of the frequency of the observed wind direction in one of the 16 elementary directions (interval is 22.5°) of the wind rose is considered to be *the prevailing wind per (elementary) direction* (PPD). For all definitions, the mean seasonal wind roses in 16 directions at each of the 12 stations during periods from Table 1 were analyzed.

Classification of CWTs and their seasonal frequencies over Serbia were investigated in Putniković et al. (2016). Applying the objective weather typing system of Jenkinson and Collison (1977), which is based on the Lamb types (Lamb 1972), daily circulation was determined by the strength, direction, and vorticity of geostrophic flow. These rules allow 26 CWTs, which are grouped into three main groups: eight pure directional types—northerly (N), northeasterly (NE), easterly (E), southeasterly (SE), southerly (S), southwesterly (SW), westerly (W), and northwesterly (NW); two pure types based on the severity of the geostrophic vorticity—cyclonic (C) and anticyclonic (A); and 16 hybrid types (eight cyclonic and eight anticyclonic for each direction). To simplify the analysis, each of the 16 hybrid types was incorporated with a weight of 0.5 into the corresponding pure directional and vorticity types (Trigo and DaCamara 2000). Therefore, only 10 main CWTs were retained: eight pure directional and two vorticity types, cyclonic (C) and anticyclonic (A). Composite maps of each CWT were constructed using the SLP during the period 1961–2010 for all seasons. The SLP fields over southeastern Europe were classified and related to the surface circulations over Serbia in order to compare the frequency of wind and weather types, and to obtain an explanation of the occurrence of the prevailing winds.

5 Results

Figures 2–5 show mean seasonal wind roses in 16 elementary directions with intervals of 22.5° in the percentage with mean wind speeds at 14 LT, as the maximum compared to 7 and 21 LT. Comparing wind roses for 7, 14 and 21 LT, similar results are obtained. In addition to making it easier to analyze our results, Tables 2–5 show the frequency of winds in four quadrants obtained as the sum of four elementary directions.

5.1 Seasonal analysis

Wind roses during the spring are presented in Fig. 2. As can be seen, there is no prevailing wind in Palić (PA), at the northernmost station. In Sombor (SO), the prevailing wind is from the north. At the remaining 10 stations, winds from the second and forth quadrant prevailed. Thus, it can be considered that northwestern (NW) and southeastern (SE) winds prevailed in Northern Serbia during the spring. Furthermore, Fig. 2 shows that the prevailing wind is associated with the maximum wind speed in VG, VR, BC, BG, SO, NS, and SM. The SE winds at stations BC, VG, and VR are influenced by orography. The Vršačke Mountains, as the highest in the target region, modified winds from the east in VR, enhancing S-SE winds. It is supposed that there is an influence of the high orographic barriers out of the target region (Carpathian Mountains in the E and SE, and Homolje Mountains in the SE) on the SE

Fig. 2 Spring wind roses in 16 directions and intensity at 14:00 LT for the meteorological stations listed in Table 1. Colors in wind roses correspond to wind speeds

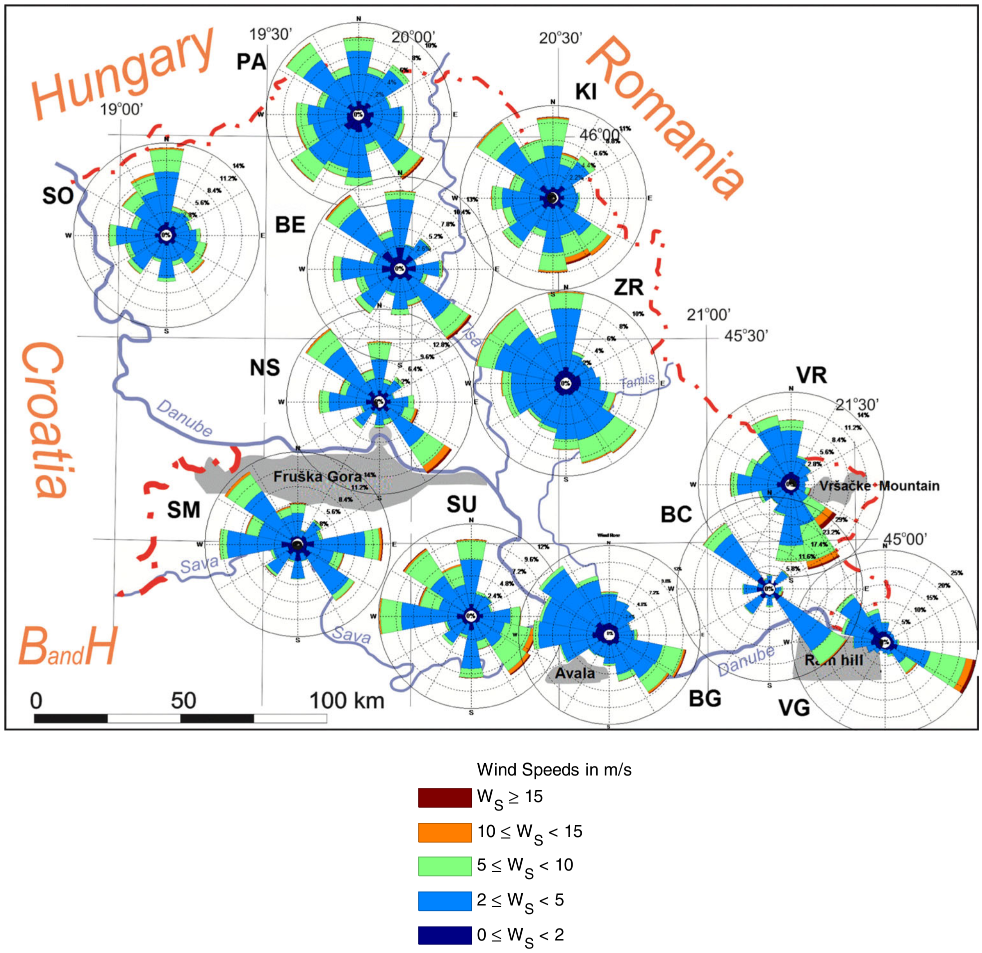


Table 2 Frequency of spring wind per quadrant in 16 directions and calm (%) for 12 meteorological stations at 14:00 LT

Quad.	Dir.	BE	BC	BG	KI	NS	PA	SO	SM	SU	VG	VR	ZR
I	22.5	2.9	0.1	4.2	5.1	3.2	4.9	3.8	1.4	2.7	1.7	3.8	3.1
	45.0	4.6	5.7	3.5	5.8	4.4	6.3	4.0	3.8	2.6	1.4	2.9	2.5
	67.5	1.6	0.1	2.3	2.2	1.7	3.1	3.2	3.1	2.1	1.1	1.9	2.8
	90.0	5.5	2.3	3.1	2.6	5.3	4.5	4.5	12.7	6.0	2.2	1.3	3.3
Sum I		14.6	8.2	13.1	15.7	14.6	18.8	15.5	21.0	13.4	6.4	9.9	11.7
II	112.5	3.2	2.6	10.2	2.7	6.1	4.7	5.7	6.7	8.4	24.9	2.3	5.2
	135.0	11.9	28.9	9.3	8.0	14.8	8.3	6.4	10.0	9.0	9.3	7.7	9.0
	157.5	4.8	1.4	6.0	7.9	3.2	3.7	4.2	1.9	3.9	2.6	13.0	8.7
	180.0	6.2	4.0	3.5	8.7	3.7	7.5	6.5	4.7	7.8	1.5	11.5	7.0
Sum II		**26.1**	**36.9**	**29.0**	**27.4**	**27.8**	24.2	22.8	**23.3**	**29.1**	**38.3**	**34.5**	**29.9**
III	202.5	3.2	1.1	2.5	4.3	1.4	6.7	3.4	2.0	2.2	0.8	4.2	5.1
	225.0	7.3	8.2	2.7	7.0	4.8	8.7	6.6	5.3	4.0	2.1	2.9	4.6
	247.5	5.8	0.8	6.4	5.7	2.4	6.5	5.8	3.5	2.9	3.7	4.4	6.5
	270.0	9.1	7.0	9.9	7.0	10.0	6.5	8.3	11.6	11.9	7.5	8.8	6.7
Sum III		25.4	**17.1**	21.5	23.9	18.6	**28.4**	**27.1**	22.4	21.0	14.1	20.3	22.9
IV	292.5	3.7	2.2	9.2	4.8	6.5	4.2	4.8	7.6	6.6	11.0	6.5	9.8
	315.0	12.5	4.6	11.1	11.0	15.2	9.4	7.6	13.1	10.5	15.2	5.6	9.7
	337.5	5.0	1.8	7.8	6.8	5.0	5.0	9.4	5.3	6.5	8.2	10.5	5.4
	0.0	10.8	2.9	5.4	9.5	10.0	8.3	13.2	5.8	9.9	4.2	9.5	9.9
Sum IV		**32.0**	11.5	**33.5**	**32.1**	**36.7**	**26.9**	**35.0**	**31.8**	**33.5**	**38.6**	**32.1**	**34.8**
Sum	00-360	98.1	93.7	97.1	99.1	97.7	98.3	97.4	98.5	97.0	97.4	96.8	99.3
Calm		1.9	6.3	2.9	0.9	2.3	1.7	2.6	1.5	3.0	2.6	3.2	0.7

The primary prevailing wind per quadrant (PPQ) is bolded and framed. The secondary prevailing wind per quadrant (SPQ) is bolded. The prevailing wind per direction (PPD) is framed wind at BC, VG, and VR. Fruška Gora as an orographic barrier channel winds in the longitudinal direction in SM.

Table 2 shows the frequency of the mean spring wind from 16 directions and calm for 12 stations in Northern Serbia. During the spring, values of calms ranged from 0.7% in ZR to 3.2% in VR, with the maximum value of 6.3% recorded in BC. PPQ appears at nine stations in the fourth quadrant (northwest wind), at two stations in the second quadrant (southeast wind), and at one station in the third quadrant (southwest wind). SPQ is the opposite of the primary prevailing wind. It is observed at eight stations in the second quadrant, and at two stations in the third and fourth quadrants. The NW and SE winds during the spring are prevailing winds in Northern Serbia, since the wind from the fourth quadrant is recorded in 11 cases and from the second quadrant in 10 cases. PPD was recorded in eight cases from the fourth quadrant, in three cases from the second quadrant, and in one case from the third quadrant, while it was not recorded at all from the first quadrant.

The wind roses during the summer (Fig. 3) show winds predominately from the northwest. The prevailing wind at nine stations is related to the maximum wind speed. In VG, the secondary prevailing wind is linked to the strongest wind. One more exception is VR, where the influence of orography is evident. The influence of high orographic barriers out of the target region (Carpathian Mountains, and Homolje Mountains) can be seen on the SE wind at BC and VG.

From Table 3, we can see that somewhat higher values of calms from 1.2% in ZR to 4.4% in SO are recorded in summer compared to spring, with the maximum value of 8.8% in BC. During the summer, PPQ is noted in the fourth quadrant at all 12 stations (Table 3). SPQ occurs at seven stations in the third quadrant, at three stations in the second quadrant, and at one station in the first quadrant (Table 3). In addition, PPD was recorded at all stations in the fourth quadrant (Table 3). Based on Fig. 3 and Table 3, it can be concluded that NW winds prevail in Northern Serbia in summer.

SE winds dominated in the majority of stations during the autumn (Fig. 4) in Northern Serbia. At 10 stations, the prevailing wind is associated with the maximum wind speed. It is not valid for VR and SU, similar to spring (Fig. 2). Comparing the wind roses for BE and ZR in autumn (Fig. 4) and spring (Fig. 2), it can be seen that they have similar characteristics but without a northern direction in autumn. A wind rose for PA has homogeneous frequencies, with dominant NW and SE directions. In SO, the prevailing winds are from the north. The Vršačke Mountains enhanced S-SE winds in VR. The Carpathian Mountains and Homolje Mountains channeled SE winds in BC and VG. The Avala Hill prevented winds from the south in BG.

The frequency of the mean autumn wind from 16 directions and calm for all stations are presented in Table 4. The maximum value of calm is recorded in BC (12.7%). PPQ appears at 11 stations in the second quadrant and once in the fourth quadrant. SPQ occurs at nine stations in the fourth quadrant, and at one station in the first, second, and third quadrants. PPD was recorded at nine stations in the second quadrant and at one station in the first, third, and fourth quadrants. It can thus be

Fig. 3 As in Fig. 2, but for the summer season

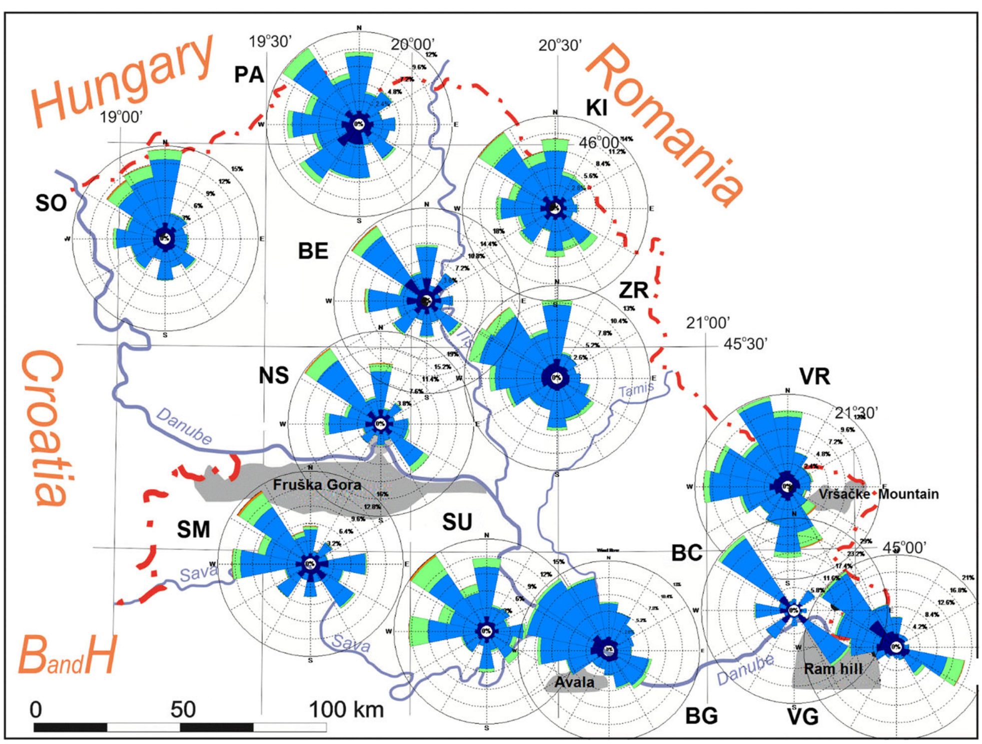


Table 3 As in Table 2 but for summer

Quad.	Dir.	BE	BC	BG	KI	NS	PA	SO	SM	SU	VG	VR	ZR
I	22.5	2.0	0.3	5.2	5.1	2.3	3.7	3.5	1.4	11.7	1.8	4.1	3.1
	45.0	5.6	6.2	3.9	4.9	4.4	4.7	3.6	3.8	3.7	1.8	2.5	2.7
	67.5	1.5	0.2	3.0	2.3	1.8	2.4	2.4	2.1	2.8	0.6	2.7	2.0
	90.0	4.2	2.1	2.6	2.6	4.8	4.2	2.9	9.2	5.6	1.6	2.3	2.6
Sum I		13.3	8.8	14.7	14.9	13.3	15.0	12.4	16.5	**23.8**	5.8	11.6	10.4
II	112.5	2.2	0.6	5.8	1.9	5.0	3.4	3.2	5.1	4.2	15.3	1.8	4.1
	135.0	7.5	20.4	6.1	7.3	11.3	5.2	5.4	8.8	5.7	6.8	3.9	5.7
	157.5	3.4	0.8	5.0	5.9	2.6	2.2	4.1	2.4	2.6	1.8	7.9	5.6
	180.0	6.3	3.2	2.9	6.9	3.5	6.7	6.2	5.0	6.0	1.3	9.0	7.0
Sum II		19.4	**25.0**	19.8	22.0	**22.4**	17.5	18.9	21.3	18.5	**25.2**	22.6	22.4
III	202.5	3.0	0.5	2.0	2.8	1.4	6.7	2.7	1.9	1.6	0.9	4.6	3.9
	225.0	7.3	9.3	2.1	5.9	3.8	9.1	5.4	6.4	3.4	1.7	3.8	4.1
	247.5	5.1	1.3	5.7	5.2	2.7	5.7	5.0	3.6	3.5	4.0	5.9	6.9
	270.0	11.6	11.2	10.0	8.5	11.0	9.2	7.9	13.3	12.4	9.9	10.8	9.2
Sum III		**27.0**	22.3	19.8	**22.4**	18.9	**30.7**	**21.0**	**25.2**	20.9	16.5	**25.1**	**24.1**
IV	292.5	4.7	3.2	12.1	6.7	6.8	6.8	5.9	8.8	7.5	13.7	9.5	12.6
	315.0	17.5	28.4	12.5	13.9	18.7	11.8	11.1	15.1	15.0	20.7	6.7	11.9
	337.5	4.9	1.5	10.7	8.5	4.9	6.3	11.9	5.1	7.3	9.2	11.8	6.6
	0.0	10.4	2.0	6.7	10.3	12.0	9.2	14.4	6.0	3.6	5.9	9.7	10.8
Sum IV		**37.5**	**35.1**	**42.0**	**39.4**	**42.4**	**34.1**	**43.3**	**35.0**	**33.4**	**49.5**	**37.7**	**41.9**
Sum	00-360	97.2	91.2	96.3	98.7	97.0	97.3	95.6	98.0	96.6	97.0	97	98.8
Calm		2.8	8.8	3.7	1.3	3.0	2.7	4.4	2.0	3.4	3.0	3	1.2

concluded that the winds from the second quadrant prevail during the autumn in Northern Serbia.

The winter wind roses in Fig. 5 show winds predominately from the southeast. At all stations, except VR, the prevailing winds are associated with the maximum wind speeds. The wind rose for PA has homogeneous frequencies, with the dominant NW direction. In winter, as for all the seasons, the winds are from the north in SO. The prevailing wind direction in SM is from the east, due to longitudinal extension of Fruška Gora. There is no wind from the south in NS and BG, due to the influence of Fruška Gora and Avala, respectively. The strongest SE winds are observed in VR, since the Vršačke Mountains enhanced S-SE winds. The Carpathian Mountains and Homolje Mountains channeled SE winds in BC and VG. At nine stations, winds from the second quadrant prevailed.

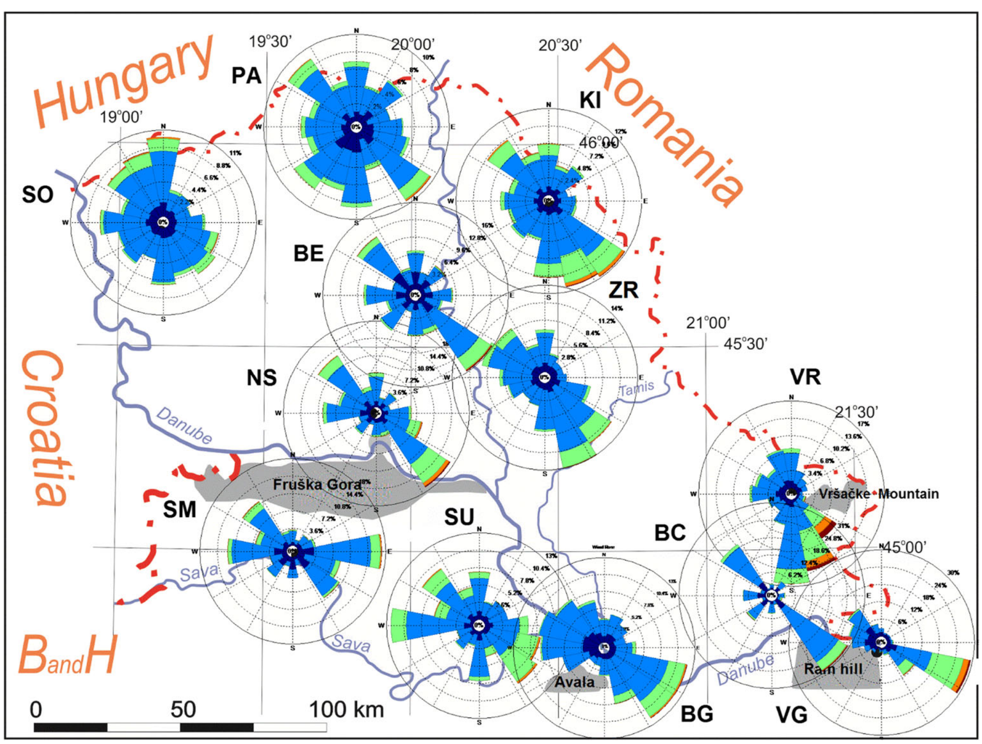


Fig. 4 As in Fig. 2, but for the autumn season

Table 4 As in Table 2 but for autumn

Quad.	Dir.	BE	BC	BG	KI	NS	PA	SO	SM	SU	VG	VR	ZR
I	22.5	3.1	0.1	4.3	4.2	2.1	4.1	3.5	1.3	2.8	1.3	3.5	3.1
	45.0	5.4	3.8	3.4	5.0	3.8	5.7	3.4	2.8	3.5	1.4	2.4	2.1
	67.5	1.9	0.3	2.5	1.9	1.7	3.3	2.8	3.5	3.4	1.4	2.0	2.0
	90.0	5.7	2.6	4.0	2.9	6.0	4.7	4.5	17.2	6.5	1.9	0.9	2.5
Sum I		16.1	6.8	14.2	14.0	13.6	17.8	14.2	**25.1**	16.2	6.0	8.8	9.7
II	112.5	3.9	1.6	12.0	3.1	8.5	5.5	6.4	8.8	8.4	29.2	1.7	6.5
	135.0	15.8	30.3	12.0	11.9	17.1	9.6	7.1	10.3	9.5	11.5	9.3	11.9
	157.5	6.2	1.4	7.8	11.3	3.8	4.4	6.2	1.8	3.8	2.4	14.3	14.0
	180.0	6.5	4.3	3.4	9.8	3.8	8.6	7.2	4.3	7.3	1.3	16.5	7.8
Sum II		**32.4**	**37.6**	**35.2**	**36.1**	**33.2**	**28.1**	**26.9**	**25.2**	**29.0**	**44.4**	**41.8**	**40.2**
III	202.5	2.1	0.5	1.9	4.7	1.3	6.8	4.0	1.9	2.2	0.4	5.0	3.7
	225.0	6.8	8.7	1.8	5.4	4.1	7.9	5.5	5.2	3.4	2.1	2.8	3.3
	247.5	4.5	1.3	5.6	4.9	2.5	5.1	5.1	3.5	2.5	4.0	3.5	5.1
	270.0	8.4	8.1	8.8	5.8	9.8	5.7	7.3	12.2	12.3	8.2	7.0	6.4
Sum III		21.8	18.6	18.1	20.8	17.7	**25.5**	21.9	22.8	20.4	14.7	18.3	18.5
IV	292.5	3.3	2.0	9.3	4.8	6.7	4.9	4.7	6.6	6.0	9.3	6.1	9.3
	315.0	11.8	19.8	8.1	9.4	13.2	8.8	7.7	11.2	9.4	11.9	4.7	8.6
	337.5	4.0	0.5	6.6	6.0	4.4	4.7	8.4	3.1	4.9	4.4	7.6	4.6
	0.0	7.1	2.0	3.6	7.1	7.2	6.9	10.1	3.2	7.2	2.9	7.7	6.9
Sum IV		**26.2**	**24.3**	**27.6**	**27.3**	**31.5**	25.3	**30.9**	24.1	**27.5**	**28.5**	**26.1**	**29.4**
Sum	00-360	96.5	87.3	95.1	98.2	96.0	96.7	93.9	97.2	93.1	93.6	95.0	97.8
Calm		3.5	12.7	4.9	1.8	4.0	3.3	6.1	2.8	6.9	6.4	5.0	2.2

According to Table 5, the highest percentage of calms is recorded in winter, from 2.3% in KI to 12.1% in VG. The maximum value of 19.8% is recorded in BC. PPQ was observed at eight stations from the second quadrant, at three stations from the fourth quadrant, and once from the first and third quadrants (Table 5). SPQ occurs at nine stations in the fourth quadrant (NW winds) and at three stations in the second quadrant (SE winds). PPD was recorded in eight cases in the second quadrant, in two cases from the fourth quadrant, and once from the first and third quadrants (Table 5). It can be concluded that the prevailing winds in Northern Serbia have a SE direction in winter.

5.2 Synoptic conditions

The impact of the synoptic conditions on the wind direction in Northern Serbia was assessed using the CWTs described by Putniković et al. (2016), which summarized the synoptic conditions over Serbia in 10 CWTs for each season. The results

Fig. 5 As in Fig. 2, but for the winter season

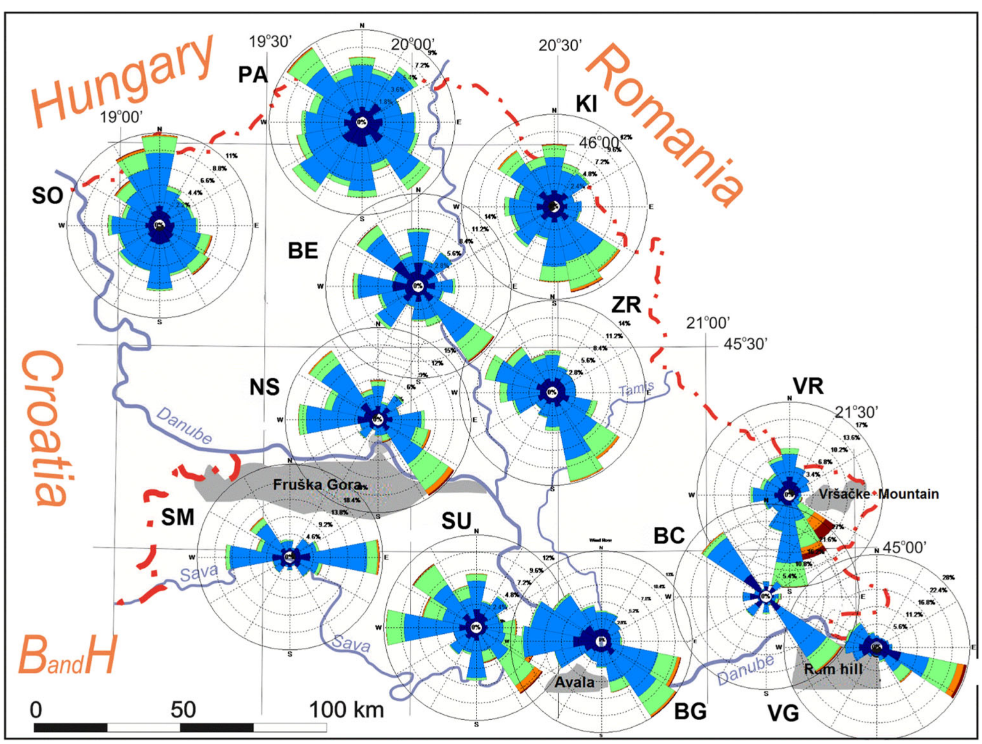


Table 5 As in Table 2 but for winter

Quad.	Dir.	BE	BC	BG	KI	NS	PA	SO	SM	SU	VG	VR	ZR
I	22.5	3.4	0.1	3.7	5.4	2.1	5.0	4.3	1.0	2.9	1.3	4.4	3.5
	45.0	5.6	4.1	2.7	5.0	4.3	6.3	3.5	4.4	4.5	1.5	3.4	2.9
	67.5	2.3	0.1	2.2	2.0	2.7	3.6	3.6	6.3	2.5	2.0	2.7	2.8
	90.0	4.9	2.8	2.3	2.9	7.0	4.9	4.1	21.9	4.7	3.0	1.0	2.8
Sum I		16.2	7.1	10.9	15.3	16.1	19.8	15.5	**33.6**	14.6	7.8	11.5	12.0
II	112.5	3.2	2.2	11.5	2.8	8.2	5.3	6.0	7.2	7.8	27.5	1.4	6.4
	135.0	13.7	26.4	13.0	10.1	14.7	7.8	6.8	4.6	10.1	11.7	9.4	12.0
	157.5	5.7	1.1	7.0	11.2	3.0	4.6	5.8	0.8	4.2	2.9	11.8	13.8
	180.0	4.7	3.6	3.1	9.6	1.8	7.2	7.5	1.9	6.5	0.8	16.9	5.2
Sum II		**27.3**	**33.3**	**34.6**	**33.7**	**27.7**	**24.9**	**26.1**	14.5	**28.6**	**42.9**	**39.5**	**37.4**
III	202.5	2.5	0.4	2.3	3.9	0.9	6.1	5.2	1.0	2.9	0.5	6.2	3.2
	225.0	7.4	5.6	2.1	5.9	2.9	8.1	5.5	3.2	3.6	1.6	2.8	2.2
	247.5	5.6	0.8	6.3	5.3	2.2	6.3	4.6	3.1	2.5	5.9	4.0	5.6
	270.0	9.6	5.4	11.3	6.1	12.7	5.7	5.8	15.5	11.6	8.4	6.5	7.5
Sum III		25.1	12.2	22.0	21.2	18.7	**26.2**	21.1	22.8	20.6	16.4	19.5	18.5
IV	292.5	3.4	1.9	10.2	4.8	8.4	4.9	4.1	7.5	6.8	8.2	4.6	10.1
	315.0	10.9	22.2	8.0	8.5	13.4	8.7	6.1	11.2	9.7	7.7	3.9	8.0
	337.5	4.7	0.5	4.8	6.3	4.4	5.1	9.3	3.3	5.1	3.1	6.5	5.5
	0.0	8.3	3.0	3.8	7.9	5.8	6.2	10.7	3.1	6.6	1.8	7.9	5.9
Sum IV		**27.3**	**27.6**	**26.8**	**27.5**	**32.0**	**24.9**	**30.2**	**25.1**	**28.2**	**20.8**	**22.9**	**29.5**
Sum	00-360	95.9	80.2	94.3	97.7	94.5	95.8	92.9	96.0	92.0	87.9	93.4	97.4
Calm		4.1	19.8	3.7	2.3	5.5	4.2	7.1	4.0	8.0	12.1	6.6	2.6

for NW and SE types for all seasons are presented in Fig. 6. For the northwestern (NW) type (Fig. 6, left), the synoptic situation is characterized by a depression over Northeastern Europe, with high pressure over the Azores (Putniković et al. 2016). This large-scale atmospheric distribution of atmospheric pressure promotes advection of NW air over Serbia. The center of the cyclone is stationary over time, but the center of the anticyclone shifts toward the Iberian Peninsula in autumn and winter compared to spring and summer. The relative seasonal frequencies of all circulation types during 1961–2010 are presented in Table 6. The highest frequency of the "northern" circulation types is noted in summer (Table 6).

In the case of the southeastern (SE) type (Fig. 6, right), high pressure lies over Eastern Europe, and low pressure dominates in the central or western Mediterranean. These two synoptic systems, together with the orography of the eastern Balkans, are the main drivers of E/SE/S wind in the southeastern part of the Carpathian Basin, known as Koshava (Romanić et al. 2015). The only exception is summer, when there is no such distinct high pressure over Eastern Europe. As a consequence, the frequency of the "southern" circulation types is lowest in the summer (Table 6).

6 Discussion

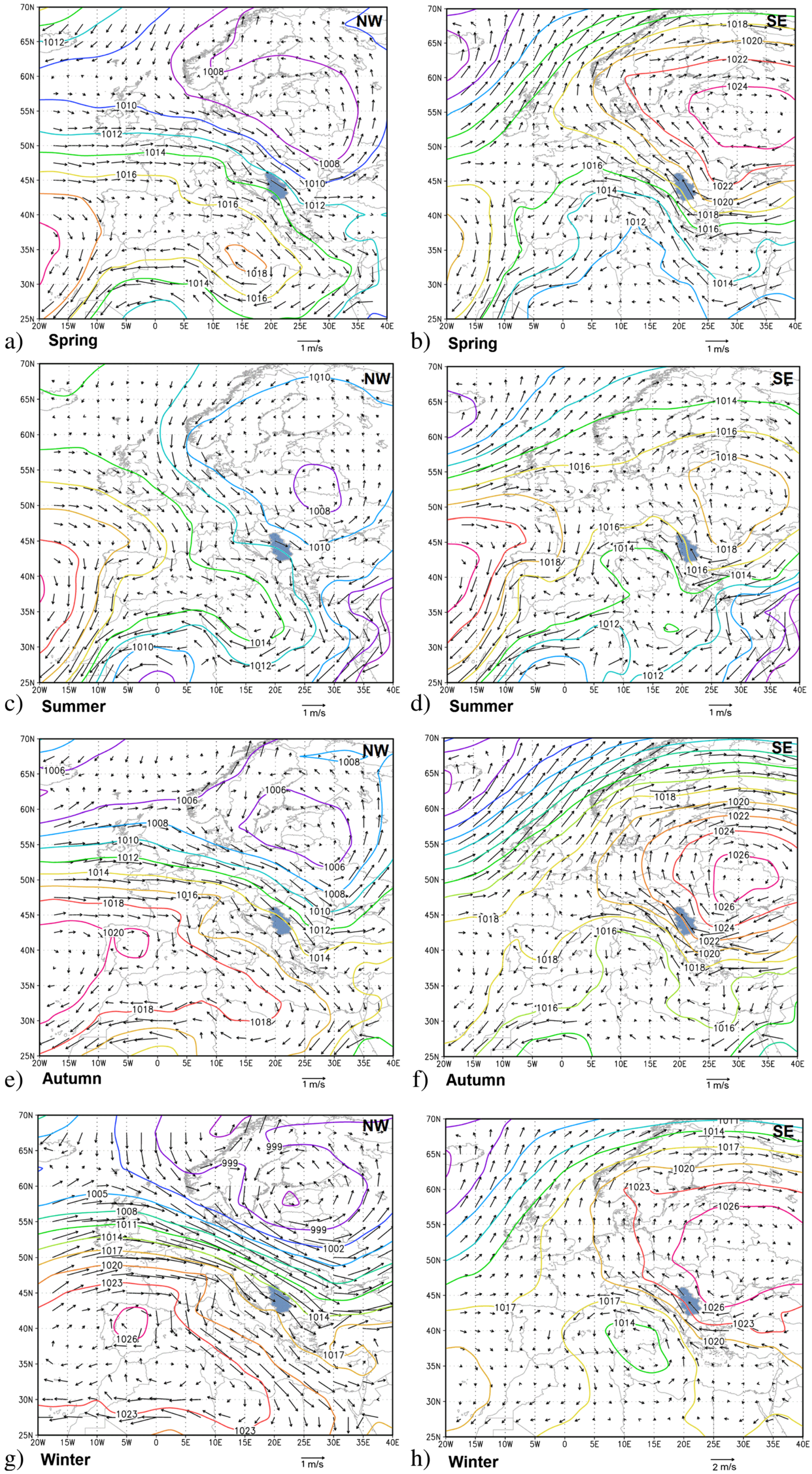
Frequency analysis of mean seasonal winds revealed that the prevailing winds in Northern Serbia have NW and SE directions. It was found that the NW winds prevailed in summer, while the winds from the second quadrant are the prevailing winds in autumn and winter. In spring, the prevailing winds in Northern Serbia are from the fourth and second quadrants.

There exist stations with similar wind roses, independent of the season (e.g., BC, in SO for all the seasons winds are from the north); others that are highly sensitive to the seasonality (e.g. ZR and BE); and there are also uniform wind roses, where the predominant direction is less clear (e.g. PA). The wind roses for summer (winter) are similar to those in spring (autumn).

It was found that the prevailing winds are associated with the maximum wind speeds. The maximum values of calms are recorded in BC in all seasons. This could be because this station is somehow tucked in/protected between the Vršačke Mountains in the north, Ram Hill in the south and the Carpathian Mountains in the east.

The primary cause for the occurrence of wind over Northern Serbia is the synoptic situation, which determines the dominant airflow. In summer, according to the wind roses, the NW winds prevailed. In addition, there is a wind from the north at several stations. Northern sector winds, known as Etesian winds, are one of the most persistent localized winds in the world, being the dominant wind regime during summer (Anagnostopoulou et al. 2014). Poulos et al. (1997) suggested that one of the dynamical mechanisms that causes Etesian winds is the extension of the Azores high pressure system over Central and Southeastern Europe, and the extension of the monsoonal deep Asiatic Low toward eastern Mediterranean.

From Table 6, it can be seen that the "northern" types prevailed in summer. The frequency of the NW, N, and NE type is 38.1%, while the frequency of the S and SE types is lowest in the summer. The reason for this lowest frequency


NW
a) Spring
1 m/s
SE
b) Spring
1 m/s
NW
c) Summer
1 m/s
SE
d) Summer
1 m/s
NW
e) Autumn
1 m/s
SE
f) Autumn
1 m/s
NW
g) Winter
1 m/s
SE
h) Winter
2 m/s

◀ **Fig. 6** Long-term mean of the reanalysis data of the sea level pressure with geostrophic wind for NW (*left*) and SE (*right*) circulation weather types that affected Serbia in: spring (**a**, **b**), summer (**c**, **d**), autumn (**e**, **f**), and winter (**g**, **h**) during the period 1961–2010. Territory of Serbia is *shaded*

can be found in the smaller thermal differences between the land and Mediterranean Sea.

In spring, as the transitional season, the NW and SE winds are prevailing winds in Northern Serbia. The frequency of the "northern" types (NW and N) is approximately equal to that of the "southern" types (SE and S). For the majority of stations, the maximum wind speed is recorded for the SE winds, although NW winds prevailed at some stations.

In winter and autumn, according to the wind roses, the SE winds prevailed. In addition, there is a wind from the south at two stations (VR and SU). Two of the CWTs (SE and S types), with a frequency of about 20% in winter and autumn, favor winds from the second quadrant in Northern Serbia. The thermal high over Eastern Europe enhances the SE winds in all seasons except summer.

Orography has an important influence on the wind direction. Two isolated mountains in Vojvodina channeled winds from the second quadrant. The spring wind rose patterns (Fig. 2) show that winds in BC, VG, VR, and SM are influenced by the local topography (Fig. 1). The Koshava wind has a narrow direction distribution in Bela Crkva (125–145°) and Veliko Gradište (100–150°). Our results for Veliko Gradište are in accordance with those obtained by Romanić et al. (2015). The directions of the winds near Vršac in the second quadrant (Koshava) shift to the south, and the maximum wind speed (48 ms^{-1} on February 11, 1987) was recorded in the region at this station (Romanić et al. 2016), because it is closest to the highest mountain (Vršačke Mountains) in the area. In the case of Sremska Mitrovica, winds from the second quadrant are shifted to the east, because this station is located south of the Fruška Gora mountain, which extends strictly longitudinally over a length of about 50 km. The influence of orography on the other stations is difficult to see, while that of the substrate is negligible because the area is very flat.

Table 6 Relative frequencies (%) of circulation weather types (CWTs) during the period 1961–2010 for spring, summer, autumn, and winter

CWT	Spring	Summer	Autumn	Winter
A	19.3	25.2	31.5	26.2
C	18.7	11.4	11.5	16.6
E	8.4	15.1	12.6	13.1
NE	9.9	21.3	7.7	5.9
N	7.5	12.3	4.3	3.4
NW	6.9	4.5	2.2	3.2
W	7.0	2.3	3.6	5.2
SW	6.1	1.8	7.4	6.3
S	7.2	2.3	8.1	7.1
SE	9.2	3.7	11.1	13.1

A anticyclonic, *C* cyclonic, *E*, *NE*, *N*, *SW* etc.—directional types

The annual analysis of prevailing winds in northern Serbia shows great similarity with seasonal results, as shown in the preliminary results of Gavrilov et al. (2016b). Our results are in agreement with those obtained for some other regions in Europe. Pandžić and Likso (2005) recognized synoptic-scale atmospheric conditions as the primary factor for the wind field patterns along the eastern Adriatic coast. They noted that some secondary factors are land-sea discontinuity and orography, including the influence of the Alps mountain chain, especially during the Bora winds. Jiménez et al. (2009) analyzed surface winds in the northeastern Iberian Peninsula (CFN), and found that patterns with northwestern circulations are dominant (60.9%) followed by southeastern ones (30.5%), showing the strong influence of orography over surface circulation, since the valleys in this region are mainly directed NW–SE. In addition, they found that the relationships between the synoptic and the regional circulation were consistent enough to understand the basic forcing mechanisms of different wind patterns and their influence on the CFN regional climate.

Compared to Jiménez et al. (2009) and Pandžić and Likso (2005), our target region is lowland, with three isolated orographic barriers, which are surrounded by mountainous regions to the E, S, and W with an indirect influence of the sea.

7 Conclusions

Prevailing winds have been analyzed in Northern Serbia over all seasons, using observed data from 12 meteorological stations. A special definition of prevailing winds was derived to determine the prevailing winds in Serbia quantitatively. It was found that the prevailing winds have NW and SE directions during spring in Northern Serbia. In addition, NW winds prevailed in summer, and SE winds in autumn and winter. The prevailing winds were found to be associated with the maximum wind speeds.

In order to determine the synoptic cause of the prevailing winds, the SLP fields over southeastern Europe were classified and related to the surface circulations over Serbia. It was found that the frequency of circulation weather types is in agreement with that of the prevailing winds over Serbia. The highest frequency of the "northern" circulation types is recorded in summer; for "southern" types (S and SE), in autumn and winter. Beside the synoptic cause of the prevailing winds, it was noted that the orography of the eastern Balkans has a major influence on winds from the second quadrant, known as the Koshava wind.

For future work, an annual analysis of the prevailing winds should be performed using climatological data of wind, geomorphological records, and numerical simulations.

Acknowledgements This study was supported by the Serbian Ministry of Science, Education and Technological Development, under Grants No. 176013 and 176020. Authors wish to acknowledge the usage of the wind roses software provided by Daniel Pereira. The authors highly appreciate comments and suggestions of reviewers that led to a considerable improvement of this article.

References

Anagnostopoulou C, Zanis P, Katragkou E et al (2014) Recent past and future patterns of the Etesian winds based on regional scale climate model simulations. Clim Dyn 42:1819–1836

Huschke RE (2000) Glossary of meteorology. American Meteorological Society, Boston, p 638

Dobrilović B (1960) Upper air flow over Yugoslavia and characteristic surface winds. Papers 3, Belgrade, Faculty of Sciences, 1–144

Gavrilov MB, Lazić L, Milutinović A, Gavrilov MM (2011) Influence of hail suppression on the hail trend in Vojvodina, Serbia. Geographica Pannonica 15:36–41

Gavrilov MB, Marković SB, Jarad A, Korać VM (2015) The analysis of temperature trends in Vojvodina (Serbia) from 1949 to 2006. Therm Sci 19:S339–S350

Gavrilov MB, Tošić I, Marković SB, Unkašević M, Petrović P (2016a) The analysis of annual and seasonal temperature trends using the Mann-Kendall test in Vojvodina, Serbia. Idöjárás 120:183–198

Gavrilov MB, Marković SB, Schaetzl RJ, Tošić I, Zeeden C, Emunds K, Sipos G, Ruman A, Putniković S, Obreht I, Perić Z, Lehmkuhl F (2016b) Prevailing winds in Northern Serbia: recent data, geomorphological evidences and numerical simulations. International Conference on Loess Research—Loess 2M—modelling and mapping. 26–29 August 2016, Novi Sad, Serbia, 10–11. ISBN 978–86–7031-408-5

Gburčik P (1960) The influence of the Alps on the change of vorticity, over the Gulf of Genoa. Geofis Pura Appl 45:238–248

Gburčik P, Gburčik V, Gavrilov MB, Srdanović V, Mastilović S (2006) Complementary regimes of solar and wind energy in Serbia. Geogr Pannonica 10:22–25

Holton JR (1972) An introducion to dynamic meteorology. Academic Press, New York, p 320

Horvath K, Lin YL, Ivančan-Picek B (2008) Classification of cyclone tracks over the Apennines and the Adriatic Sea. Mon Wea Rev 136: 2210–2227 http://www.hidmet.gov.rs/. Accessed 15 May 2016

Hrnjak I, Lukić T, Gavrilov MB, Marković SB, Unkašević M, Tošić I (2014) Aridity in Vojvodina, Serbia. Theor Appl Climatol 115:323–332

Jenkinson AF, Collison FP (1977) An initial climatology of gales over the North Sea. Synoptic Climatology Branch Memorandum 62, Meteorological Office, Bracknell, UK

Jiménez PA, González-Rouco JF, Montávez JP, García-Bustamante E, Navarro J (2009) Climatology of wind patterns in the northeast of the Iberian Peninsula. Int J Climatol 29:501–525

Kalnay E, Kanamitsu M, Collins W, Deaven D, Gandin L, Iredell M et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–470

Klaić ZB, Prodanov AD, Belušić D (2009) Wind measurements in Senj—underestimation of true bora flows. Geofizika 26:246–252

Küttner J (1940) Der Kosava in Serbien. Meteorol Z 57:120–123

Lamb HH (1972) British Isles weather types and a register of daily sequence of circulation patterns, 1861–1971, Geophysical Memoir 116, HMSO, London UK, pp 85

Lorente-Plazas R, Montávez JP, Jiménez PA, Jerez S, Gómez-Navarro JJ, García-Valero JA, Jiménez-Guerrero P (2015) Characterization of surface winds over the Iberian Peninsula. Int J Climatol 35:1007–1026

Mahongo BS, Francis J, Osima SE (2011) Wind patterns of coastal Tanzania: their variability and trends. Western Indian Ocean J Mar 10:107–120

Milosavljević M (1950) Physical characteristics of winds in Belgrade. Scientific Book, Belgrade, Serbia, pp 67 (in Serbian)

Palmén E, Newton CW (1969) Atmospheric circulation systems. In: Their structural and physical interpretation. Academic Press, New York, p 606

Pandžić K, Likso T (2005) Eastern Adriatic typical wind field patterns and large-scale atmospheric conditions. Int J Climatol 25:81–98

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

Prakash MD, Roper RG (1981) Prevailing wind in the meteor zone (80–100 km) over Atlanta and its association with midwinter stratospheric warming. J Atmos Sci 38:182–188

Poulos S, Drakopoulos P, Collins M (1997) Seasonal variability in sea surface oceanographic conditions in the Aegean Sea (eastern Mediterranean): an overview. J Mar Syst 13:225–244

Putniković S, Tošić I, Đurđević V (2016) Circulation weather types and their influence on precipitation in Serbia. Meteorol Atmos Physics. doi:10.1007/s00703-016-0432-6

Radinović Dj (1962) Thermal and dynamical conditions of the cyclone formation in the West Mediterranean. Doctoral Thesis. University of Belgrade, Belgrade (in Serbian)

Radinović Dj (1981) Weather and climate in Yugoslavia. IRO Građevinska knjiga, Belgrade, pp 423 (in Serbian)

Romanić D, Ćurić M, Lompar M, Jovičić I (2015) Contributing factors to Koshava wind characteristics. Int J Climatol 36:956–973

Romanić D, Ćurić M, Zarić M, Lompar M, Jovičić I (2016) Investigation of an extreme Koshava wind episode of 30 January–4 February 2014. Atmos Sci Lett 17:199–206

Sokolović G, Radičević D, Ranković S (1984) Climate Atlas of Socialist Federal Republic of Yugoslavia, Belgrade (in Serbian)

Stegall TS, Zhang J (2012) Wind field climatology, changes, and extremes in the Chukchi–Beaufort Seas and Alaska North Slope during 1979–2009. J Clim 25:8075–8089

Stull BR (1988) An introduction to boundary layer meteorology. Kluwer Academicals Publishers, Boston, p 666

Tošić I, Hrnjak I, Gavrilov MB, Unkašević M, Marković SB, Lukić T (2014) Annual and seasonal variability of precipitation in Vojvodina, Serbia. Theor Appl Climatol 117:331–341

Trigo RM, DaCamara CC (2000) Circulation weather types and their influence on the precipitation regime in Portugal. Int J Climatol 20:1559–1581

Trigo FI, Bigg GR, Davies TD (2002) Climatology of cyclogenesis mechanisms in the Mediterranean. Mon Wea Rev 130:549–569

Unkašević M, Mališić J, Tošić I (1998) On some new statistical characteristics of the wind "Koshava". Meteorog Atmos Phys 66:11–21

Unkašević M, Mališić J, Tošić I (1999) Some aspects of the wind 'Koshava' in the lower troposphere over Belgrade. Meteorol Appl 6:69–79

Unkašević M, Tošić I (2006) Košava. Academic mind. Belgrade, pp 82 (in Serbian)

Unkašević M, Tošić I, Obradović M (2007) Spectral analysis of the "Koshava" wind. Theor Appl Climatol 89:239–244

Unkašević M, Tošić I (2013) Trends in temperature indices over Serbia: relationships to large-scale circulation patterns. Int J Climatol 33: 3152–3161

Vukmirović D (1985) The spatial structure of the Koshava wind (in Russian). In XI International Conference on Carpathian Meteorology, Hungarian Meteorological Service, Hungarian, Budapest, 10–15

Ward R (1919) The prevailing winds of the United States. Mon Wea Rev 47:575–576

World Meteorological Organization (1979) Technical Regulations. Basic Documents No. 2. Geneva, Switzerland