



Prevailing surface winds in Northern Serbia in the recent and past time periods; modern- and past dust deposition



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ARTICLE INFO

Keywords:

Wind rose
Dunes
Loess
Holocene
LGM
Banatska Peščara

ABSTRACT

This study utilizes four different methodological approaches to examine the prevailing surface winds and their associated aeolian processes in Northern Serbia, focusing on the southeastern part of the Carpathian Basin. We utilized wind and atmospheric pressure data from 1939–2014 and 1960–2010 for the climatological analyses. Geomorphological data and numerical simulations were used to estimate prevailing paleowind systems. Northern Serbia is currently dominated by surface winds coming from the fourth (270°–360°) and second (90°–180°) quadrants, with frequencies of ca. 116 and 105 days/year, respectively. Comparable frequencies within Banatska Peščara are 115 and 129 days/year, respectively. Crestal orientations of the vast majority of the ≈ 1300 parabolic dunes here suggest that they have formed from winds derived from the second quadrant, indicating formation during the early Holocene. The remaining dunes, of the transverse type, have orientations aligned to the third quadrant. Grain size analysis of loess deposits near Banatska Peščara points to deposition driven by southeasterly winds, probably during the period between the Last Glacial Maximum (LGM) and the early Holocene. Modern wind measurements and geomorphological data showed that the prevailing winds in the recent and past periods were from the same quadrant, in and around Banatska Peščara. These results were confirmed with an explicit numerical simulation that modelled prevailing winds from the second quadrant during the LGM. Thus, the various geomorphologic and climatic data analyzed in this study show that the general air circulation patterns in the recent period are not dissimilar to those operative during the LGM.

1. Introduction

Atmospheric circulations are often divided into planetary, synoptic, meso-, and small horizontal scales, ranging from 10⁴ km to 10 km, respectively, and into temporal scales that range from hours to years (Charney, 1948; Haltiner and Williams, 1980). In this paper, atmospheric circulations will be analyzed for the prevailing surface winds in Northern Serbia, for both the recent and past periods.

1.1. Prevailing winds and planetary circulations

The term “prevailing wind” is usually applied to descriptions of

permanent winds. We employ the definition from the American Meteorological Society (2000) for prevailing wind: the wind most frequently observed during a given time period, over spans of days, months, seasons, and years. White (1831) defined the term “prevailing wind” by describing the regularity in the distribution of the wind at eight compass points, over periods of time measured in days and months. The methods for determination of prevailing winds vary from a simple count of periodic observations to the computation of a wind rose.

The best known and most frequently studied prevailing wind is the Prevailing Westerlies or Westerlies (e.g., Palmén and Newton, 1969). In this case, the term “prevailing” is used to mark westerly surface winds

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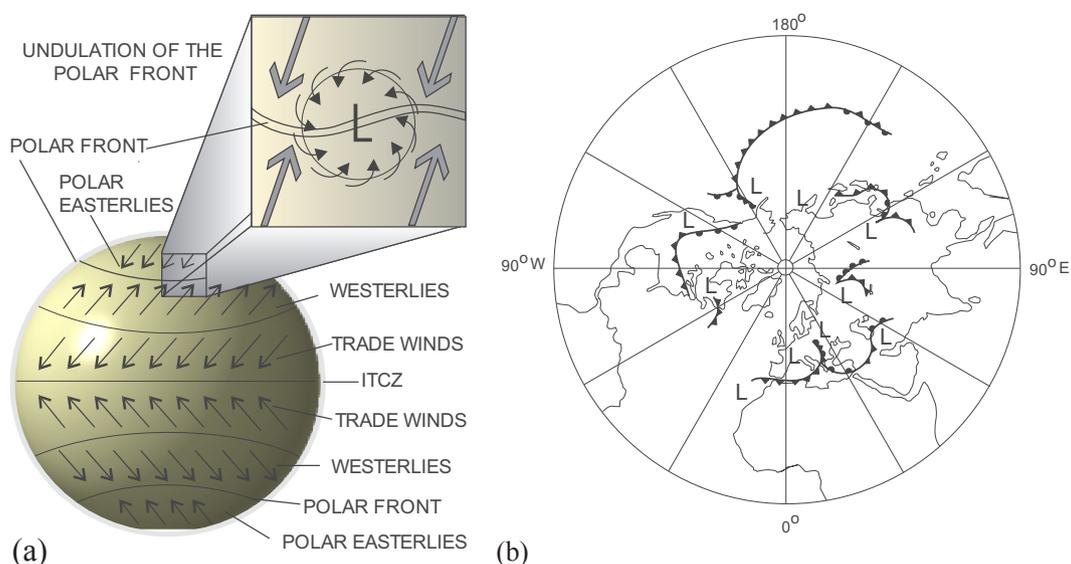


Fig. 1. (a) Generalized representation of the global circulation of the atmosphere, the position of the Polar Front, the prevailing surface winds (arrows), and (b) a typical position of the Polar Front in the Northern Hemisphere, showing centers of low pressure (L), cold, warm, and occluded fronts.

that flow in an approximately constant direction within the Ferrel circulation cells (Fig. 1a). Prevailing easterly surface winds blow out of the Hadley circulation cells on both sides of the Inter Tropical Convergence Zone (ITCZ; Fig. 1a), (e.g., Holton, 1972); these winds are widely known as the Trade winds. Other easterly winds (Polar Easterlies; Fig. 1a) diverge out of the Polar circulation cells, poleward of the Polar Front (Bjerknes and Solberg, 1922). Unlike the surface winds in the Ferrel cells, Trade winds and Polar Easterlies do not have the term “prevailing” in their names, but they do have some “prevailing” characteristics. In all three cases, these winds blow from approximately constant directions, as a result of the general and semi-permanent circulation of the atmosphere (e.g., Lorenz, 1967).

Other, less permanent, circulations, such as monsoons (e.g., Saha, 2010), also lead to important prevailing wind patterns that undergo seasonal reversals. The surface winds of the summer monsoon blow from the ocean onto the continent, whereas the winter monsoonal flow is in the opposite direction.

The Polar Front is a planetary circulation (Charney, 1973), along which extra-tropical depressions and/or cyclones develop (e.g., Djuric, 1994). The Polar Front and its accompanying circulations are the dominant influences on the weather and winds in the middle latitudes, and especially in Central Europe, Southeastern Europe, the Mediterranean, and Northern Serbia (e.g., Gburčik, 1960; Fig. 1).

1.2. Studies of prevailing winds

The study of prevailing winds rose to a higher level of interest very early, before many other world problems. This is understandable, because prevailing winds were drivers for seafaring ventures and other endeavors. In recent decades, research on prevailing winds has become of great practical use around the world for the estimation of wind power (e.g., Troen and Lundtang Petersen, 1989), for spatial planning (e.g., Seemi and Bharat, 2012), in health research (e.g., Cho, 2007) and for wind erosion research (e.g., Chepil et al., 1964). Geomorphology and aeolian science use information about prevailing winds in research on aeolian landforms and sediments.

According to Janc (2002), the Serbian scientist Andrija Stojković in his 1802 book “Physics II” described a northeasterly wind which he called “Szededinac” (i.e., coming from the town of Szeged in Hungary) near the town of Ruma (Srem subregion) in Northern Serbia. This statement is considered one of the first written descriptions of a wind in

Serbia. One of the first articles about observed prevailing winds in Serbia was published by Jakšić (1863), showing the frequency of winds at four compass points (or quadrants) per months and seasons, as of 1862.

During the first half of the 20th century, research continued on the winds of Serbia and/or Yugoslavia. Conrad (1921) investigated the strong winds (in terms of the Beaufort scale) in southwestern Serbia, and in the mountainous and coastal areas of Montenegro, during World War I. Vujević (1930) explored the winds on the Adriatic island of Hvar (Croatia) for the period of 1871–1880. Küttner (1940) was one of the first to author a paper on the local southeasterly prevailing wind Košava (a.k.a., Koshava, Kossava, Kosava) over Northern Serbia, which is known as the “Banat wind” (i.e., blowing in Banat subregion) (Barbu et al., 2009). Several publications about the Košava wind followed. Climatological characteristics of the Košava were studied by Milosavljević (1950). The spatial structure of the Košava was presented by Vukmirović (1985). Unkašević et al. (1998, 1999) discussed a statistical analysis of wind data in the main influence area of the Košava wind. A spectral analysis of the Košava wind was presented by Unkašević et al. (2007), whereas a comprehensive analysis, including basic characteristics, vertical structure and modelling, of the Košava wind was given by Unkašević and Tošić (2006). More general works regarding winds over Serbia and/or Yugoslavia can be found in Vujević (1953), Sokolović et al. (1984), and Gburčik et al. (2006). Upper air flow over Yugoslavia, as well as characteristic surface winds in this area, was examined by Dobrićević (1960).

In this study, we focus on the prevailing winds over Northern Serbia, using meteorological, geomorphological, and sedimentological data, as well as data generated in numerical simulations. The main objective of this study is to link climatological, synoptic, geomorphological, and numerical (simulated) data, so as to better understand the atmospheric dynamics of Northern Serbia.

2. Study area

Northern Serbia is located in the southeastern part of the Carpathian (Pannonian) Basin (Fig. 2). The region is mostly flat, but contains four mountain zones: Vršacke Planine (641 m above mean sea level (AMSL)) and Ramsko Pohrdje (282 m AMSL) in the southeast, Fruška Gora (539 m AMSL) in the southwest, and Avala (511 m AMSL) in the south. Other significant geomorphological features include two sandy terrains,

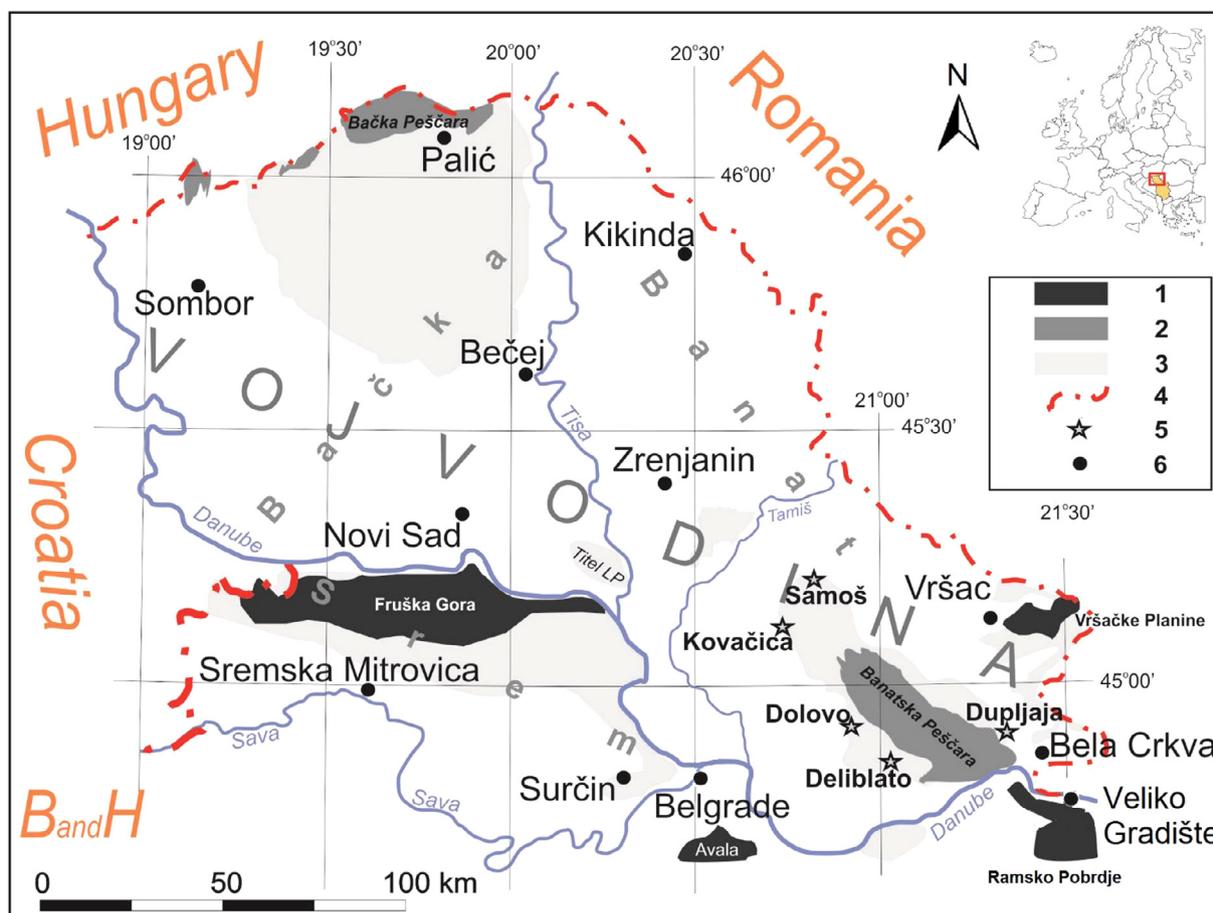


Fig. 2. Map of Northern Serbia, showing geomorphological characteristics, locations of meteorological stations used in this study, and loess/dune sampling sites. Legend: 1 – Mountainous areas, 2 – Sandy areas, 3 – Loess plateaus, 4 – National border, 5 – Sampling sites, and 6 – Meteorological stations (Table 1).

Banatska Peščara (Banat/Deliblato Sands, 250 m AMSL) in the south-east, and Bačka Peščara (Bačka Sands, 134 m AMSL) in the north; as well as six large loess plateaus (Marković et al., 2008). Forests comprise only about 7% of the investigated region and mainly occur in the mountains and in parts of the sandy terrain along the banks of the Danube, Sava, and Tisa Rivers, and along their main tributaries, while the agriculture land occupies about 84% (70% cereals, 20% industrial crops, and 10% other crops). The six loess plateaus and two sandy terrains preserve important information about aeolian systems during the Late Pleistocene and Holocene (e.g., Zeeden et al., 2007; Marković et al., 2008; Bokhorst et al., 2009, 2011; Obrecht et al., 2015). Dune formation and movement has even been observed in the historical period (Sipos et al., 2016).

In this study, we chose to focus on Banatska Peščara and its surrounding loess mantle. During the late Quaternary, the investigated area was primarily influenced by fluvial (Smalley and Leach, 1978) and aeolian processes. Banatska Peščara extends from the Danube River on the SE, to the villages Kovačica and Samoš on the NW, covering an area of about 600 km² (Fig. 2). The region can be roughly divided into two parts. On the NE, near the village Dupljaja, there is the highest part of Banatska Peščara with narrow ridge that is dominated by unusual orographic shapes: sandy loess and loess-like sediments called Zaga-jačka Brda (Zagajica Hills, 250 m AMSL) and Dumače (235 m AMSL) (Lukić et al., 2013). The remainder of the region is covered with dune fields, with the central part of the region dominated by dunes that are 1–2 km long and a that area few tens of meters in height. The dune field was active until a few decades ago (personal observation), having

formed under the influence of the local wind Košava. However, after successfully implementing land amelioration that included reforestation, from the middle of the 18th century to the end of the 20th century, the dune field has since stabilized.

Northern Serbia is well suited to the study of prevailing winds. First, the low relief and general lack of forest cover provide few obstacles to the wind, i.e., the boundary layer is thin and surface friction is low. These conditions facilitate the (1) establishment of simple (quasi-geostrophic) relationships between winds and larger atmospheric circulations (e.g., Gavrilov, 1985), and (2) exploration of wind-forcing mechanisms. Second, the loess plateaus and dune fields can potentially provide excellent geomorphic information about paleowind systems.

Climatically, the study area is often influenced by undulations of the Polar Front. When the Polar Front moves across the area from across the Atlantic Ocean, across western and central Europe, without retention in the Alps, incursions of cold fronts from the north/northwest follow, which reduce surface temperatures on northwesterly winds, and bring precipitation (Radinović, 1981). When the Polar Front is positioned over the Alps, cyclonic developments usually begin in the western Mediterranean Basin, mostly in the Gulf of Genoa. These processes lead mainly to the incursion of warm fronts into Northern Serbia, which are usually preceded by winds from the southern quadrants. These winds are stronger if a large pressure gradient sets up between a Mediterranean cyclone and an anticyclone over the European part of Russia (Gburčik, 1960; Radinović, 1962; Trigo et al., 2002). Occasionally, the study area is under the influence of high pressure ridges of the Azores/Atlantic or the Siberian anticyclone. In that case, stable, dry weather

usually occurs over Serbia (Putniković et al., 2016), with mainly calm conditions and very high temperatures in the summer, and correspondingly low temperatures during the winter (Unkašević and Tošić, 2013).

The climate of Northern Serbia is moderate continental, with cold winters and hot summers. The average annual air temperature is 11.1 °C (Gavrilov et al., 2016), and the average annual precipitation is 606 mm (Tošić et al., 2014). According to the De Martonne aridity index, Northern Serbia is characterized by a semi-humid climate (Hrnjak et al., 2014).

3. Methods and data

Our study of prevailing winds utilized four distinct methods. The first two are based on the identification of prevailing winds using two special definitions of this term (Tošić et al., 2017), as applied to meteorological data on winds and sea level pressure data. The third method uses proxy geomorphologic data from dunes and loess deposits to estimate prevailing paleowinds. Lastly, we also employed a numerical atmospheric model to simulate prevailing winds during the Last Glacial Maximum (LGM).

3.1. Recent/modern prevailing winds

We applied two additional definitions of the term prevailing wind (Tošić et al., 2017). The first involves the maximum value of the frequency of the observed wind direction, in each of four compass quadrants: I (00°–90°), II (90°–180°), III (180°–270°), and IV (270°–360°). We note that these quadrants are generally equivalent to NE, SE, SW and NW winds, respectively. This value is obtained as the sum of all of the elementary frequencies in a given quadrant, and is considered to be *the prevailing wind per quadrant*. In the second definition, the maximum value of the elementary frequency of the observed wind direction in one of the sixteen elementary directions (interval size is 22.5°) is considered to be *the prevailing wind per (elementary) direction*. Using each definition, the mean annual wind data in sixteen directions at each of the 12 meteorological stations within the study area were analyzed (Table 1).

Daily anemometer wind data, reported in degrees (direction) and speed in m/s, from 12 meteorological stations in Northern Serbia (Fig. 2 and Table 1), in accordance with the World Meteorological Organization (1979) and Republic Hydrometeorological Service of Serbia (<http://www.hidmet.gov.rs/>), were used for the analysis of modern winds. Time series data on winds, i.e., their maximum length periods, from the beginning to the end of year of the observation were also examined (Table 1). At eleven of the 12 stations, the data span a time period > 50 years. As shown in Table 1, data sets were incomplete at three stations, although missing data comprised < 4% of the total data set. Missing values were not estimated; analysis proceeded with

incomplete data as necessary. A quality control check of wind data was passed.

3.2. Classification of circulation types

Putniković et al. (2016) classified the weather types over Serbia using the system of Jenkinson and Collison (1977), which is based on Lamb (1972). In this method, grid-point mean sea level pressure (MSLP) values over the area from 32.5°N to 52.5°N and 5°E to 35°E were used to determine direction, strength and vorticity of the geostrophic (Gavrilov, 1985), or upper level, winds. Data from the National Center for Environmental Prediction/National Center for Atmospheric Research's (NCEP/NCAR) reanalysis (Kalnay et al., 1996), performed on a 2.5° × 2.5° longitude-latitude grid for the period 1961–2010, were employed for the characterization of the circulation types (CTs). Such data enabled us to develop composite maps for each CT, for the period 1961–2010. The MSLP fields over southeastern Europe were classified and related to the surface circulations over Serbia in order to compare the frequency of wind and circulation types, and to obtain a synoptic characterization of the occurrence and duration of the prevailing winds.

3.3. Geomorphological and sedimentological analysis

Geomorphological analysis was conducted in order to obtain proxy data for prevailing paleowinds for two different areas in and around the Banatska Peščara. Paleowind data were obtained by digitizing dune crests from 1:25,000 topographic maps and satellite images, using a GIS (Fig. 3). Following the identification and classification of the majority of the dunes, the dominant (prevailing) wind directions during their formation were determined, based on the alignments of dune wings and crests (Sipos et al., 2016).

Paleowind directions near Banatska Peščara were also determined from sedimentological characteristics of loess deposits in the vicinity of the villages Dupljaja (DU1), Deliblato (DE1), Dolovo (DO1), Kovačica (KOV1), and Samoš (SAM1) (Figs. 2 and 7). All samples were taken ca. 15 cm below the recent soil (S0), which according to Marković et al. (2015) is in the uppermost part of the youngest loess unit, L1.

Grain size analysis of the loess samples was performed following the methods outlined by Nottebaum et al. (2014) and Schulte et al. (2016). In short, fine-earth subsamples of 0.1–0.3 g (< 2 mm dia.) were pre-treated with 0.70 ml of 30% H₂O₂ at 70 °C for 12 h. This process was repeated until bleaching occurred (Allen and Thornley, 2004), but no longer than three days. To keep particles dispersed, the samples were treated with 1.25 ml, 0.1 M Na₄P₂O₇·10H₂O for 12 h (Pye and Blott, 2004). Particle size characteristics were measured with a LS 13320 Laser Diffraction Particle Size Analyser (Beckman Coulter). To calculate the grain-size distribution, the Mie theory was used (Fluid RI: 1.33; Sample RI: 1.55; Imaginary RI: 0.1) (ISO International Standard 13320,

Table 1
Characteristics of the 12 meteorological stations that supplied data for this study.

No	Abbreviation	Station	Latitude (N)	Longitude (E)	Altitude (m AMSL)	Altitude anemometer (m)	Period of record	Missing data (%)
1	BE	Bečej	45°37'	20°02'	84	10	1949–2009	0
2	BC	Bela Crkva	44°54'	21°25'	90	10	1995–2014	0
3	BG	Belgrade	44°48'	20°28'	132	24	1939–2014	0
4	KI	Kikinda	45°51'	20°28'	81	10	1949–2014	0
5	NS	Novi Sad	45°20'	19°51'	86	10	1949–2014	0
6	PA	Palić	46°06'	19°46'	102	10	1949–2013	3.1
7	SO	Sombor	45°46'	19°09'	87	10	1965–2014	4.0
8	SM	Sremska Mitrovica	44°58'	19°38'	82	10	1949–2001	1.9
9	SU	Surčin	44°47'	20°16'	73	10	1966–1997	0
10	VG	Veliko Gradište	44°45'	21°31'	82	10	1965–2014	0
11	VR	Vršac	45°07'	21°18'	83	10	1965–2014	0
12	ZR	Zrenjanin	45°24'	20°21'	80	10	1966–2014	0

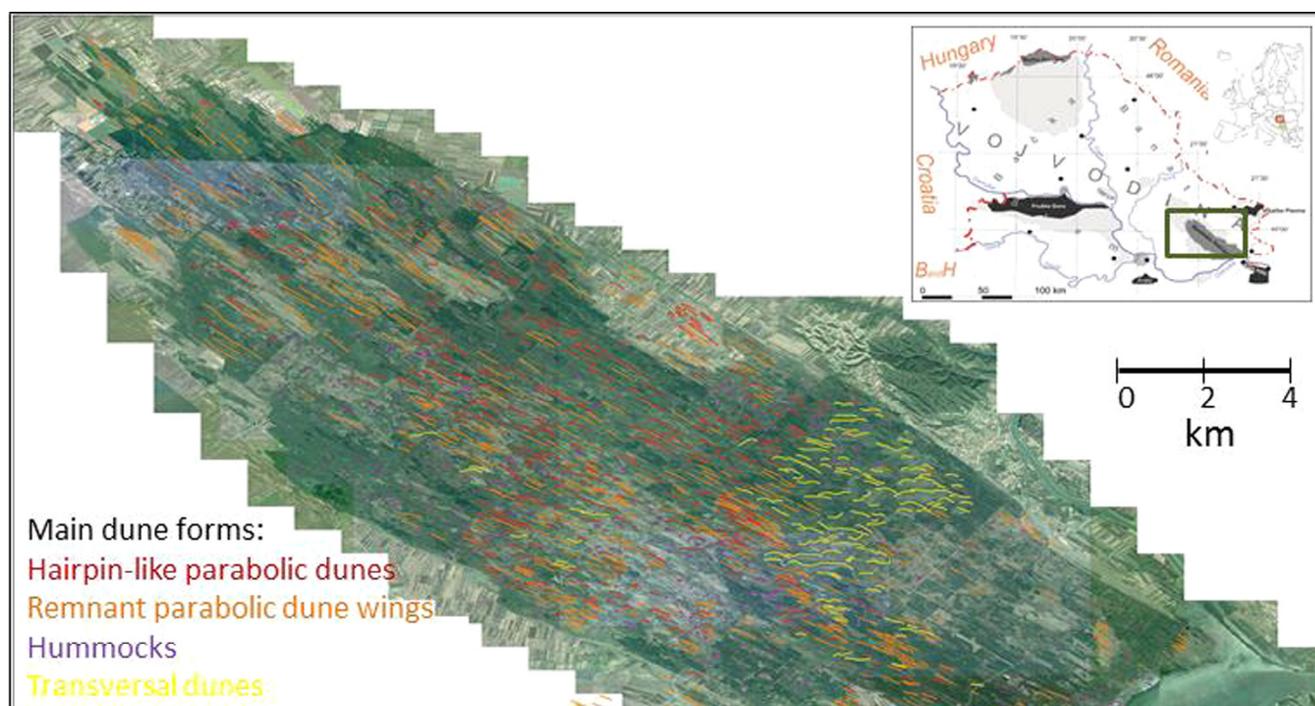


Fig. 3. Satellite and locational maps of the Banatska Peščara, with dunes marked and classified by directionality of wind.

2009; Schulte et al., 2016). Particle size classes are assumed to be as follows: clay is $< 2 \mu\text{m}$ dia., fine silt is from $2 \mu\text{m}$ to $6.2 \mu\text{m}$, medium silt is from $6.2 \mu\text{m}$ to $20 \mu\text{m}$, coarse silt is from $20 \mu\text{m}$ to $63 \mu\text{m}$, and sand is $> 63 \mu\text{m}$ (Blott and Pye, 2012). The anisotropy of the magnetic susceptibility (AMS) of the loess samples was measured using protocols described in Zeeden et al. (2011, 2015), by applying an AGICO KLY-3S Kappabridge.

3.4. Simulation of prevailing winds

Generally, contemporary modelling approaches (e.g., Gavrilov et al., 2014) can provide satisfactory predictions of atmospheric circulations, especially for the Polar Front (e.g., Gavrilov et al., 2011). We utilized the ECHAM5 atmospheric general circulation model (Roeckner et al., 2003, 2004) for numerical simulations of prevailing winds during the LGM. This fifth-generation atmospheric general circulation model was developed at the Max Planck Institute for Meteorology (<https://www.mpg.de/institutes>) from the spectral weather prediction model of the European Centre for Medium Range Weather Forecasts (ECMWF; Simmons et al., 1989). The model has yielded good results with significantly modified geological and hydrological conditions (e.g., Marković et al., 2014), such as in this study, of LGM conditions. The horizontal resolution (spectral transaction) of the ECHAM5 model is T63 (192×96 grid point or $147 \text{ km} \times 147 \text{ km}$ on latitude 45°). The model had 31 vertical layers and a time step of 600 s. Other parameters of the model were standardized and/or adjusted to the available computing power.

Data from the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3) were used to simulate atmospheric circulations during the LGM, using the following general data: glacier mask, land sea mask, land surface elevation, orbital parameters, pre-industrial trace gases, and solar constant. More information about PMIP3 data can be found in Crucifix et al. (2005, 2012), Haywood et al. (2011), and at <https://pmip3.lscce.ipsl.fr>. The main atmospheric data used here are the ERA-Interim (ERA-I) reanalysis from ECMWF (Dee et al., 2011). For the purposes of the LGM integrations, information on these initial data have

been modified: surface pressure, sea and land surface temperature, temperature of atmosphere, soil wetness, snow depth, field capacity of soil, surface background albedo, surface roughness length, sea-ice concentration, vegetation type and ratio, soil data flags, and lake mask.

4. Results

4.1. Recent/modern prevailing winds

Fig. 4 shows mean annual wind roses for Northern Serbia, in 16 elementary directions with intervals of 22.5° , with mean speed winds in the percentage at 14 local time (LT) for 12 meteorological stations (Fig. 2). In addition, to make it easier to analyze results, Table 2 shows calm periods and frequencies (in the percentage) of winds in 16 elementary directions and 4 quadrants (obtained as the sum of 4 elementary directions). These data show that the prevailing winds in Northern Serbia are from the NW (IV) and SE (II) quadrants (Fig. 4). For a quantitative verification of this impression, the mean annual wind frequency of both quadrants was calculated as the sum of the frequency at each station per quadrant, divided by the number of stations (12). These data show that the mean annual frequency of prevailing winds in Northern Serbia in the fourth (NW) and second (SE) quadrants is 31.9% and 28.8% of the time, respectively, or ≈ 116.4 and 105.1 days/year. Thus, it can be considered that the prevailing winds in Northern Serbia are from the NW and SE quadrants. These winds occur $> 60\%$ of the time, or about 222 days/year. The prevailing wind per quadrant is in the fourth (NW) quadrant at nine stations (BE, BG, KI, NS, PA, SO, SM, SU, and ZR), while at the remaining three stations (BC, VG, and VR) it occurs in the second (SE) quadrant (Table 2).

Our analysis indicated the following prevailing winds per (elementary) direction: six cases in the fourth (NW) quadrant, four cases in the second (SE) quadrant, and in one case in the first (NE) and third (SW) quadrants (Table 2). It should be noted that three cases of the prevailing winds per direction do not belong to quadrants with the prevailing wind per quadrant. At all three stations with SE winds, the prevailing winds per direction are located in the second (SE) quadrant.

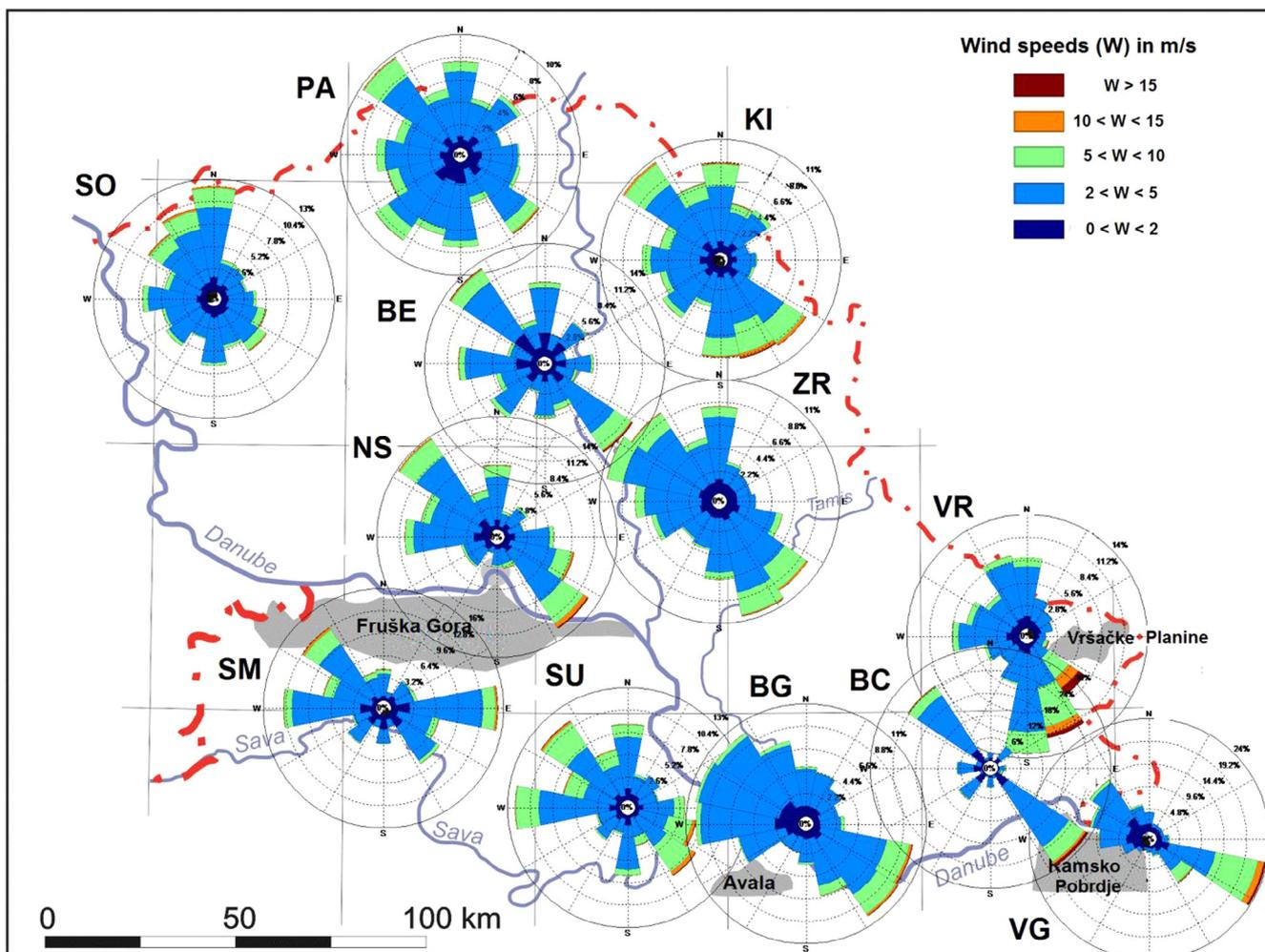


Fig. 4. Wind roses showing the mean annual direction of winds, in 16 directions, and their intensities, at the 12 meteorological stations (Table 1; Fig. 2) for the period 1939–2014.

Table 2

Mean annual wind frequency (%) per quadrant in 16 directions and calm (%), for the 12 meteorological stations at the 14 LT.

Quad.	Dir.	BE	BC	BG	KI	NS	PA	SO	SM	SU	VG	VR	ZR
I	22.5	2.8	0.1	4.3	5.0	2.3	4.5	3.8	1.3	3.0	1.8	3.9	3.2
	45.0	5.3	5.2	3.4	5.2	3.6	5.8	3.6	3.7	3.6	1.7	2.8	2.5
	67.5	1.8	0.2	2.5	2.1	2.4	3.1	3.0	3.8	2.7	1.6	2.3	2.4
	90.0	5.1	2.1	3.0	2.8	6.1	4.5	4.0	15.1	5.7	2.7	1.4	2.8
Sum I	15.0	7.6	13.2	15.1	14.4	17.9	14.4	23.9	15.0	7.8	10.4	10.9	
II	112.5	3.1	1.5	9.9	2.6	8.8	4.7	5.3	6.9	7.2	23.7	1.8	5.5
	135.0	12.2	29.1	10.1	9.3	12.7	7.7	6.4	8.4	8.6	9.5	7.6	9.6
	157.5	5.0	1.0	6.4	9.0	3.2	3.7	5.0	1.7	3.6	2.2	11.8	10.5
	180.0	5.9	3.2	3.2	8.7	2.8	7.5	6.9	4.0	6.9	1.3	13.4	6.8
Sum II	26.2	34.8	29.6	29.6	27.5	23.6	23.6	21.0	26.3	36.7	34.6	32.4	
III	202.5	2.7	0.5	2.2	3.9	1.2	6.5	3.8	1.7	2.3	0.7	5.0	4.0
	225.0	7.2	8.2	2.2	6.1	3.6	8.4	5.8	5.0	3.6	1.8	3.1	3.6
	247.5	5.2	0.9	6.0	5.3	3.6	5.9	5.2	3.5	2.8	4.2	4.4	6.0
	270.0	9.7	6.9	10.0	6.8	10.5	6.8	7.3	13.2	12.1	9.0	8.3	7.5
Sum III	24.8	16.5	20.4	22.1	18.9	27.6	22.1	23.4	20.8	15.7	20.8	21.1	
IV	292.5	3.8	2.0	10.2	5.3	8.7	5.2	4.9	7.6	6.7	11.1	6.7	10.4
	315.0	13.2	24.3	9.9	10.7	13.8	9.7	8.2	12.8	11.1	13.6	5.3	9.6
	337.5	4.7	0.9	7.5	6.9	5.1	5.3	9.7	4.2	6.0	6.0	9.1	5.5
	0.0	9.2	2.2	4.9	8.7	8.0	7.7	12.1	4.5	8.8	4.2	8.7	8.4
Sum IV	30.9	29.4	32.5	31.6	35.6	27.9	34.9	29.1	32.6	34.9	29.8	33.9	
Sum	00–360	96.9	88.3	95.7	98.4	96.4	97.0	95.0	97.4	94.7	95.1	95.6	98.3
Calm		3.1	11.7	4.3	1.6	3.6	3.0	5.0	2.6	5.3	4.9	4.4	1.7

The prevailing wind per quadrant is bolded.
The prevailing wind per direction is framed.

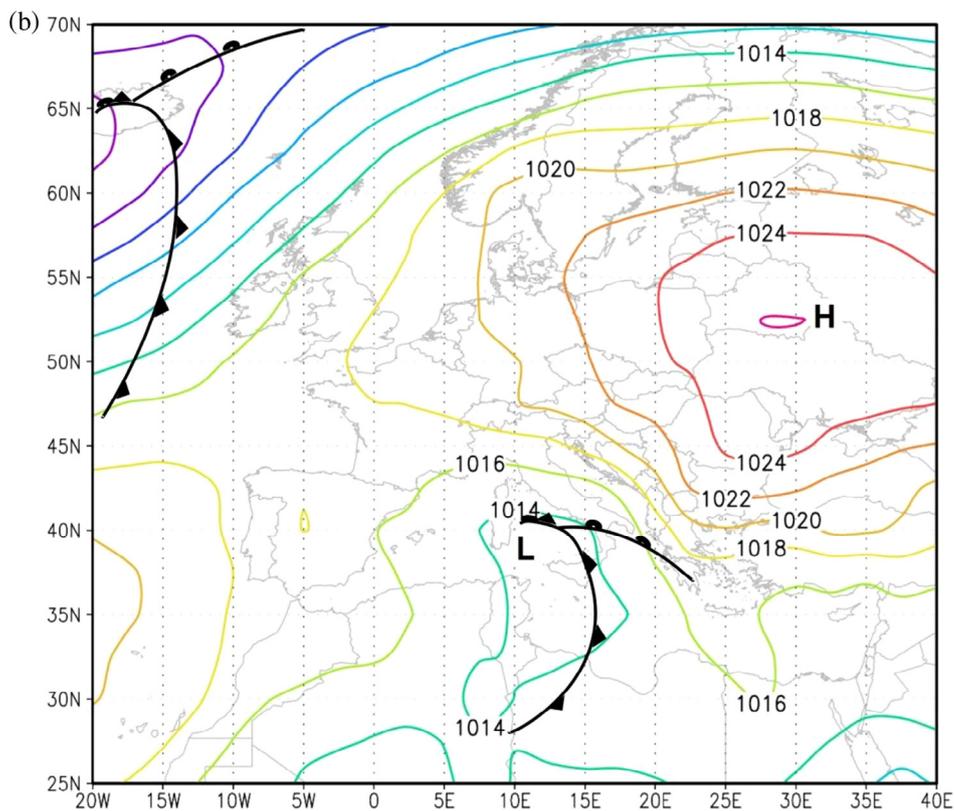
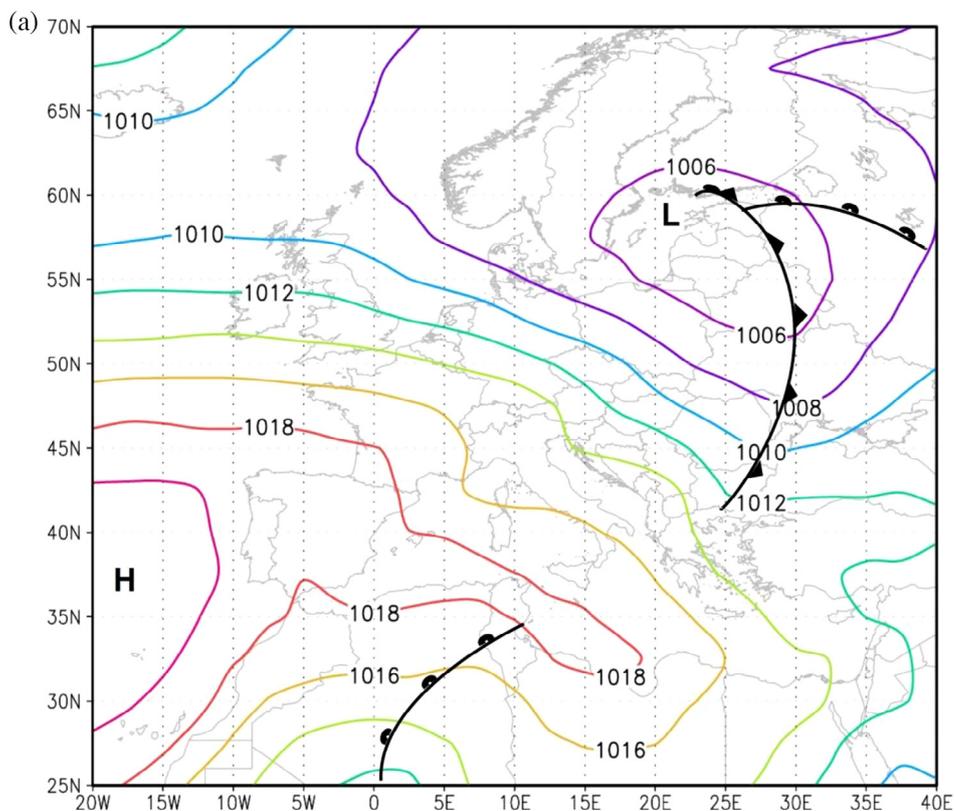


Fig. 5. Long-term, annual, mean of sea level pressures for NW (a), and SE (b) weather types, that affected Serbia during the period 1961–2010, showing the typical positions of cyclones (L), anticyclones (H), and fronts, as parts of the Polar Front.

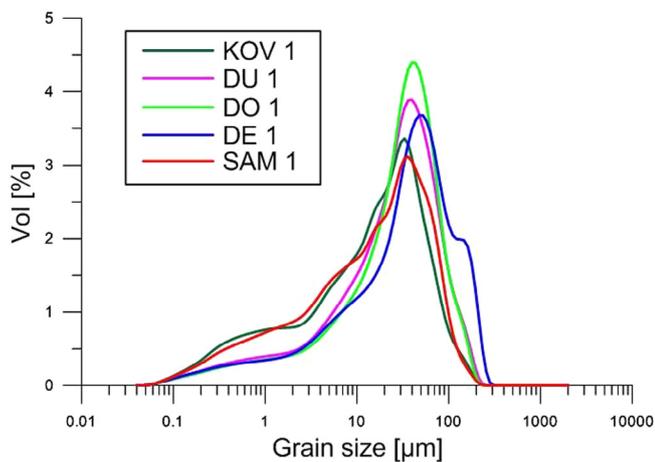


Fig. 6. Grain size density distribution curve of studied for the loess at the sampling sites DU1 – Dupljaja, DE1 – Deliblato, DO1 – Dolovo, KOV1 – Kovačica, and SAM1 – Samoš.

In order to better compare modern vs paleowinds, we analyzed data from the three stations (BC, VG, and VR) that are closest to Banatska Peščara. For these stations, the prevailing wind per quadrant were as follows: 34.8%, 36.7%, and 34.6%, all from the second (SE) quadrant, respectively (Table 2). Average prevailing wind frequencies from the second (SE) and fourth (NW) quadrant near Banatska Peščara are 35.4% and 31.4% of the time, or ≈ 129.2 and 114.6 days/year, respectively. Although the difference in the number of days (14.6) between the two quadrants seems small, the effects of the wind are very different. Winds from the second (SE) quadrant are dry and warm, and during their presence there is no significant rainfall, whereas winds from the fourth (NW) quadrant are generally accompanied by precipitation (Putniković et al., 2016).

Prevailing winds in (and around) Banatska Peščara differ from those in Northern Serbia. In Banatska Peščara, prevailing winds blow with the greatest annual frequency (129.2 days) from the second (SE) quadrant, whereas generally in Northern Serbia they blow mainly (116.4 days) from the fourth (NW) quadrant. Hence, the duration of the prevailing wind per quadrant in Banatska Peščara is 12.8 days longer than in Northern Serbia. Additionally, the annual wind duration from the second (SE) quadrant in Banatska Peščara (129.2 days) is 24.1 days longer than in Northern Serbia (105.1 days). The importance of this difference is that, in Northern Serbia, the prevailing winds may better potentially preserve evidence of SE winds within dunes and loess.

4.2. Analysis of circulation types

Among the 26 circulation weather types (CTs) of Putniković et al. (2016), the relative annual frequencies of CTs that produce winds from the fourth and second quadrants during the period 1961–2010 over Serbia were 13.3% and 18.0%, or ≈ 48.5 and 65.7 days/year, respectively. Additionally, the mean annual duration of prevailing winds from the fourth (NW) quadrant was 116.4 days/year, whereas the duration from the second (SE) quadrant was 105.1 days in Northern Serbia and 129.2 days near Banatska Peščara. A strong correlation exists between the frequency of prevailing winds and the CT that drives them. The NW circulation type (Fig. 5a), representative of the fourth quadrant, has the synoptic situation characterized by High pressure over the Azores and Low pressure (embedded in the Polar Front) over northeastern Europe (Putniković et al., 2016). This large-scale distribution of atmospheric pressure promotes advection of northern and northwestern cold and humid air, with frequent precipitation, over Serbia. In the case of the SE type (Fig. 5b), representative of the second quadrant, high pressure

dominates over Eastern Europe (Russia), with low pressure (an undulation of the Polar Front on the Alps) over the western and/or central Mediterranean. This distribution of atmospheric pressure leads to advection of warm and dry air, almost without precipitation, into Northern Serbia. These synoptic systems, together with the orography of the eastern Balkans, are the main drivers of southeastern prevailing winds from the second quadrant in Northern Serbia, especially frequent and intensified in the area around the Banatska Peščara. This wind is commonly referred to as Košava wind (Unkašević et al., 1998). In addition, analyzing the seasonal surface winds in Northern Serbia, Tošić et al. (2017) that the highest frequency of the “northern” circulation types is recorded in summer and “southern” types (S and SE) in autumn and winter.

4.3. Proxy wind data from loess and dunes

Four basic types of dunes were identified in the study area. SW–NE forms were formerly interpreted as longitudinal dunes (e.g., Bukurov, 1953), which would normally suggest unstabilized, dryland aeolian processes. These were instead newly interpreted as elongated parabolic dunes (320 dunes), i.e., remnant wings (535 dunes) of former parabolic dunes. These dunes are located in the central and NW part of the Banatska Peščara (Fig. 3). Wing lengths can reach up to 1.5 km and have heights of ca. 5–10 m (Menković, 2013). The dunes have formed under significant vegetative control and with a moderate sand supply, and are dated to the Early Holocene (Sipos et al., 2016). Hummocks (345 dunes), the initial forms of the parabolic dune association, were detected mostly near the Danube River and on the southwestern margin of the dune field (Fig. 3).

Roughly 100 transverse dunes occur superimposed on parabolic dunes in the central part of the dune field (Fig. 3). These transverse undulating features often form a 2 km long crest, and have heights of ca. 50 m. Transverse dune formation is enabled by an abundant sand supply and a very limited vegetation control (personal observation). The last phase of their formation at Banatska Peščara has been placed around the 18th century (Sipos et al., 2016).

Dune crest orientations from the two dune associations reflect varying dominant winds. The older, parabolic dunes have mean and standard deviations of crest directions of $117 \pm 6^\circ$, which fit well to the second (SE) quadrant, and with prevailing winds for the recent period (stations BC, VG, and VR) surrounding Banatska Peščara. In the case of transverse dunes, the indicated wind direction is $186 \pm 9^\circ$, or about a 60° difference between the two wind directions. But if this case is compared with the prevailing winds per direction in the station VR, which is 13.4% from the direction of 180° , one notices the appearance of a southerly wind, which is often present in the recent period.

Grain size analyses of loess deposits at the five sample sites (KOV1, SAM1, DU1, DE1, and DO1) around Banatska Peščara show a spatial trend from relatively coarse grain sizes in the southeast, to finer grain sizes in the northwest. This trend occurs across all five sites (Fig. 6).

AMS is a measure of the anisotropic shape of magnetic particles, a lineation in a direction, or in a perpendicular direction, can be interpreted as loess deposition direction (e.g., Bradák, 2009; Liu et al., 2005; Nawrocki et al., 2006; Zeeden et al., 2015 and references therein), which can represent larger scale atmospheric circulations. AMS data from the loess deposits at three sample sites (DU1, DE1, and DO1) (Emunds, 2015) indicate a preferential SE–NW directionality (Fig. 7). The results from SAM1, on the northeastern margins of Banatska Peščara, are here interpreted as showing SSE–NNW directionality. Samples from KOV1, on the northwestern margins of Banatska Peščara, show a more NE–SW directionality of sedimentary fabric, which may, however, due to their low anisotropy, be regarded as less reliable than other data (Jelinek, 1977).

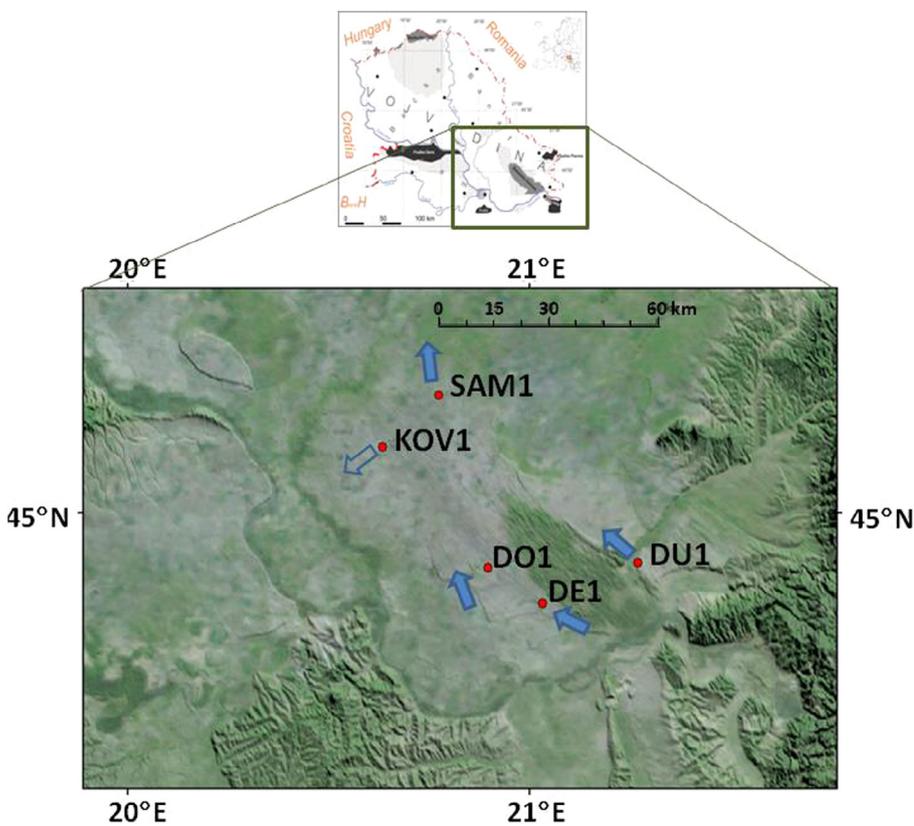


Fig. 7. Shaded topography map of the area around the Banatska Peščara, showing selected loess sampling sites (abbreviations same as in Fig. 6) and AMS results of the prevailing paleowind directions (arrows).

4.4. Numerical simulation

Our analysis included a numerical simulation of the undulation of the Polar Front for the SE weather type using ECHAM5, based on assumed LGM conditions over the European continent, but especially over Northern Serbia. The SE type was selected, as it is the most common cause of winds from the second (SE) quadrant. This type of weather has the greatest impact on aeolian processes around Banatska Peščara for which the geomorphological analysis of paleowinds was performed.

The results of these simulations are displayed using two LGM maps: mean sea level pressure (Fig. 8a) and winds at 10 m (Fig. 8b). Fig. 8a shows that the LGM Polar Front undulated similarly at the LGM as in the recent times. In northeastern Europe, over modern-day Russia, the mean synoptic conditions placed an anticyclone (H), and to the southeast of Europe in the western Mediterranean, a cyclone (L). This is the same type of the synoptic circulation shown in Fig. 5b for the SE weather type. As shown, the numerical simulation can reconstruct SE type of weather for the LGM, and thereby reconstruct surface winds in Northern Serbia. As it can be seen in Fig. 8b, during the LGM most of Northern Serbia was dominated by winds from the second (SE) quadrant, whereas a smaller part of the territory to the northwest, on the border of Croatia and Hungary, was affected by a wind from the fourth quadrant.

4.5. Summarized results and two wind zones

Table 3 summarizes the key results of the research on prevailing, modern- and paleo-, winds in Northern Serbia. These results are classified according to the different methods used in this study and can be compared to results from previous studies. From the last glacial to the present, Northern Serbia, even though it is a relatively small region, has been divided into two zones with different influences from prevailing winds. The prevailing winds in Banatska Peščara blow from the second (SE) quadrant, whereas in the Bačka subregion winds have predominantly come from the fourth (NW) quadrant. It should be noted

that the results are most complete for Banatska Peščara, for which a richer suite of analyses could be completed.

5. Discussion

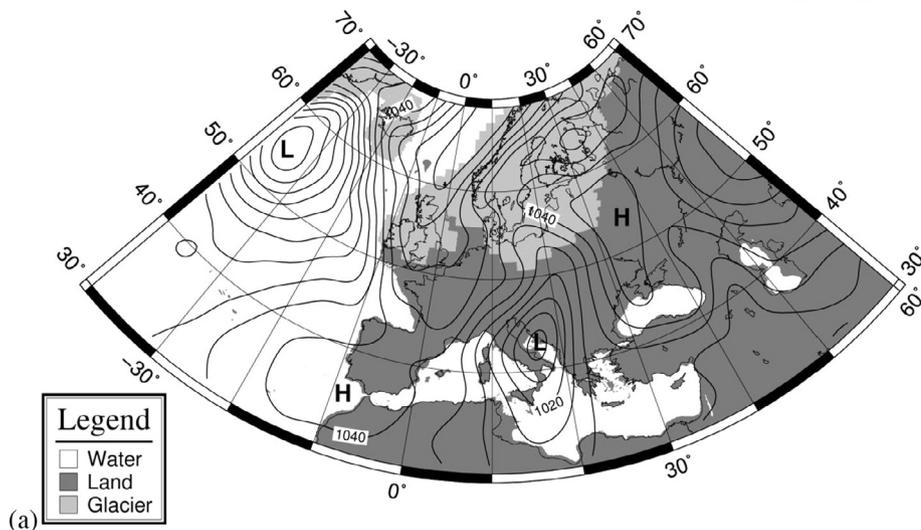
Our goal in this research was to investigate the prevailing surface winds in the recent and past periods in Northern Serbia, and especially for the sandy terrains in and around Banatska Peščara.

5.1. Prevailing winds and circulation types for the modern period

Prevailing modern winds were analyzed using surface wind data from 12 meteorological stations spanning the period 1939–2014. Results showed that the most common directions of winds in Northern Serbia and Banatska Peščara are from the fourth (NW) and second (SE) quadrants with an average of 116.4, 105.1, 114.6, and 129.2 days/year, respectively. As shown, the average number of days with prevailing winds from the fourth (NW) quadrant exceeds the that for prevailing winds from the second (SE) quadrant by 11.3 days/year. The situation is quite different in the area of Banatska Peščara. There, the number of days with winds from the second (SE) quadrant is 14.6 days greater than for winds from the fourth (SE) quadrant.

Winds from the second quadrant are not usually accompanied by precipitation, whereas winds from the fourth quadrant are often associated with ample precipitation. Thus, different synoptic circulations accompany these two types of winds, as explained in the discussion on the classification of weather types over Serbia (Putniković et al., 2016). Among the 26 circulation weather types observed over the period 1961–2010 in Serbia, the CTs that produce significant winds are from the fourth and second quadrants, with an annual prevalence of 48.5 and 65.7 days, respectively. In addition to these types, other types of weather, such as the A (anticyclone) type, with a prevalence of 67.0 days, can lead to weak winds from all quadrants. Transitions between different types of weather are typically not abrupt in either time or space.

Simulated Mean Sea Level Pressure [mb]



Simulated wind at 10m

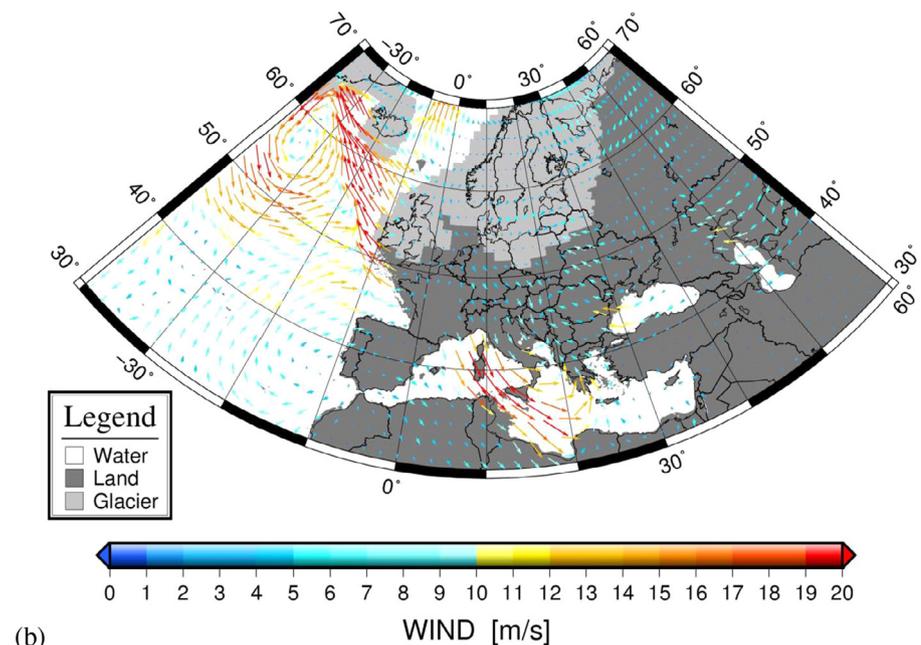


Fig. 8. The LGM maps of simulated (a) mean sea level atmospheric pressure, and (b) marked fields of surface winds. Maps show: current configuration of land, sea, and state borders, and configurations of land, sea, and ice in the LGM conditions, all in accordance with the legend.

Table 3
Prevailing winds per quadrant in Northern Serbia, Banatska Peščara and Bačka subregion, by different analytical methods.

Result	Current results				Previous results (Marković et al., 2008)	
	Period					
	1939–2014	Early Holocene	The latest last glacial period	LGM	The last glacial period	
	Method					
Area	Modern measured winds	Dune directionality	Loess grain size data	AMS	Numerical simulation SE weather type	Isopach direction
Northern Serbia	IV	-	-	-	II	-
Banatska Peščara	II	II	II	II	II	II
Bačka subregion	IV	-	-	-	IV	I&IV

The similarities between the prevailing winds and the circulation types that formed these winds can be explained based on our understanding of the Polar Front. Undulations of the Polar Front over Northwestern Europe create CTs and winds from the fourth (NW) quadrant, and bring moist air, accompanied by precipitation. Unlike the previous synoptic situations, which are characterized by high pressure over Eastern Europe (Russia) and low pressure over the Western and/or Central Mediterranean (undulation of the Polar Front on the Alps), this wind type creates CTs over Serbia with little precipitation, and dry winds from the second (SE) quadrant.

The Polar Front is one of the most complex atmospheric circulations, and is associated with a number of different weather types (e.g., 26 over Serbia), each one variable with respect to frequency and duration. In this study, we found a significant regularity in the behavior of the Polar Front through the presentation of some statistical data, concerning the appearance of various synoptic circulations and prevailing winds in Northern Serbia.

Of the many the nested atmospheric circulation systems associated with the Polar Front, the southeasterly wind known locally as Košava is especially important to this study. This local wind has Foehn characteristics and is often a warm, dry, and gusty wind, similar to many winds around the world such as the Foehn (Föhn, slopes of the Alps), Santa Ana (Southern California), and Zonda (Argentina) (e.g., Gavrilov, 2001). The Košava wind occurs in a relatively small area in the southeastern Carpathian Basin, approximately between stations VG and NS (Fig. 4). The speed and duration of the Košava wind depend on the horizontal differences in the surface air pressure between the center of the cyclone in the Western and/or Central Mediterranean and the center of anticyclone over Russia. As the difference in the pressure increases, the strength of the Košava wind increases. At station VR, the maximum wind speed recorded was 48 m s^{-1} on February 11, 1987 (Romanić et al., 2016). As we have seen, the Košava wind is a mesoscale circulation (order of magnitude 10^2 km and durations of a few days). In summary, the Košava wind is not a random event, but rather represents a very organized process that occurs in a complex hierarchy of other circulations, which persist in the atmosphere.

Similar to the way the winter monsoon brings dry air onto the continent, the CTs which lead to winds from the second (SE) quadrant bring dry air, usually without precipitation, to Northern Serbia. In contrast, the summer monsoon on the continent brings moist air with rainfall, while in Northern Serbia the CTs from the fourth (NW) quadrant create advection of moist air, and precipitation. The difference between fourth (NW) and second (SE) quadrant's circulations types, and the monsoon circulation, is only in terms of continuous duration. The monsoon lasts for months, whereas the synoptic situation has durations of a few days, but can occur many times annually.

5.2. Geomorphologic evidence

Prevailing paleowinds were studied in the region near Banatska Peščara by analyzing the orientations of 1300 parabolic dunes. The vast majority (ca. 1200) dunes were formed from winds from the second (SE) quadrant, which is similar to the direction of the recent prevailing winds, and which are often a dry, warm wind. If we take into account the fact that the dunes likely formed in the Early Holocene (Sipos et al., 2016), one could argue that the prevailing winds since then have not changed significantly. However, winds that formed the remaining, ca. 100 transverse dunes were mainly from the third (SW) quadrant. The reason for this wind shift was not understood until recently. However, as we can see in Table 2, prevailing wind per direction at the station VR (13.4%) is just 180° . Therefore, we argue that these dunes arose from high-frequency winds from other directions that are close to that of the second (SE) quadrant.

Characteristics of prevailing paleowinds have also been obtained from grain size analysis of loess deposits around Banatska Peščara (Fig. 6). The loess is coarser textured in the southeastern sections of the

loess plateaus here, when compared to more northeasterly sites. Because the Danube River catchment, situated to the south of Banatska Peščara, is the main source of these loess particles (Smalley and Leach, 1978), our grain size data point to prevailing winds from the SE during the loess depositional interval. This finding fits well into the pattern of the prevailing modern winds at three stations (BC, VG, and VR) surrounding Banatska Peščara. Thus, we conclude that wind directions during the loess depositional interval were generally similar to those of modern times.

Of the five AMS results, four cases (DU1, DE1, DO1, and SAM1) show the SE–NW and SSE–NNW directionality, again suggesting the dominance of southeasterly paleowinds (second quadrants) in Banatska Peščara during the last glacial (Fig. 7). Data from the KOV1 site (Fig. 7) suggest prevailing paleowind systems from the NE, which we are unable to explain.

5.3. Previous geomorphological evidence

Although previous studies have suggested that northerly and northwesterly paleowinds were the dominant winds in the southeastern Carpathian Basin during the LGM (Bokhorst et al., 2009, 2011; Sebe et al., 2011), our study provides strong evidence for prevailing southeasterly winds in this region at that time. Previously, the possibility of the southeasterly winds had been proposed by Marković et al. (2008), based on geomorphological evidence. Grain size data for the Orlovat section (Obreht et al., 2015) suggested that southeasterly winds were dominant in the southeastern Carpathian Basin during the previous interglacial, but these data could not be used to determine whether similar winds were also dominant during glacial periods. Our data suggest that it is plausible that the Košava (SE) wind was a dominant wind system during the last several glacial cycles. Obreht et al. (2016) has proposed an interplay of different atmospheric systems between the Balkans and the southern Carpathian Basin during past $\sim 350 \text{ ka}$, where the Košava wind may have played an important role as a border between these two air systems. Nonetheless, our study suggests that southeasterly winds have been dominant in the southeastern Carpathian Basin, at least during the late last glacial and into the Holocene.

5.4. Simulation data

Numerical simulations confirmed that undulations of the Polar Front could have led to the formation of the SE weather type during the LGM; these conditions favor formation of southeasterly surface winds similar to the Košava wind in study area (e.g., Obreht et al., 2015). Wind data from the numerical simulation also agree with the geomorphological and grain size data. The simulated winds of the second (SE) quadrant correspond with dune orientations, most of the loess grain size data, and the analysis of isopachs (Marković et al., 2008) in the area of Banatska Peščara. Additionally, the results for the northwestern area (Bačka subregion), i.e., winds from the fourth quadrant, coincide with the results obtained by Marković et al. (2008); isopachs of the last glacial loess (L1) indicate that loess deposition occurred primarily on northerly winds.

6. Conclusions

Ours is an integrative study about prevailing winds in Northern Serbia, from the last glacial maximum to the present. We provided analyses of prevailing winds based on the instrumental data over the past 50–75 years. These data are compared to those during typical paleo intervals (early Holocene, the latest last glacial period, and LGM) (Table 3), which were reconstructed from loess grain size, AMS, aeolian dunes morphology, and model results. All of these data suggest that predominance of two wind directions: southeasterly winds in Banatska Peščara, for all paleo and modern intervals, and northwesterly winds over the rest of the Northern Serbia in the recent and last glacial period

(Marković et al., 2008). The study has shown that the SE winds are probably responsible for the formation of dunes in Banatska Peščara and perhaps much of the loess in Northern Serbia. This conclusion is very important for paleoclimate reconstructions of Serbian loess depositional systems.

The cause of prevailing winds across our study area involves the complex undulations of the Polar Front over Northern Serbia, which create the dominant weather circulations (SE and NW types), leading to the prevailing winds we observe today. The numerical simulation of the SE weather type showed that, during the LGM it was possible the undulation of the Polar Front as in the recent period, as well as the predominance of southeasterly winds in Northern Serbia.

Further work may determine the extent to which such winds assisted in the transport of dust accumulated on the six loess plateaus in Northern Serbia. The most important issue to a better understanding of loess provenance in this region could be the confirmation of whether specific undulations of the Polar Front and the corresponding circulation in Northern Serbia, such as prevailing winds from the second and fourth quadrants, may have led to its accumulation, similar to monsoons in Asia (e.g., Porter, 2001).

Acknowledgements

This study was supported by the Serbian Ministry of Science, Education and Technological Development – Serbia, under Grants No. 176013 and 176020. FL, CZ and IO wish to thank the German Research Foundation – Germany (Deutsche Forschungsgemeinschaft – Deutschland, DFG) for funding in the frame of the Collaborative Research Center (CRC) 806 ‘Our way to Europe’, subproject B1 *The Eastern Trajectory*. We acknowledge the use of wind rose software, provided by Daniel Pereira. The authors are grateful to Mirosljub Zarić, who helped to determine the positions of weather fronts. All sedimentary data are available in the Pangaea database.

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