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Reconstructed Malacothermometer July Paleotemperatures from the Last Nine Glacials over the South-Eastern Carpathian Basin (Serbia)

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Abstract: In this study, the compiled malacological record of the two most important loess–palaeosol sequences (LPS) in Serbia was used to reconstruct the Malacothermometer July Paleotemperature (MTJP) of the last nine glacials. The sieved loess samples yielded shells of 11 terrestrial gastropod species that were used to estimate the MTJP. Veliki Surduk (covering the last three glacial cycles) and Stari Slankamen (covering the last fourth to ninth glacial cycle) LPSs previously lacked the malacological investigations. After the sieving, a total of 66,871 shells were found, from which 48,459 shells were used for the estimation of the MTJP. Through the studied period, the reconstructed MTJP was ranging from 14.4 °C to 21.5 °C. The lowest temperature was recorded during the formation of the loess unit L5, equivalent to the Marine Isotope Stage (MIS) 12. The second-coldest summers were occurring during the MIS 16 glacial. Although the warmest glacial was L8 (MIS 20) according to MTJP, these July temperatures might be overestimated due to only two samples from the poorly preserved L8 unit. The malacological material derived from the loess units at Veliki Surduk and Stari Slankamen LPSs showed great potential for July temperature reconstruction, as the comparison with other regional records showed similar climate changes. Further work is necessary to validate the age scale of the oldest samples, and a higher resolution sampling could lead to more detailed July temperature fluctuations, as was shown for the youngest glacial in this study. Likewise, estimating the July temperature using different proxies (e.g., pollen) from the same LPSs could be used to confirm the observed climate trends.

Keywords: malacofauna; Titel loess plateau; July temperature; Veliki Surduk; Stari Slankamen; loess; Serbia; Middle Pleistocene

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1. Introduction

Although studies on future temperatures for the Carpathian Basin (CB) are numerous nowadays [1–3], and the references therein], there are not as many papers on long-term paleotemperature reconstructions. The investigation of future temperature fluctuations is reasonable as the CB is experiencing droughts, with serious socio-economic and environmental consequences [4,5]. Regional Climate Models (RCM) are used for summer temperature predictions until the end of the 21st century, and a general concern exists that the current rising trend will continue. For example, PRECIS (Providing Regional Climates for Impact Studies) RCM for the southern CB region gave an 80–95% chance that the summer temperature will increase by 4 °C until 2100 (reference period 1960–1991) [6]. Other RCMs which include the CB (e.g., REMO, ALADIN-Climate, RegCM, with the resolutions of 25 km [7], 10 km [8], and 10 km [9], respectively) also confirm the highest temperature increase during the summer in 2071–2100. By analyzing the temperatures over the CB, not only the temporal trends can be estimated, but also spatial ones. Furthermore, it was found that the spatial trends for the future temperatures over the CB by ALADIN-Climate [2] were also present during the Last Glacial Maximum (LGM) by using the WRF (Weather Research and Forecast) RCM [10]. The same spatial patterns for the July temperatures over the CB can be provided by malacofauna [10]. This finding shines a light on the possible role that mollusks can have in the validation of the RCM. It seems that mollusks are valuable records of the past climate change over the south-eastern CB. Therefore, it is of utmost importance to study this region in the context of paleoclimatology in order to understand the rates at which temperatures are changing, by reconstructing the past temperature range over the CB and what one might expect for the current interglacial. Obtaining new long-term records from proxy data can contribute to an extensive understanding of the climate in this region.

The usage of numerical simulations in Ice Age studies started in 1974, when the NCAR model showed July temperatures before 20 ka [11], and soon after the CLIMAP project obtains the July temperatures at 18,000 years BP [12]. Since then, global, and later also regional paleoclimate models improved [13], but in order to do so, they needed to be compared with the geological record or some independent proxy. Environmental reconstructions based on the proxy data play a central role to validate and improve the ability of climate models to simulate past, present, and future climate change. Luckily, as the number of high-resolution proxy data increases, combined model-data interpretations of the climate system became more accurate [14]. However, a special knowledge on the ecological tolerances of the considered species is required to reasonably estimate the paleotemperatures. After this is established, further transfer functions can be developed in order to obtain the desired temperature from the found biota [15,16] e.g., the Mutual Climatic Range Method [17], which relies on the fact that the space is shared by multiple species and thus the climate of the studied region is suitable for them. This implies that if the species' temperature tolerance is well understood, a paleoclimatic reconstruction becomes possible. For the evaluation of the newly obtained paleotemperatures, multi-proxy studies are needed.

In this study, we provide for the first time a long-term July temperature record obtained from the assemblages of mollusks found in the Veliki Surduk and Stari Slankamen loess–paleosol sequences (LPSs). These LPSs provide a rare opportunity to reconstruct environmental conditions from the terrestrial record over the last nine glacial periods. The aim of this study is to (1) present how July temperatures were fluctuating during the mentioned ice ages, (2) compare these estimations with already known European records, and (3) provide a realistic insight into the usage of malacological data in July temperature reconstructions.

2. Materials and Methods

2.1. Study Area

The CB is known for its up to 55 m thick loess sediments [18]. The provenance for these deposits is linked with the surrounding geology of the CB and fluvial transport of the Danube River, as well as short-distance aeolian transportation from alluvial plains [19,20]. The composite Veliki Surduk/Stari Slankamen LPS together provide an almost 1 Ma record of sediments and soils generated during glacial–interglacial cycles [21]. Both sites are situated near the confluence of the Tisza and Danube rivers, in the Autonomous province of Vojvodina in Serbia. The coordinates of Veliki Surduk LPS are 45°17′40′′ N and 20°11′17′′ E. The top of this LPS is currently at 121 m above the median sea level (m a.m.s.l.) It is located in the Titel loess plateau, a remarkable elongated geomorphological feature rising from the alluvium of the mentioned rivers (Figure 1). The photo of the Veliki Surduk LPS is shown in Figure 1c.

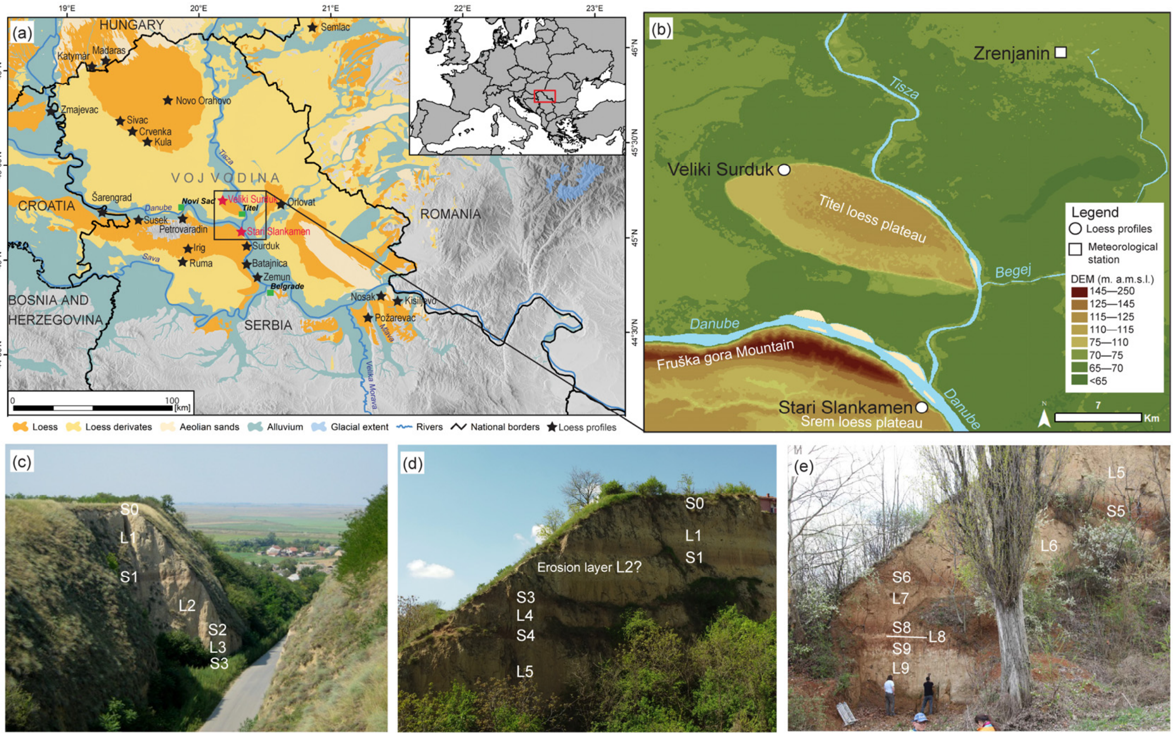

Figure 1. (**a**) Southern part of the CB with some of the investigated LPS [22], modified, (**b**) Digital elevation model (DEM) of the studied region with the location of the Veliki Surduk and Stari Slankamen LPSs, (**c**) Photo of Veliki Surduk LPS, (**d**) Photo of the upper part of Stari Slankamen LPS, (**e**) Photo of the lower part of Stari Slankamen LPS.

The Stari Slankamen LPS is located in the Srem loess plateau, on the northern slope of Fuška gora mountain, at 45°7′53′′ N and 20°15′41′′ E. Figure 1d shows the younger part, and Figure 1e shows the older part of the Stari Slankamen LPS. The top of this LPS is currently at 140 m a.s.m.l. The altitudes in this study will be presented as the altitudes of each loess unit at which they are located today, thus not including the possible neotectonic movements over the last nine glacial cycles. Due to the lack of the neotectonic investigation on the northern slopes of the Fruška gora mountain, it is still unknown what was the elevation when the loess units were deposited. These two LPSs are used for the development of the Danube loess stratigraphy [23]. In this study, the loess units are presented by the letter "L" and paleosols with "S" and the number indicating the glacial cycle, respectively. This stratigraphy is indicated on the lower panels of Figure 1. The loess accumulated over the colder climate periods and is correlated to MIS 2-24 [24]. The absolute dating of Veliki Surduk and Stari Slankamen loess was performed in multiple studies: post-IR infrared stimulated luminescence (IRSL) on Middle Pleistocene loess of Stari Slankamen [18], optically stimulated luminescence (OSL) in Veliki Surduk [25,26], but also OSL on younger parts of Stari Slankamen [27]. The existence of the Matuyama–Brunhes Boundary (MBB) which represents the magnetic reversal is observed in L9 loess unit of Stari Slankamen [28]. Until now, no detailed malacological investigation was performed on both profiles. According to the available measured data from the Republic Hydrometeorological Service of Serbia, the average July temperature from the closest meteorological station in Zrenjanin shows the value of 22.0 °C for the period 1949–2021 [29].

2.2. Sampling

The sampling for the purpose of malacological investigations was carried out in 2018 and 2019. The profiles were cleaned and the colluvial material was removed prior to sampling. In this study, loess units L1LL1, L2, and L3 were taken from the Veliki Surduk, while L4, L5, L6, L7, L8, and L9 are taken from the Stari Slankamen LPS. The first 0.5 m of the Veliki Surduk profile was not sampled, as this represents the Holocene soil which is used for agricultural purposes. The sampling resolution of the Veliki Surduk LPS was 5 cm for the first 0.5–5.0 m from the topographic surface, which is covering the most recent loess accumulation. This high resolution allows studying the malacological record from the last glacial loess in more detail. For the rest of the profile, the resolution was 20 cm. Samples from 6.7 to 10.9 m depth, representing the lithological unit L1LL2, were skipped, as this loess was previously shown to have a poor malacological record at the Titel loess plateau [30]. The last samples of this profile were taken in the upper part of the S3 paleosol. From Veliki Surduk 156 samples were taken. For the Stari Slankamen LPS, the sampling resolution was 20 cm for all the samples, adding up to 82 samples in total. Each of the samples in this study had the weight of 10 kg, and all of them were sieved through a 0.5 mm sieve. The identification was done by using the binocular microscope, and the species were determined if possible. Sampling for the earlier study showed that the pedogenesis has an influence on the carbonate shells, leaving the interglacial soils malacologicaly sterile [31]. Thus, paleosols were not sampled for this study.

2.3. Amino Acid Racemization

From the Veliki Surduk and Stari Slankamen LPSs, terrestrial gastropods were taken for the amino acid racemization geochronology (AAR) which is a method already used on shells from loess in Serbia [31,32]. Principles of AAR have been applied to loess deposits in different regions of Europe [33,34] with specific applications to Serbian LPSs [21,35]. Fossil land snail shells are commonly present in loess units and provide an opportunity to measure L- and D-isomers in multiple amino acids preserved in the crystalline structure of the shells. In living systems, amino acids originate as L-isomers. Over time, amino acids racemize from their L- to D-isomer. Thus, the ratio of D to L isomers is a representation of the geologic age of the sample and the enclosing sedimentary unit. Comparing D/L ratios of individual amino acids in land snails from different loess units serves as a relative age indicator and can facilitate correlation of loess sequences across a region. In Veliki Surduk LPS, the *Pupilla* genus was taken from the three loess units: one shell from L1LL2, five shells from L2, and five shells from L3. From Stari Slankamen LPS, samples were taken from the loess units: L4—five shells, five from the L6, and five from the L7. The rate of amino acid racemization in land snail shells has been observed to be taxonomically dependent [33]. Therefore, it is necessary to compare data measured in a single genus of a land snail in order to minimize taxonomic variability. In this study, while different taxa were present, we selected *Pupilla* spp. for the amino acid analysis because of their relative abundance through the loess sequence and because they have been used successfully in other loess–AAR studies in the region. Generally, up to 5 individual shells are selected for analysis from a single loess unit. The AAR data are measured in a single shell, and the average values are reported for the multiple measurements within a loess interval. Amino acid racemization data were measured in shell samples in the (former) Amino Acid Geochronology Laboratory in the Department of Geology, University of South Florida, Tampa, Florida. The preparation and analysis of shells followed the methods outlined in a previous study [36].

2.4. Malacothermometer July Paleotemperature

The optimal temperatures for some snail species were defined as well as the minimal and maximal temperature that the same species tolerates [37–42]. This method is based on the fact that snails are only active during the year when the temperature and humidity allow it, and they construct their shells during the vegetation period when food is available.

Therefore, the reconstructed paleotemperature from snail species data is best interpreted as mean July temperature (°C). The equation for this method considers the mollusk species and their abundances per sample. Usually, the sample has many snail species. The original sources for the estimation of the July temperature can be found in the Supplementary Table S1. In the same table are the references for the found snail species [43–49].

It is important that all the samples are sieved through the same sieves, so the smallest species as well as the shell apices and apertures are saved. We counted a single apex, or a single aperture as one shell. If both the apex and aperture from the same species are found, they are counted as one shell. The Malacothermometer July Paleotemperature (MTJP) method has already been used in loess studies in Serbia. Thus, the results can be compared between the younger loess units [31,35].

3. Results

3.1. Chronostratigraphy of LPSs

Aminostratigraphy of the Veliki Surduk and Stari Slankamen LPSs according to the *Pupilla* genus is presented in Figure 2. The alloisoleucine/isoleucine ratio (A/I) as well as the glutamic amino acid (GLU) D/L is steadily increased as the loess gets older, which is expected. The values from both ratios are similar. The three youngest values are related to shells from the Veliki Surduk LPS. The results show greater values for GLU in L1 and L2 mollusks. In the shells from L3 and L4 loess units, the values of the two methods are the closest. As the shells get older, the A/I values are greater than GLU. According to the correlation made between AAR values and MIS for LPS in the nearby loess section Ruma (see Figure 1a) [32], the values obtained from shells in Veliki Surduk LPS can be interpreted as MIS 2-3, MIS 6-7, and MIS 8-9. In other words, these are the glacial cycles B, C, and D after [50], respectively. From Stari Slankamen LPS only the loess unit L4 can be compared to Ruma LPS, as in Ruma this is the last loess unit. In both profiles, this value can be correlated to MIS 10-11, or glacial cycle E. Table 1. is showing the obtained values.

Table 1. The results of AAR for GLU and A/I for the genus *Pupilla* with the standard deviation for L1, L2, and L3 from Veliki Surduk LPS, and L4, L6, and L7 for Stari Slankamen LPS.

Loess Unit	GLU D/L		A/I		No. of Shells
	Mean	σ	Mean	σ	
L1	0.276		0.185		1
L2	0.277	0.022	0.202	0.009	5
L3	0.313	0.020	0.331	0.049	5
L4	0.406	0.012	0.393	0.054	5
L6	0.427	0.025	0.536	0.043	5
L7	0.496	0.042	0.562	0.017	5

The role of low-field magnetic susceptibility is important in establishing chronostratigraphy of the loess sediments. For this reason, this parameter was measured in Veliki Surduk and Stari Slankamen multiple times [23,28,51], and results are plotted next to the AAR relative geochronology in Figure 2. The absolute dating of Stari Slankamen sediments [18] are also shown in Figure 2. The quartz from the L1 unit of Veliki Surduk was dated by OSL [25] and the results of this study will refer to these ages. The tephra layer previously discovered in the Veliki Surduk LPS serves as a clear marker of the age of the sediment. In the L2 loess unit, the L2 tephra was found, and it can be used as a link to other regional records [52,53]. Due to the lack of the dating of the older loess units, and due to the good agreement of magnetic susceptibility to the marine isotope stratigraphy, it was decided that the start and end ages for L2, L4, L5, L6, L7, L8, and L9, would be taken from respective marine isotope stages [24] when these layers were forming: 191–130 ka, 374–337 ka, 478–424 ka, 676–621 ka, 761–712 ka, 814–790 ka, and 938–866 ka ago, respectively. As the sampling of L3 included the lower part of the S3, the ages of the obtained results enter MIS 9, and go until the end of MIS 8.

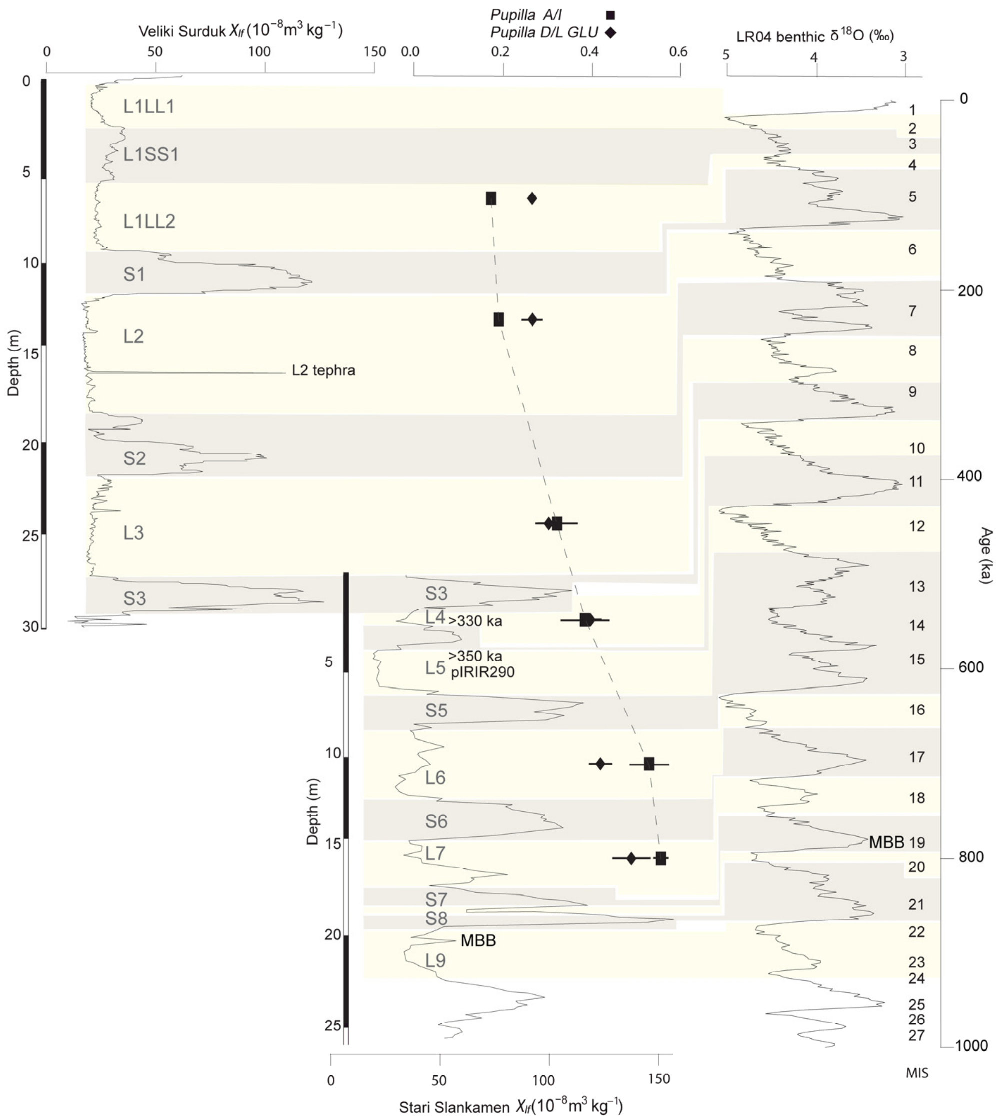

Figure 2. Low-field magnetic susceptibility of Veliki Surduk and Stari Slankamen [21,23] with the results of aminostratigraphy (this study) compared to benthic δ^{18}O from LR04 [24]. Luminescence ages are from [18].

3.2. Malacothermometer July Paleotemperature Results

From a total of 66,871 shells retrieved from the sieved sediments, 48,459 shells were used for the estimation of the MTJP, where 18,320 are from the Stari Slankamen, and 30,139 are from the Veliki Surduk LPS. There were 11 species used for this estimation: *Granaria frumentum*, *Pupilla muscorum*, *P. triplicata*, *Punctum pygmaeum*, *Clausilia dubia*, *Columella columella*, *Vallonia costata*, *V. tenuilabris*, *Vitrea crystallina*, *Succinella oblonga*, and *Trochulus hispidus*. The obtained MTJP is shown in Figure 3. As only the loess was sampled, the curve is discontinuous. Furthermore, paleosols formed during humid and warm interglacial periods were not sampled as it was shown in earlier studies that they are malacologicaly sterile. The temperatures will be described from the earliest part of the record.

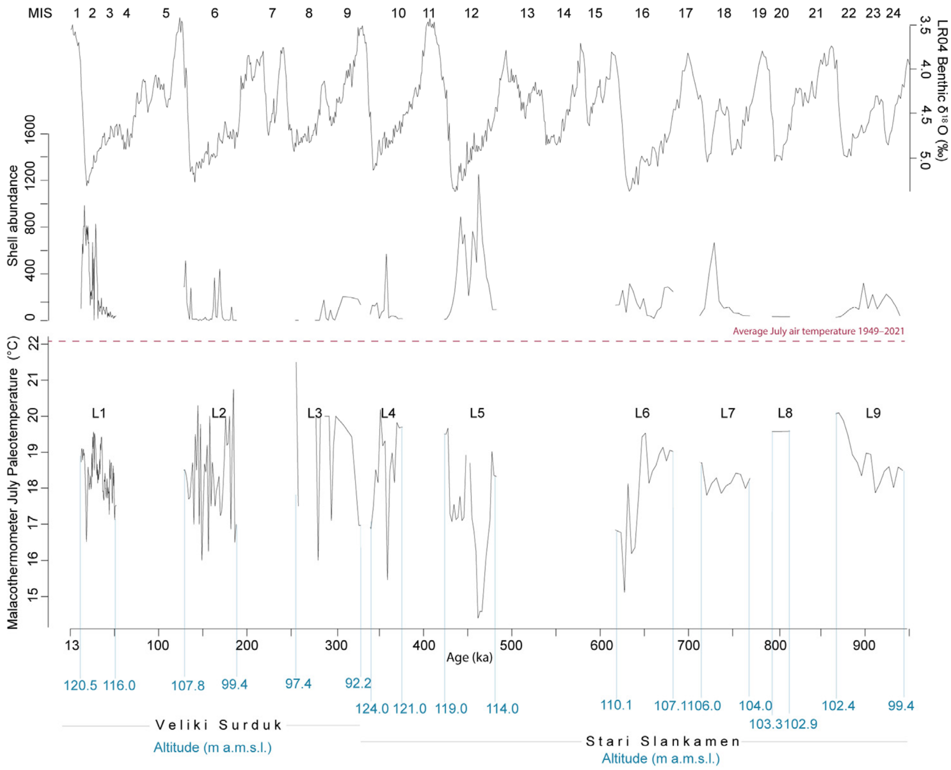

Figure 3. Reconstructed optimal MTJP (°C) for the last nine glacials in Veliki Surduk and Stari Slankamen LPS compared to LR04 benthic $\delta^{18}O$ (‰) [24] for time scale. The blue numbers present the current altitude of the loess units in which the MTJP was obtained (neotectonics was not considered). The red line presents the average July temperature from 1949–2021 for the closest meteorological station in Zrenjanin [29].

Based on the correlation to the marine isotope stratigraphy, the earliest results correspond to 938 ka ago (18.5 °C). Slightly colder summers occurred at 927 ka ago as they dropped by 0.5 °C. From there on they are increasing to 18.6 °C at 922 ka ago. For the next 15 ka, the MTJP is gradually decreasing and reaching the lowest value for this glacial period at 17.9 °C. In the next 7 ka, the temperature is again rising and reaching 19.0 °C. The third colder phase in this glacial occurred 891 ka ago when the MTJP was 18.3 °C. The temperatures were increasing towards the interglacial. The last obtained MTJP was at 20.1 °C at 866 ka ago. Overall, the average MTJP for the oldest recorded glacial in Serbia, L9, was 18.8 °C. This record was obtained from the 3 m of sediments which today correspond to the altitude of 99.4 m a.m.s.l. to 102.4 m a.m.s.l.

The MIS 20 glacial was poorly preserved in Stari Slankamen LPS, allowing only two samples to be taken, thus providing only two estimates. The malacological record was identical in both samples, leading to the same MTJP of 18.6 °C; thus, it can be considered also the average value for this glacial. This loess unit is today located at about 103 m a.m.s.l.

The MTJP record for the MIS 18 glaciation starts at 760 ka ago and ends at 712 ka ago. The starting value was 18.0 °C, and in the next two samples, this number increased to 18.4 °C corresponding to 750 ka ago. From there on the estimate decreased steadily to 17.9 °C at 734 ka ago. After this the MTJP is getting warmer, reaching 18.3 °C at 728 ka ago. The last colder phase of this glacial was at 717 ka when the coldest temperature was obtained (17.8 °C). As the glacial is ending, it increases to the maximum value of 18.7 °C. The average MTJP for this glacial is found to be 18.2 °C, which is until that time the coldest glacial in the analyzed period. The L7 is currently at the altitude of 104.0–106.0 m a.m.s.l.

The MIS 16 glacial period starts 676 ka ago with a temperature of 19.0 °C. The temperature curve is generally showing lower estimates until 652 ka when the MTJP was 18.1 °C. In the next 7 ka, a warmer phase was observed, with the MTJP reaching up to 19.5 °C. After this phase, the environment is getting colder reaching 16.2 °C at 632 ka ago. This was until then the lowest recorded MTJP in all glacial periods from this record. The next temperature is 18.1 °C indicating rapid warming, after which comes a very cold period with yet unrecorded MTJP of 15.1 °C. The glacial ended with a temperature of 16.6 °C at 621 ka ago. This glacial represented by the 3 m of samples had the largest variability of estimates and is considered the coldest until then, with an average value of 18.0 °C.

The very beginning of MIS 12 glaciation had high values of temperature, ranging between 18.4 °C and 19.0 °C (478 ka ago). About 473–460 ka ago, a pronounced cold phase occurred based on the malacological record from Stari Slankamen. During this period, the MTJP is very low, reaching a minimum of 14.4 °C. From 460 ka to 446 ka ago, the summers were again warmer, with MTJPs of 18.9 °C. Then, another cool episode lasted from 444 ka to 431 ka ago, in which the estimate fluctuated between 17.0 °C to 17.8 °C. At the end of MIS 12, it began to increase, reaching up to 19.7 °C. A comparison with previous glaciations shows that this glacial exhibited the most diverse MTJP ranging up to 5.3 °C. The average value of MIS 12 was 17.1 °C. The trend of colder glaciations continues, as this becomes the coldest recorded. The current position of the loess unit L5 is between 114.0 m and 119.0 m a.m.s.l.

The next glacial period started 374 ka ago with a relatively constant temperature up to 368 ka ago between 19.6–19.8 °C. A first colder phase was obtained 366 ka ago when it dropped to 18.1 °C. Through the next 5 ka, the MTJP again increased to 19.0 °C, after which the main cooling occurred. This cooling reached its maximum at about 358 ka ago when the estimate was 15.5 °C. After this, the MTJP was never as low throughout the rest of the MIS 10 glacial. The temperature started to rise, and it reached a maximum of 20.2 °C 350 ka ago. Then, until the end of glaciation, another cooling phase occurred, but not as severe as the previous one with the MTJP decreasing to 16.9 °C. The average value of this glaciation was 18.5 °C, which makes it generally warmer than the previous three glaciations. This loess unit provided 3 m of sediments located today at about 121–124 m a.m.s.l.

A rare situation occurred in MIS 8 loess—1.2 m of the profile was malacologically sterile, thus a continuous MTJP reconstruction could not be established for this glaciation. The sampling started with three samples in paleosol S3, which is why this curve is starting at 326 ka ago. As this represents the end of the interglacial period, the MTJP were relatively high, reaching values from 19.4 °C to 20.0 °C. The first colder phase in this record was placed at the beginning of the loess formation when the temperature dropped to 17.1 °C. After this cool event, it was very high and constant at 20.0 °C. Due to the lack of malacological material in L3 loess unit it is hard to tell the fluctuations of temperatures in the younger part of the MIS 8 glaciation. The authors propose the hypothesis that due to the dryness of the climate, the snails could not inhabit the location of the studied profile. The existing data in MIS 8 point to an average of 19.1 °C, which is very warm compared to the previous glaciations.

The next glaciation exhibits a similar situation to that in MIS 8. Even though there were always shells present, their abundance was very low, in some cases below ten. Due to this, in the next text such samples will be mentioned. The record for MIS 6 glaciation starts at 17.0 °C from 191 ka ago. The peak at 20.6 °C is possibly an overestimation as it was obtained from only three shells from 185 ka ago. All other samples for this glacial have lower temperatures. One cold episode was recorded about 181 ka ago (16.9 °C). After this, the estimate is between 19.0 °C and 20.0 °C in the next 6 ka. The gradual decrease of MTJP is present from 174 ka to 170 ka ago when it reached 17.2 °C. From 168 ka to 165 ka the cooling trend continues. From 165 ka to 158 ka ago the MTJP is increasing, and reached 20.0 °C. After this, an abrupt drop in values was obtained at 156 ka ago and 149 ka ago, 16.3 °C and 16.0 °C, respectively. Again, these two temperatures are possibly underestimations as there were only seven and four shells, respectively. The next cold phase is at 146 ka ago (17.0 °C) but is based only on one shell. A high peak at 20.3 °C from 145 ka ago is based on only five shells and the authors do not find it reliable. From then on, the results are more likely to be reliable due to higher abundances. The temperatures are fluctuating between

17.0 °C and 19.5 °C from 141 ka to 137 ka ago. The MIS 6 glaciation ended with gradually increasing MTJP at 136 ka and 130 ka, from 17.8 °C to 18.5 °C, respectively. When including all of the samples regardless of the abundances, the average value for this glaciation is 18.3 °C. This loess unit today covers the altitude from 99.4 m to 107.8 m a.m.s.l.

For the last glacial, the sampling resolution was four times higher than for the previous glacials. The record starts at 51 ka ago when the MTJP was 17.5 °C. In the next two thousand years it was increasing to 18.6 °C. The sudden drop of 1 °C was present from 49 ka to 47 ka ago. After this, it was again above 18.6 °C. At about 45 ka ago, the MTJP was 17.3 °C. In the next 5 ka, the temperature was fluctuating between 17.7 °C and 18.4 °C. The values are generally high during two warm phases. The first phase started at 37 ka to 35 ka ago when the MTJP was up to 19.4 °C. From 35 ka to 31 ka ago the MTJP were ranging from 18.1 °C to 18.7 °C. The second warm phase was occurring from 31 ka to 26 ka ago, as the values again reached 19.6 °C. After this, lower values of 18.0 °C were obtained. The main colder phase in this glacial occurred from 21 to 18 ka ago, as the MTJP dropped to 16.5 °C. We note that such low value should not be considered an outlier as more than 800 shells in this sample were used for estimation. After this, the environment is getting hotter towards the end of the MIS 2 where the values are above the 19.0 °C. The average MTJP for this glacial is 18.4 °C and it refers to the altitude of 116.0 to 120.5 m a.m.s.l.

4. Discussion

4.1. Local Malacothermometer July Paleotemperature

Figure 4 is showing the average, maximum, and minimum MTJP obtained from the malacological record of this study, compared with the data from the Požarevac LPS [31]. As both profiles are situated in the Danube catchment, the Danube loess stratigraphy is presented on the *x*-axis, with the corresponding MIS. The average MTJPs for the existing malacological records over the last four glacials show very similar values, although the distance between the Požarevac LPS and the analyzed loess sections from this study is ca. 100 km (Figure 1a).

The maximum recorded July temperatures in each glacial period are indicated with red color, and they vary from 18.7 °C in loess unit L7 (Stari Slankamen LPS) to 21.5 °C in the loess unit L3 (Veliki Surduk LPS). The malacological record of the Požarevac LPS indicates that the maximal MTJP for MIS 10, MIS 8, MIS 6, and MIS 2-4, equals 21.5 °C. Generally, samples from the Požarevac LPS show warmer preferring mollusk assemblage than the ones in Veliki Surduk/Stari Slankamen. The average MTJPs for MIS 10, MIS 6, and MIS 2-4 are higher in Požarevac for 0.8 °C, 0.4 °C, and 0.6 °C, respectively.

The minimum MTJP have a wide variety through the studied period, from 14.4 °C to 19.6 °C according to Veliki Surduk/Stari Slankamen mollusk assemblage. A lot of MTJP variation is related to the glacial MIS 8 and MIS 12. For the Požarevac LPS, the minimum temperatures coincide with those from the Veliki Surduk at MIS 2 and MIS 8, which is the consequence of the presence of the same mollusk species at these depths of the LPSs. For the remaining two glacials, the minimum MTJP is again warmer in the Požarevac LPS.

The MTJP method seems to be sensitive enough to distinguish the fluctuations of the MTJP over MIS 3 and MIS 2, which might be synchronous to the Heinrich Events (HE) 5, HE3, and HE2 [54]. The problem with these comparisons is the age scale. The first 5 m of the Veliki Surduk LPS covering these events are dated by OSL [25], and the age errors must be considered when interpreting MTJP. Regardless of the obtained MTJP for MIS 2 and MIS 3, the mollusk assemblage points to the colder environmental conditions, also confirmed in the more northern loess record from Hungary [55].

The average July surface air temperature, which is measured from the meteorological station in Zrenjanin (Figure 1b), is presented by a dashed line in Figure 4. This value of 22.0 °C is calculated as the average temperature from 1949 to 2021. This is the longest existing publicly available measured record from the meteorological stations in Serbia. The used method never derived such high July temperatures over the last nine glacial cycles. The greatest difference between the modern July air temperature and MTJP occurred about 473–460 ka ago, and this value is 7.6 °C.

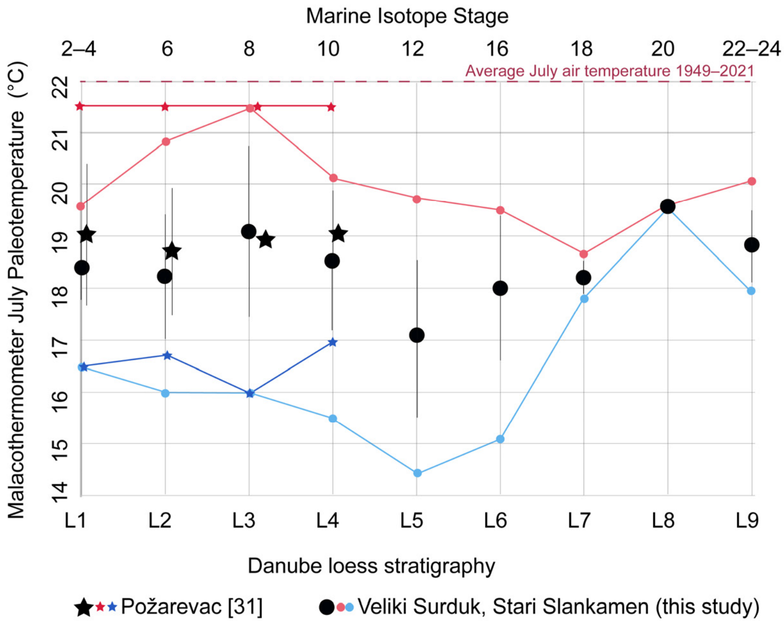

Figure 4. Average (black), maximum (red), and minimum (blue) MTJP (°C) for each of the nine glacial periods at the Veliki Surduk and Stari Slankamen (this study), and the last four glacial periods from Požarevac LPSs [31], indicated by circles and stars, respectively. Error bars represent 2σ.

4.2. Comparison to Other Balkan Records

The only way to check the temperature trends in the nine glacials obtained in this study is to compare them to the existing paleoclimate records in the region. As there are no LPSs analyzed with a similar methodology and such long temporal coverage in Serbia, further comparison is possible only with lacustrine proxies and glacier extents of the region, in case they are preserved. Previous papers have shown that glaciers had been present in the Prokletije Mts. [56], Pindus Mts. [57], Durmitor Mt. [58], and Orjen Mt. [59] during MIS 12 and MIS 6. During the LGM (MIS 2), glaciers were also present in these mountains as well as in other areas such as the Rila [60], Šar Mts. [61], Retezat Mts. [62], and Jablanica Mt. [63].

The strongest glaciation based on the extent of the ice caps was MIS 12, as in central Montenegro an extended ice cap existed over the mountains Durmitor, Moračke, Sinjajevina, Prekornica, and Maganik at this time [58]. Two different studies from Greece point to this temperature depression, one from the Mount Tymphi glacial relief [64] and the other from the Tenaghi Philipon lacustrine record [65]. This decrease in the temperatures in the Balkans is also the consequence of a more continental climate due to the lowered sea level. Reconstructed summer temperatures for the Mount Tymphi during MIS 12 suggest that it should be lower than modern summer temperatures by at least 11 °C [64]. At one point in Stari Slankamen LPS, the difference between the longest measured record of July air temperature (derived as a 73-year average at meteorological station Zrenjanin) and MTJP is 7.6 °C, or 8.6 °C if only the last 30 years are considered. The cold conditions 550 km south of Stari Slankamen LPS, at the Tenaghi Philipon in Greece, are in agreement with the contraction of the forests which occurred at MIS 12, MIS 6, MIS 2, MIS 10, and MIS 8 (the stages are put in descending order of severity) [65]. The lowest concentration of tree pollens from the Ohrid Lake in Northern Macedonia, which is 450 km south of Stari Slankamen LPS, was recorded in MIS 12, while in younger glaciations open and steppe environment was surrounding the lake [66].

Such cold conditions over the region are also reflected based on the malacological assemblage, as the lowest MTJP is related to MIS 12. The MIS 6 glaciation in the Balkans was usually larger than in MIS 10 and 8, thus destroying much of the geomorphological evidence from these preceding glacial cycles [58,59,64]. According to the malacofauna, the average MTJP for MIS 10 and MIS 8 was higher than in MIS 6. This finding suggests that summer melting would have been greater in MIS 10 and 8 compared with MIS 6, resulting in larger glaciers in MIS 6, and partially explains the ideas of "missing" glaciations of the Middle Pleistocene [67]. Generally, malacothermometer method is showing acceptable results and MTJP trends but could be improved by a higher resolution of sampling and dating of shell material instead of loess.

5. Conclusions

For the first time, the MTJPs were obtained from the two LPSs in the south-eastern part of the CB. Nine loess units were sampled for malacological material. In total 48,459 terrestrial gastropod shells, representing 11 species, were used for the MTJP reconstructions. The AAR from the *Pupilla* genus showed comparable values of A/I and GLU D/L between the two sections and previous aminochronology of the Ruma LPS that can be related to glacial cycles A-E. Taking into consideration the fit between low-field magnetic susceptibility of the two Veliki Surduk and Stari Slankamen LPS and LR04 benthic $\delta^{18}O$, most of the results refer to the ages of MIS. It was found that the July temperature during the formation of the three oldest loesses was varying less than in the younger sediments. On average, the summers were generally getting colder until the end of MIS 12. After this, MIS 10 was milder, and MIS 8 had even warmer summers. The last two glaciations had on average colder summers compared to MIS 8. This is likely to explain why glacial deposits associated with MIS 8 or 10 are rare or absent in the Balkans since glaciers in MIS 6 were larger as a result of cooler summers. The coldest glaciation was found to be MIS 12 when the minimal MTJP was obtained (14.4 °C). The MTJP shows that the warmest glaciation was MIS 20, but just two samples were used for the estimation of it. There are several shortcomings of using malacological material for the reconstruction of the July temperature: (1) lack of shells in sediments which is the case mostly during MIS 8 but also present sporadically in other glacial periods, (2) poorly preserved shells that cannot be determined, which is the case with the larger shells, (3) ages of the shells, which are in this study considered the same as the age of the sediment, (4) defining the abundance of shells necessary for the reliability of results, as the abundances of shells through the nine glacials was varying drastically. To solve these problems, further work is required for these LPSs, as well as more regional long-term paleoclimate records.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14050791/s1, Table S1. Names of the species with their temperatures are indicated.

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