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FREQUENCY ANALYSIS OF ABSOLUTE MAXIMUM AIR TEMPERATURES IN SERBIA

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Abstract: This paper describes the frequency analysis of absolute maximum air temperatures, using annual maximum series (AMS) in the period 1961–2010 from 40 climatological stations in Serbia with maximum likelihood estimation of distribution parameters. For the goodness of fit testing of General Extreme Value (GEV), Normal, Log-Normal, Pearson 3 (three parameters), and Log-Pearson 3 distribution, three different tests were used (Kolmogorov-Smirnov, Anderson-Darling, chi-square). Based on the results of these tests (best average rank of certain distribution), the appropriate distribution is selected. GEV distribution proved to be the most appropriate one in most cases. The probability of exceedance of absolute maximum air temperatures on 1%, 0.5%, 0.2%, and 0.1% levels are calculated. A spatial analysis of the observed and modeled values of absolute maximum air temperatures in Serbia is given. The absolute maximum air temperature of 44.9 °C was recorded at Smederevska Palanka station, and the lowest value of maximum air temperature 35.8 °C was recorded at Zlatibor station, one of the stations with the highest altitude. The modeled absolute maximum air temperatures are the highest at Zaječar station with 44.5 °C, 45.6 °C, 47.0 °C, and 48.0 °C and the lowest values are calculated for Sjenica station with 35.5 °C, 35.8 °C, 36.1 °C, and 36.2 °C for the return periods of 100, 200, 500, and 1000 years, respectively. Our findings indicate the possible occurrence of much higher absolute maximum air temperatures in the future than the ones recorded on almost all of the analyzed stations.

Keywords: absolute maximum air temperatures; frequency analysis; annual maximum series; Serbia

1. Introduction

One of the primary reasons for the analysis of the extreme climatic events is based on the need to secure an equilibrium between fulfilling strict and costly criteria in civil engineering and to prevent of serious damages that might occur on the infrastructure during the time (World Meteorological Organization, 2009). An occurrence of extreme climatic events in a certain area might have a drastic impact on ecosystems, many spheres of human society, and human life in general. In that sense, it is important to conduct researches oriented toward the frequency, duration, and intensity of certain climate extremes. For example, concerning air temperature, the

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main focus of the research activities should not be on the mean state, but on the variability and occurrence frequency of extreme values of this climatic element. Because of its current and probable impact (along with other climatic elements) in the future, research should be focused on the severity, frequency, and duration of a certain climatic phenomenon (Kyselý, 2002). On almost the entire territory of Europe, during the last two decades there were severe heat waves (Zhang et al., 2020). Furthermore, according to Russo et al. (2015), there is an increase of probability of extreme heat waves in Europe in the period 2021–2040. Meehl and Tebaldi (2004) suggest that heat waves will last longer and will be more severe in the second half of 21st century. Similar projections are made for the southeast part of Europe (Chervenkov & Malcheva, 2023). Maybe the most obvious impact of extreme maximum air temperatures can be found in the fields of agriculture and human health. For example, the consequence of the heat waves and drought observed in Europe during the summer of 2018 was a serious decrease in agricultural production in many European countries. According to Brás et al. (2021), in the period between 1964 and 2015, those two climatic phenomena in the European Union caused a reduction in cereal yields by 9% (drought) and 7.3% (heat waves), and non-cereal yields by 3.8% (drought) and 3.1% (heat waves). In the period 2000–2019, as a consequence of extreme weather events, Serbia lost nearly eight billion euros in agricultural production (Vuković Vimić et al., 2022). It could be expected that higher frequency of extreme air temperature in the upcoming years will lead toward negative consequences in agriculture productivity (Hatfield & Prueger, 2015).

As it is mentioned, compared to other climate extremes, absolute maximum air temperature occurrence (along with the prolonged duration of the heat wave) might have prompt effects on human health which in some cases might result in a lethal outcome (Basu, 2009). For example, the heat wave that occurred in Europe in 2003 resulted in the death toll of over 45000 people (Dankers & Hiederer, 2008). Although the relation between extremely high temperatures and their impact on human health is a very complex issue which includes seasonality, latitude variation, air pollution, humidity, duration of exposure to extreme temperature together with the risk on a particular day, etc., one very important aspect of it is the daily temperature peak. It differs from region to region—e.g., in Japan, the greatest possibility of the lethal outcome occurs when daily absolute maximum air temperatures are above 100 °F (37.8 °C). Also, an exponential dependence on the number of extremely warm days may be noticed (Nakai et al., 1999). In Serbia, based on the research conducted in Belgrade (the capital of the state), it is found that the highest number of lethal outcomes (94 deaths) occurred during the severe heat wave in July 2007 when the absolute maximum air temperature was 43.6 °C (Stanojević et al., 2014). Arsenović et al. (2019) found significant correlation between the number of deaths and maximum temperatures in Novi Sad for the summer of 2015. Based on the analysis of the average summer daily temperatures (Ta) in Serbia, Arsenović et al. (2023) found that for increase in Ta of 1 °C there is an increase in risk of crude rate of deaths of 1%.

Based on the previously mentioned information, the main purpose of this study is to gain more detailed insight in the intensity and spatial distribution of absolute maximum air temperatures in Serbia. Bearing in mind that the studies of absolute maximum temperatures in Serbia so far were mainly focused on trends in the data and/or dealing with the data from a few climatological stations, in this paper a stochastic approach to the data from a large number of the climatological stations is chosen. There are two key questions raised in the paper: How high absolute maximum air temperatures in Serbia can go? What is the spatial distribution of the observed and modeled absolute maximum air temperatures?

This paper is structured as follows: first, some basic information concerning the study area are provided (position of Serbia inside Europe and climate factors that affect the climate of Serbia); Data and methods section provides the description of the source, quality, time span, and spatial distribution of the data, along with the methodological approach that we used in the paper; Results and discussion section gives the quantitative and spatial analysis of the observed and modeled absolute maximum air temperatures in Serbia brought into the context with neighboring regions; and in the Conclusion section, together with the guidelines for further research, some of the main conclusions are drawn.

2. Study area

Serbia is located between 41.88° and 46.18° of northern latitude, and 18.82° and 23.00° of eastern longitude, partly covering Central Europe (with its Pannonian Plain) and partly covering South-Eastern Europe (with its Balkan Peninsula). The area of Serbia is 88443 km^2 and it has a highly diversified relief with mainly low terrains in its northern part. On the other hand, in the central and southern (south-eastern and south-western) parts of the country there are hilly and mountainous terrains. The altitude varies from 28 m a.s.l. in the north-eastern part of Central Serbia to 2660 m in the southern part of the country. During the period 1961–2010, average annual air temperatures range from 3 °C on the heights above 1800 m a.s.l. to above 12 °C in Belgrade (Milovanović, Radovanović, et al., 2017). Average amounts of precipitation for the same period are below 600 mm in the northern part of Serbia and more than 1100 mm in the mountains of western and south-western Serbia (Milovanović, Schuster, et al., 2017). The climate of Serbia may be divided into three main types, where continental type is mainly represented in the north, the modified Mediterranean climate in the southwest, and the moderately continental type covers the largest area in the rest of Serbia. According to Köppen classification system, there are Cfa, Cfb, Dfb, Dfc, and Efc climates in Serbia (Milovanović, Ducić, et al., 2017). Some of the main air masses that affect the climate of Serbia are continental or maritime arctic, polar, and tropical (Milovanović, Radovanović, et al., 2017). Continental tropical air masses with the origin in North Africa are connected with the occurrence of high air temperatures in Serbia. Due to certain synoptic conditions, intensive advection of heat from the southwest, together with favorable local factors, causes extremely high air temperatures in Serbia (Stanojević et al., 2014).

3. Data and methods

The data for the annual absolute maximum air temperatures are obtained from 64 climatological stations which are evenly distributed in Serbia. From Kosovo and Metohija (southern region of Serbia), the data from only one station were gathered. The rest of Serbia has relatively good and evenly distributed network of climatological stations. The data are taken from Meteorological yearbook (Republic Hydrometeorological Service of Serbia, 2022). At 24 stations, time series are incomplete and therefore we used the data from only 40 climatological stations. This completeness criterion is frequently used and it allows a limited number of missing observations per year. Certain types of extremes analyses are crucially connected with the completeness of the data series, so such a rigorous criteria is necessary (Klein Tank et al., 2009). The spatial distribution of climatological stations by altitude ranges is as follows: 22 stations are located below 200 m a.s.l., 10 stations between 200 and 400 m a.s.l., five stations between 400 and 600 m a.s.l., no stations in the belt between 600 and 800 m a.s.l., one station in the belt between 800 and 1000 m a.s.l., and two stations between 1000 and 1200 m a.s.l. (Table 2). The monthly values of the absolute maximum air temperatures in the period 1961–2010 (50 years) were available.

For the frequency analysis, we chose the highest value in each year (the total of 50 cases per station), i.e., we applied the annual maximum series (AMS) approach. Comparing AMS and peaks over threshold (POT) analysis, Tanaka (2020) concluded that the POT may be a better solution when time series are 50 (and more) years long. Still, because of the nature of the dataset we had—i.e., 50 years long time series (only one value of absolute maximum air temperature per month in each year) and the sensitivity of the question of threshold choice in POT analysis—we chose AMS over POT.

There is a variety of methods for obtaining a value of distribution parameter from a sample (i.e., method of moments, the probability weighted moment, *L*-moment, maximum likelihood estimation [MLE], entropy, jackknife, bootstrap). For the Log-Normal and Gumbel distribution MLE is recommended by the results of many Monte Carlo experiments. On the other hand, a mix of the lower bound estimator and the method of moments could be applied for most of the three-parameter distributions. The probability weighted moment or L-moments method for GEV distribution are recommended (Takara & Stedinger, 1994).

One of the commonly used methods (also used in this paper) is the MLE method which Law and Kelton (1991) considered as appropriate method of parameter estimation in the distribution fitting process. According to Kottegoda and Rosso (2008, p. 107), "Maximum likelihood, or ML, is an alternative to the method of moments. As a means of finding an estimator, statisticians often give it preference. For a random variable *X* with a known probability density function, $f_X(x)$, and observed values x_1, x_2, . . . , x_n, in a random sample of size n, the likelihood function of θ, where θ represents the vector of unknown parameters". The Equation (1) is as follows:

$$L(\theta) = \prod_{i=1}^{n} fx(x_i \mid \theta) \quad (1)$$

Stochastic analysis of some extreme hydrometeorological features (in our case, extreme maximum air temperatures) is essentially based on the adjustment of some theoretical probability distribution to the observed data. In this paper we used General Extreme Value (GEV), Normal, Log-Normal, Pearson 3, and Log-Pearson 3 distributions, and for that purpose we used EasyFit 5.0 trial version (MathWave Tecnologies, 2022) statistical software.

Probability density function of GEV distribution (parameters κ, σ, μ) is given in Equation 2:

$$f(x) = \begin{cases} \frac{1}{\sigma}\exp(-(1+kz)^{-\frac{1}{k}})(1+kz)^{-1-\frac{1}{k}} & k \neq 0 \\ \frac{1}{\sigma}\exp(-z-\exp(-z)) & k = 0 \end{cases} \quad (2)$$

where k is scale parameter, σ is shape parameter ($\sigma > 0$), μ is location parameter, and z is calculated as $z = (x - \mu) / \sigma$.

Probability density function of Normal distribution (parameters σ, μ) is given in Equation 3:

$$f(x) = \frac{\exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right)}{\sigma\sqrt{2\pi}} \quad (3)$$

where σ is scale parameter ($\sigma > 0$) and μ is location parameter.

Probability density function of Log-Normal distribution (parameters σ, μ) is given in Equation 4:

$$f_x(x) = \begin{cases} \dfrac{1}{x\sqrt{2\pi\sigma^2}} \exp\left(-\dfrac{1}{2}\dfrac{(\ln(x)-\mu)^2}{\sigma^2}\right) & \text{if } x \in R_x \\ 0 & \text{if } x \notin R_x \end{cases} \tag{4}$$

where σ is scale parameter ($\sigma > 0$) and μ is location parameter.

Probability density function of Pearson 3 distribution (parameters α, β, γ) is given in Equation 5:

$$f_x = \frac{1}{\beta\Gamma(\alpha)}\left(\frac{x-y}{\beta}\right)^{\alpha-1} e^{-(x-y)/\beta} \tag{5}$$

where α is shape parameter, β is scale parameter, γ is location parameter, and Γ is gamma function.

Probability density function of Log-Pearson 3 distribution (parameters α, β, γ) is given in Equation 6:

$$f_{(x)} = \frac{1}{x\,|\,\beta\,|\,\Gamma(\alpha)}\left(\frac{\ln(x)-y}{\beta}\right)^{\alpha-1} \exp\left(-\frac{\ln(x)-y}{\beta}\right) \tag{6}$$

where α is shape parameter, β is scale parameter, and γ is location parameter. The validation of the probability density functions proposed to fit empirical one(s) may be achieved by the application of several methods (graphical or analytical). Graphical methods are mostly grounded in the visual comparison of some probability density function and a certain empirical density function. Therefore this method is subjective to some extent. Because of the importance of the choice of the distributions proposed to fit the empirical one, it is reasonable to found such a choice on information from various objective methods. For that purpose, several formal/objective analytical tests have been proposed in order to test the goodness of fit of the assumed distributions (Shin et al., 2012). Among others goodness-of-fit criteria (Takara & Takasao, 1998), we chose three formal tests: Kolmogorov-Smirnov, Anderson-Darling, and chi-square test. We could have relied on the results of just one of these tests. Still, triangulation of methods, that is, the use of multiple methods, improves the validity of research findings (Mathison, 1988).

According to Lilliefors (1967) and dos Reis et al. (2022), the calculation of Kolmogorov-Smirnov statistic D is based on the largest difference between two distributions (theoretical and empirical cumulative distribution function). The D in Equation 7 is defined as:

$$D = \max_{1\le i\le n}\left[\left|\hat{F}(x_{(i)}) - \frac{i-1}{n}\right|, \left|\frac{i}{n} - \hat{F}(x_{(i)})\right|\right] \tag{7}$$

When $x_{(1)}, x_{(2)} \ldots x_{(k)}$ are the data ordered in an ascending order, then $\hat{F}$ is an estimation of cdf.

Anderson and Darling (1954) describe the test which gives more weight on the tails of a distribution where usually very small or big values are located. The test statistic in this test is defined in Equation 8:

$$A^2 = -n - \sum_{i=1}^{n} \frac{(2i-1)(\ln F_0[x_i] + \ln\{1 - F_0[x_{(n-i+1)}]\})}{n} \tag{8}$$

where the observations are ordered from the smallest to the biggest (Kottegoda & Rosso, 2008).

For the chi-square goodness of fit test, the test statistic in Equation 9 is defined as:

$$X^2 = \sum_{i=1}^{l} \frac{(O_i - E_i)^2}{E_i} \tag{9}$$

where O_i are observed frequencies and E_i are the expected frequencies in each class *i* out of the total of classes into which n observations are located.

Finally, we calculated the probability of exceedance of absolute maximum air temperatures for return periods of 100, 200, 500, and 1000 years. A return period might be defined as average time between exceedances of a specified value of some (climatological, hydrological, or other) feature. According to Plavšić (2006), if distribution function $F_{(x)}$ is defined, then classical definition of return period might be used (Equation 10):

$$T_x = \frac{1}{P\{X > x\}} = \frac{1}{1 - F_x}, \ x > X_0 \tag{10}$$

4. Results and discussion

The tested distributions for the data series from each of the stations are ranked according to the results from each of the mentioned tests. After that, average rank of each distribution is calculated (Table 1). Based on these results, theoretical distribution for the calculation of maximum air temperatures for different return periods is chosen. The highest frequency of the best average rank was found in GEV distribution (21 cases), followed by Log-Pearson 3 (seven cases), Normal distribution (five cases), Log-Normal (four cases), and Pearson 3 distribution (three cases). It was rather expected that GEV distribution will show the best results. According to Rypkema and Tuljapurkar (2021), the mathematical description of probability distribution of some extreme value is described by GEV distribution in a similar way as it is in Normal distribution. That is why GEV gives natural and good description of many extremes and has the long history in climatology and many other scientific disciplines (Coles, 2001; Gumbel, 1958). The best way for modeling a certain climate extreme (such is maximum air temperature) is to use extreme value theory (Hyndman & Fan, 2010). The records located around the central value are neglected in GEV methods and the parameters estimation of theoretical distribution is based on extreme values (Gençay & Selçuk, 2004). This approach augments its efficiency. Lazoglou et al. (2019) showed that GEV and General Parreto Distribuiotion (GPD) are appropriate for the modeling of extremely high or extremely low temperatures, while Goubanova and Li (2007) considered GEV distribution as an appropriate one to study different aspects of temperature extremes. According to dos Reis et al. (2022), in the modeling of some extreme events, GEV distribution shows a wide range of applicability in different scientific fields and it has been applied in many world regions (Reiss & Thomas, 2007).

Table 1. Average rank of goodness of fit tests: Kolmogorov-Smirnov, Anderson-Darling, and chi-square for theoretical distributions

Station name	Average rank of tested distributions				
	GEV	Log-Pearson 3	Lognormal	Normal	Pearson 3
Aleksandrovac	3.3	2.7	3.0	**2.3**	3.7
Babušnica	3.7	2.3	3.7	**1.7**	3.7
Bački Petrovac	**1.7**	3.0	3.3	5.0	2.0
Bečej	**1.7**	3.0	2.7	3.3	4.3
Beograd	**1.7**	2.0	4.0	5.0	2.3
Bosiljgrad	**1.7**	2.3	4.3	2.0	4.7
Ćuprija	**2.0**	2.3	2.7	3.3	4.7
Dimitrovgrad	4.3	2.3	**2.0**	3.3	3.0
Jagodina	2.0	3.7	**1.7**	3.0	4.7
Kikinda	**2.7**	3.0	3.0	3.0	3.3
Kragujevac	**1.0**	2.7	3.0	4.7	3.7
Kraljevo	**1.7**	2.3	4.0	5.0	2.0
Kruševac	3.3	2.0	3.7	4.7	**1.3**
Kuršumlija	3.7	3.0	**1.7**	2.7	4.0
Leskovac	4.3	4.7	2.7	2.0	**1.3**
Loznica	**1.0**	2.7	3.7	3.3	4.3
Negotin	2.7	**1.3**	4.0	4.3	2.7
Novi Pazar	4.0	**1.0**	4.0	2.3	3.7
Palić	**1.7**	3.3	3.0	4.0	3.0
Požega	2.0	**1.3**	4.0	4.7	3.0
Prizren	4.0	3.7	2.3	**1.7**	3.3
Prokuplje	**1.7**	2.0	4.0	5.0	2.3
Rimski Šančevi	2.0	**1.7**	3.7	5.0	2.7
Šabac	**2.0**	3.3	3.0	3.3	3.3
Senta	**1.0**	3.7	3.7	4.7	2.0
Sjenica	**1.0**	2.7	3.3	3.7	4.3
Smederevska Palanka	2.3	**2.0**	4.0	4.3	2.3
Sokobanja	2.3	**2.0**	3.7	2.3	4.7
Sombor	**2.0**	3.0	3.7	4.0	2.3
Sremska Mitrovica	**1.7**	3.0	2.7	4.7	3.0
Valjevo	**1.7**	2.0	3.7	4.0	3.7
Veliko Gradište	2.0	3.7	**1.7**	3.0	4.7
Vlasotince	**1.3**	3.3	3.7	2.7	4.0
Vranje	4.0	3.0	3.0	**1.7**	3.3
Vrnjačka Banja	**2.0**	2.3	3.0	4.3	3.3
Vršac	2.0	3.3	**1.7**	3.7	4.3
Žagubica	2.3	2.3	4.0	**1.3**	5.0
Zaječar	2.3	**2.3**	3.7	4.0	2.7
Zlatibor	**1.7**	2.7	3.0	3.7	4.0
Zrenjanin	2.0	2.3	4.3	4.7	**1.7**

Note. The best ranked distributions are bolded.

At almost all the stations, the highest air temperatures are observed during July. Also, absolutely the highest maximum of air temperature for the observed period was measured on July 24, 2007. This heat wave lasted ten days (from July 15, 2007 to July 24, 2007) with the maximum intensity on July 24, 2007 (Drljača et al., 2009). An analysis of synoptic maps of sea level pressure for this date indicated the existence of cyclone system over the British Isles which allowed intense moving of hot and dry air masses with the origin in North Africa toward Balkan Peninsula. As a consequence of such a persistent advection, the previous air temperature records were exceeded at almost all stations in Serbia (Milovanović, Radovanović, et al., 2017). The highest air temperature of 44.9 °C in Serbia was recorded at Smederevska Palanka station on July 24, 2007 (Figure 1; Table 2). This station is located in the valley and has a specific micro location with southern exposition which is convenient for the additional cooling of air during winter and additional warming of air during summer time in stable atmospheric conditions. This might be a reason for the appearance of extremely high or extremely low air temperatures comparing to the wider area, or even comparing to the entire territory of Serbia (Andjelković, 2007). Besides Smederevska Palanka, on the mentioned date, the maximum air temperatures above 44.0 °C were recorded at just three more stations (Zaječar—44.7 °C, Ćuprija—44.6 °C, and Vrnjačka Banja—44.1 °C). As expected, the lowest values of maximum air temperature were observed at two stations with the highest altitude—Zlatibor station (35.8 °C) and Sjenica station (36.2 °C). At nine stations (Bački Petrovac, Negotin, Palić, Prizren, Prokuplje, Šabac, Senta, Sombor, and Žagubica), the observed values of maximum air temperatures are lower than the calculated ones for the 100-year return period. At three stations (Bečej, Požega, and Valjevo), the observed values of maximum air temperatures are equal to those calculated for the 100-year return period, and at another three stations (Aleksandrovac, Kikinda, and Kragujevac) they are equal to those for the 200-year return period. At the highest number of stations (Babušnica, Bosiljgrad, Ćuprija, Dimitrovgrad, Kraljevo, Kruševac, Leskovac, Loznica, Rimski Šančevi, Smederevska Palanka, Sremska Mitrovica, Zaječar, and Zlatibor—13 in total), the observed values of maximum air temperatures have calculated values that correspond to those between 100- and 200-year return period. At another nine stations (Belgrade, Jagodina, Kuršumlija, Novi Pazar, Sokobanja, Vlasotince, Vranje, Vrnjačka Banja, and Zrenjanin), the observed values can occur once between 200 and 500 years. At two stations (Veliko Gradište and Vršac), the observed values of maximum air temperatures correspond to those calculated for the return periods between 500 and 1000 years. At only one station (Sjenica), the observed value is equal to the one calculated for 1000-year return period.

The highest values of maximum air temperatures for all the return periods are calculated for Zaječar station (from 44.5 °C for a 100-year return period to 48.0 °C for 1000-year return period). Slightly lower values are calculated for Smederevska Palanka station (from 44.4 °C for a 100-year return period to 47.9 °C for 1000-year return period). It should be noticed that in Belgrade, which is on a very similar altitude as the previously mentioned stations and is well-known as urban heat island (Andjelković, 2005), the calculated values of maximum air temperatures are 1.8–3.2 °C lower than those at previously mentioned stations. Furthermore, in Belgrade, the value of 44.8 °C calculated for 1000-year return period is still 0.1 °C lower than the one measured in Smederevska Palanka on July 24, 2007. On the other hand, it is interesting that though the lowest observed value of maximum air temperature was recorded at Zlatibor station, the lowest calculated values for all the return periods are calculated for Sjenica station. At Zlatibor station, the calculated values range from 35.6 °C for 100-year return period to 36.5 °C for 1000-year return period. Those values are only 0.1–0.3 °C higher than calculated ones for Sjenica station—35.5 °C for a 100-year return period and 36.2 °C for 1000-year return period (Table 2).

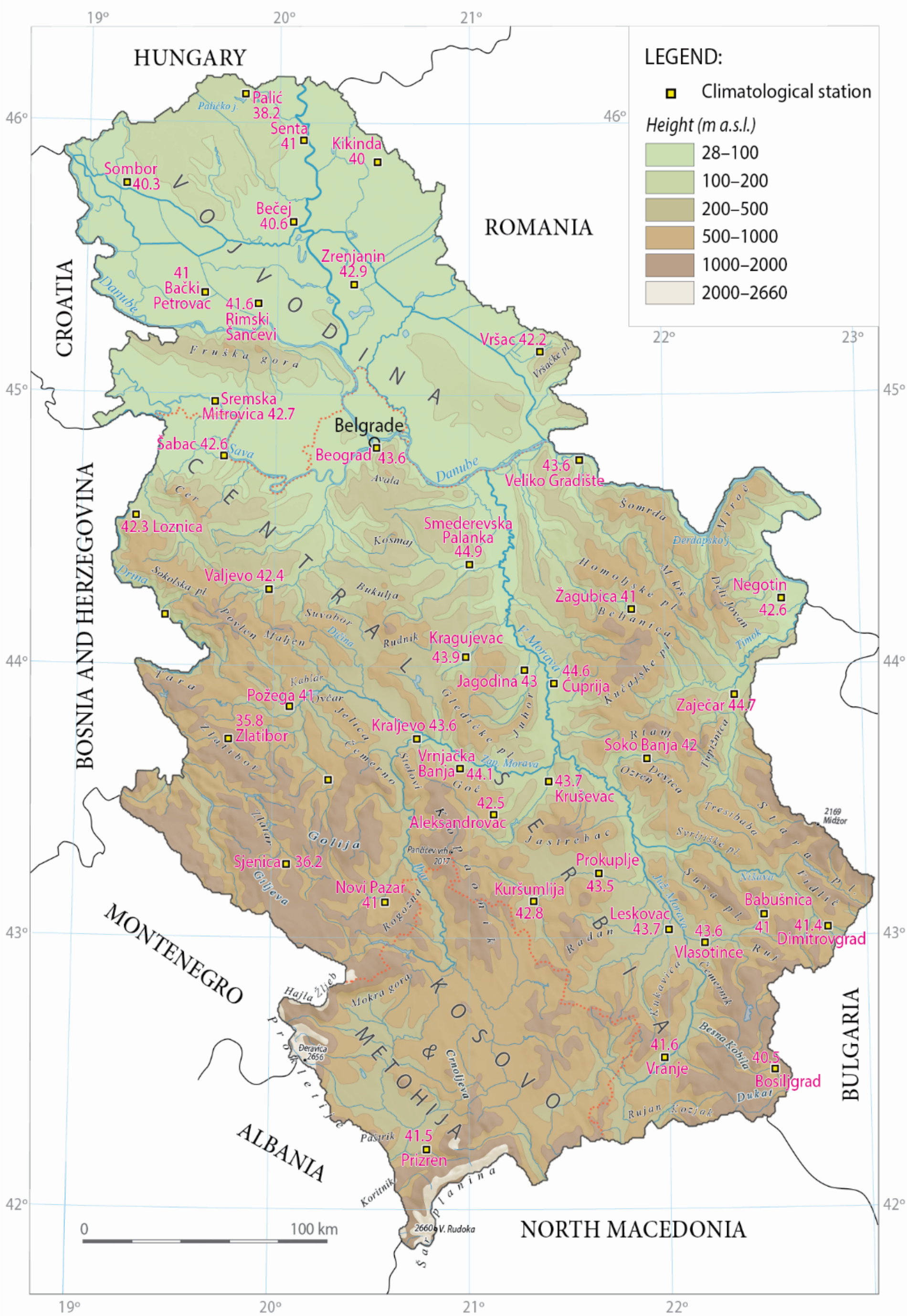

Figure 1. Climatological stations in Serbia with the observed maximum air temperatures (1961–2010).

Table 2. Observed absolute maximum air temperatures (1961–2010 period) and modeled values for different return periods

Station	Latitude (°N)	Longitude (°E)	Height (m a.s.l.)	Observed Tmax (°C)	Tmax Ret. period 100	Tmax Ret. period 200	Tmax Ret. period 500	Tmax Ret. period 1000
Aleksandrovac	43.45	21.07	360	42.5	41.8	42.5	43.3	43.9
Babušnica	43.07	22.43	495	41	40.8	41.4	42.1	42.6
Bački Petrovac	45.37	19.57	85	41	41.6	42.2	42.9	43.4
Bečej	45.63	20.03	75	40.6	40.6	41.1	41.8	42.2
Beograd	44.8	20.47	132	43.6	42.6	43.3	44.2	44.8
Bosiljgrad	42.5	22.47	830	40.5	40.3	40.7	41.1	41.4
Ćuprija	43.93	21.38	123	44.6	44.1	44.9	45.8	46.4
Dimitrovgrad	43.02	22.75	450	41.4	41.2	41.9	42.7	43.2
Jagodina	43.98	21.23	115	43	42.6	43.2	44.0	44.6
Kikinda	45.85	20.47	81	40	39.7	40.1	40.5	40.8
Kragujevac	44.03	20.93	185	43.9	43.2	43.9	44.7	45.3
Kraljevo	43.73	20.68	215	43.6	43.3	44.3	45.4	46.3
Kruševac	43.57	21.35	166	43.7	43.5	44.4	45.5	46.3
Kuršumlija	43.13	21.27	382	42.8	41.8	42.5	43.3	43.9
Leskovac	43.02	21.95	230	43.7	43.5	44.3	45.4	46.1
Loznica	44.55	19.23	121	42.3	41.9	42.5	43.1	43.5
Negotin	44.23	22.55	42	42.6	42.8	43.7	44.9	45.8
Novi Pazar	43.13	20.52	545	41	40.5	40.8	41.1	41.3
Palić	46.1	19.77	102	38.2	39.1	39.5	40	40.3
Požega	43.85	20.03	310	41	41	41.7	42.6	43.2
Prizren	42.22	20.73	402	41.5	42.1	42.6	43.4	43.9
Prokuplje	43.23	21.6	266	43.5	43.6	44.3	45.1	45.6
Rimski Šančevi	45.33	19.85	84	41.6	41.3	42	43.1	43.8
Šabac	44.77	19.68	80	42.6	43	43.7	44.6	45.2
Senta	45.93	20.08	80	41	41.8	42.5	43.5	44.2
Sjenica	43.27	20.02	1038	36.2	35.5	35.8	36.1	36.2
Smederevska Palanka	44.37	20.95	121	44.9	44.4	45.5	46.9	47.9
Sokobanja	43.65	21.85	300	42	41.2	41.7	42.4	42.8
Sombor	45.77	19.15	88	40.3	40.4	40.9	41.5	41.9
Sremska Mitrovica	44.97	19.63	81	40.7	40.6	41.2	41.8	42.2
Valjevo	44.28	19.92	176	42.4	42.4	42.9	43.5	43.9
Veliko Gradište	44.75	21.52	82	43.6	41.8	42.5	43.3	43.9
Vlasotince	42.97	22.13	271	43.6	42.8	43.4	44.2	44.7
Vranje	42.55	21.92	432	41.6	41	41.5	42.2	42.7
Vrnjačka Banja	43.62	20.9	235	44.1	43	43.7	44.6	45.2
Vršac	45.15	21.32	84	42.2	40.7	41.3	42.1	42.6
Žagubica	44.2	21.78	314	41	41.1	41.7	42.5	43.1
Zaječar	43.88	22.3	144	44.7	**44.5**	**45.6**	**47.0**	**48.0**
Zlatibor	43.73	19.72	1028	35.8	35.6	36	36.3	36.5
Zrenjanin	45.4	20.35	80	42.9	41.3	42.1	43.1	43.9

Note. The highest values for return periods are bolded.

It is interesting to notice that the highest absolute maximum air temperatures for 1000-year return period (temperatures above 46.0 °C) are calculated mostly for the stations located in the valleys or the rear of the Zapadna Morava, Južna Morava, Velika Morava, and Veliki Timok River valleys. Stations with the calculated values for this return period with temperature range from 43.0 to 46.0 °C are heterogeneously dispersed through the entire territory of Serbia. The same might be stated for the spatial distribution of the stations for which the temperature range is between 40.0 and 43.0 °C. Stations with the calculated air temperatures below 40.0 °C are located in southwestern (mountainous) part of Serbia (Table 3). Although temperature ranges are somewhat arbitrary, it is obvious that for the values of maximum air temperature calculated for other return periods, different thresholds must be defined. Even then, similar spatial pattern might be observed—e.g., for 500-year, 200-year and 100-year return periods (temperature thresholds of 45.0 °C, 44.0 °C, 43.0 °C respectively) only two stations (Prokuplje and Kragujevac) could be added to the warmest category. On the other hand, into the coldest category there are always Sjenica and Zlatibor stations. Stations within the categories between the warmest and coldest one are dispersed through the entire territory of Serbia without any notable spatial pattern. Still, for possible depiction of homogenous regions with similar temperature features, different methodological approach with the usage of adequate analytical tools is needed.

Table 3. Stations within different classes of calculated absolute maximum temperatures for 1000-year return period

Station name	Temperature range (°C)
Leskovac, Kraljevo, Kruševac, Ćuprija, Smederevska Palanka, Zaječar	> 46.0
Žagubica, Dimitrovgrad, Požega, Bački Petrovac, Loznica, Rimski Šančevi, Aleksandrovac, Kuršumlija, Prizren, Valjevo, Veliko Gradište, Zrenjanin, Senta, Jagodina, Vlasotince, Beograd, Šabac, Vrnjačka Banja, Kragujevac, Prokuplje, Negotin	43.0–46.0
Palić, Kikinda, Novi Pazar, Bosiljgrad, Sombor, Bečej, Sremska Mitrovica, Babušnica, Vršac, Vranje, Sokobanja	40.0–43.0
Sjenica, Zlatibor	< 40.0

On a global scale, the highest values of daily maximum temperatures that occurred once in every twenty years in the 1981–2000 period, will occur in every five years in the period 2046–2065. At the end of the century (2081–2100), it will occur in every one or two years (Intergovernmental Panel on Climate Changes, 2012). In Europe, in the near future (2020–2030) there is likely to be the rise in daily maximum temperatures in summer of up to +1.7 °C (European Environmental Agency, 2017). Auld et al. (2021), by analyzing the gridded dataset of daily temperatures in Europe, noticed that there are changes in statistical distribution for the period 1950–2018. Those changes are the most obvious in the GEV location parameter with the distribution of daily maximum temperatures moving toward higher values (values based on 2018 are 2 °C higher than those based on 1950). Within the Balkan Peninsula and in the countries surrounding Serbia, changes in absolute maximum temperatures are also detected. An increase of maximum temperatures is recorded in Bosnia and Herzegovina (Popov et al., 2018), Montenegro (Burić et al., 2014), Bulgaria (Alexandrov, 2005), Romania (Croitoru & Piticar, 2013), and Croatia (Branković et al., 2013). As a summary for the mentioned areas, Kuglitsch et al. (2010) found that maximum temperatures in the period 1960–2010 rose for ~0.38 °C per decade. Spatial distribution of maximum air temperatures in Serbia and its connection with the atmospheric circulation, i.e., dependence of absolute maximum air temperatures on warm and dry continental tropical air masses is shown in Milovanović, Radovanović, et al. (2017). Annual maximum temperatures in Serbia are characterized by downward trend in 1961–1980 and upward trend during 1981–2010 (Ruml et al., 2017). Although the mentioned studies focus on particular countries and provide some information about the spatial and temporal characteristics of maximum air temperatures, their results are based solely on the trend analysis. To the best of authors' knowledge, a frequency analysis of the absolute maximum air temperatures has been done only for Belgrade by Unkašević and Tošić (2009). Based on the data from the period 1888–2003, they found that at this meteorological station the highest absolute maximum air temperature observed is 41.8 °C. By fitting GEV distribution, they calculated the value of 41.2 °C for a 100-year return period. Our analysis has shown that in the period 1961–2010, the highest absolute maximum air temperature observed in Belgrade was 43.6 °C, which is 1.8 °C higher than the previous one. For a 100-year return period we calculated the value of 42.6 °C, which is 1.4 °C higher than the one shown in Unkašević and Tošić (2009).

5. Conclusion

The main findings of this paper refer to the absolute maximum air temperatures in Serbia. An analysis of the datasets from 40 climatological stations for the period 1961–2010 has shown that the observed maximum air temperatures range from 35.8 °C at Zlatibor station (one of the two stations located above 1000 m a.s.l.) to 44.9 °C at Smederevska Palanka station. The main cause of the appearance of extremely high maximum air temperatures in Serbia is the specific synoptic situation which is characterized by constant inflow of warm and dry air from the southwest direction (with the origin of air masses in North Africa). Still, relief—through its altitude and local terrain features – also has certain impact on the values of absolute maximum air temperatures. A frequency analysis of the datasets is done by AMS approach and with MLE method of parameter estimation of the assumed distributions. Three different tests (Kolmogorov-Smirnov, Anderson-Darling, chi-square test) of goodness of fit between empirical and assumed theoretical distributions were used. It is shown that in most cases GEV distribution is the most appropriate one for modeling absolute maximum air temperatures in Serbia. Other tested distributions (Log-Pearson 3, Normal distribution, Log-Normal, and Pearson 3 distribution) were less successful. The highest values of 44.5 °C, 45.6 °C, 47.0 °C, and 48.0 °C for the return periods of 100, 200, 500, and 1000 years, respectively, were calculated for the eastern part of Serbia at Zaječar station. On the other hand, the lowest values of 35.5 °C, 35.8 °C, 36.1 °C, and 36.2 °C for the return periods of 100, 200, 500, and 1000 years, respectively, were calculated for the southwestern part of Serbia (Sjenica station—one of the stations with the highest altitude). Because of the characteristics of the datasets we had (only one value of the absolute maximum air temperature per year), we were not able to deal with heat waves issues in Serbia. Also, analysis is done only for particular stations, and no intepolation has been performed for the whole territory of Serbia. Still, to the best of authors' knowledge, this study is the first one which treats absolute maximum air temperatures in Serbia on such a large number of climatological stations in a stochastic manner. Although there was a limitation in the data availability (lack of the climatological stations on the higher altitudes and especially on Kosovo and Metohija), the results of this study could provide a solid basis for the spatial modeling of the observed and calculated absolute maximum air temperatures in dependence of the terrain characteristics. Such a model could be included in planning and development of infrastructure in order to prevent and minimize risks of major damages in many spheres of human existence, i.e., agriculture, healthcare system, water resource management, energy system etc. Furthermore, in the future research, comparison of the achieved results with the extended dataset (period 1961–2020) analysis, it will be possible to assess spatial distribution of climate fluctuation signal on the territory of Serbia.

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