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Temporal Analysis of Urban-Suburban PET, mPET and UTCI Indices in Belgrade (Serbia)

Milica Pecelj [1,2,*], Andreas Matzarakis [3,4], Mirjam Vujadinović [5], Milan Radovanović [1,6], Nemanja Vagić [7], Dijana Đurić [8] and Milena Cvetkovic [7]

[1] Geographical Institute "Jovan Cvijić" Serbian Academy of Science and Arts, Djure Jakšića Street 9, 11000 Belgrade, Serbia; m.radovanovic@gi.sanu.ac.rs
[2] Department of Geography, Faculty of Philosophy, University of East Sarajevo, Alekse Šantića Street 1, 71432 Pale, Republic of Srpska, Bosnia and Herzegovina
[3] Research Centre Human Biometeorology, Deutscher Wetterdienst, Stefan-Meier-Str. 4, 79104 Freiburg, Germany; andreas.matzarakis@dwd.de
[4] Institute of Earth and Environmental Sciences, University of Freiburg, 79085 Freiburg, Germany
[5] Faculty of Agriculture, University of Belgrade, Nemanjina Street 6, 11000 Belgrade, Serbia; mirjam.mv@gmail.com
[6] Institute of Sports, Tourism and Service, South Ural State University, Sony Krivoy Street 60, 454080 Chelyabinsk, Russia
[7] Faculty of Geography, University of Belgrade, Studentski Trg 3, 11000 Belgrade, Serbia; vagic@live.com (N.V.); milena.cvetkovic4@gmail.com (M.C.)
[8] Faculty of Civil Engineering Subotica, University of Novi Sad, Kozaračka 2a, 21102 Novi Sad, Serbia; dijana.djuric.gf@gmail.com
* Correspondence: m.pecelj@gi.sanu.ac.rs or milica.pecelj@ffuis.edu.ba

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Abstract: The analysis of the bioclimatic conditions is becoming increasingly relevant in climate interpretations for human needs, particularly in spatial planning, tourism, public health, sports events, bio-prognosis, etc. In this context, our study presents general temporal bioclimatic conditions in Belgrade, defined based on the PET, mPET and UTCI heat budget indices. Monthly, seasonal and annual indices were analyzed for urban and suburban weather stations based on 43 annual sets of meteorological data obtained by hourly observations at 7 h and 14 h CET. This study aims to present the distribution of PET, mPET and UTCI indices to show the pattern of each index in a mild climate location and to examine annual and seasonal differences of each index in the Belgrade urban center and suburban part of the city. The study results indicate higher biothermal stress in the urban area compared to the suburban zone and that the indices are congruent during the summer. At the same time, during the winter, they are more difficult to compare due to their peculiarities becoming more noticeable. The results obtained of all mean monthly and mean annual values of all three indices clearly indicate the difference that follows the definition of the urban heat island (UHI), particularly those from morning observation and winter season. The UTCI index shows the most significant monthly, seasonal and annual difference between urban and suburban areas for both observations. The annual difference of $\Delta UTCI_{7h}$ amounts to 1.5 °C is the same as the annual difference of minimum temperatures (Δtmin). In contrast, the annual differences of ΔPET_{7h} $\Delta mPET_{7h}$ are °smaller (0.8 °C and 0.7 °C) and closer to the annual differences of maximum temperatures Δtmax amounted of 0.6 °C.

Keywords: biothermal conditions; PET; mPET; UTCI; urban-suburban area; Belgrade

1. Introduction

A large portion of the world's population lives in tightly built and thus densely populated urban areas. The urbanization process accounts for many ecological problems impacting human health, the most typical being pollution and increase in heat stress in some parts of urban heat islands (UHI). Many climate changes generated by the urban environment negatively affect people's health and quality of life. Some examples are higher night temperatures during the summer and weak ventilation, leading to increased overall temperature and air pollution. Studies of the Belgrade climate conducted to date have mostly been based on individual meteorological parameters used for the analysis of the urban climate characteristics. These mainly referred to the characteristics of urban heat islands defined by average air temperatures or extreme air temperatures [1–7], air humidity characteristics in urban and suburban areas [8] and heatwave analysis [9–19]. Regarding the assessment of bioclimatic indices, simple index Steadman apparent temperature [20] was analyzed by Stanojevic et al. [21] and Humidex by Lukic [22], while in terms of the heat budget indices, an analysis of heat load (HL) on man derived from Menex model [23,24] and UTCI only for extreme months, January and July [25], were analyzed for Belgrade no more than a ten-year data series. The previous literature review on heat budget indices in Belgrade indicates the possibilities for a more detailed review of urban and suburban biothermal conditions.

It seems important to recognize that the air temperature is not the only i parameter which can describe the overall effect of weather and climate conditions on human health particularly because of thermal risk factors shown by climate change projections for the end of the century [26,27]. Together with the air temperature, air humidity, wind velocity and radiation count as important factors in the context of subjective thermal sensations and assessments of meteorological conditions, i.e., thermal comfort. Subjective thermal comfort sensations are also affected by the (weak, medium or intensive) physical activity manifested by the physiological component of the metabolic energy and the clothing insulation. Additionally, urban environment characteristics (open sky, shades, city traffic, parks, etc.) profoundly impact the subjective weather perception. The causes of UHI can be attributed to the geometric effects of the city center where the weather station is located. Compact buildings in the city center absorb sunlight, increasing heating efficiency in the central city zone. Furthermore, the position of buildings often causes the wind to be blocked, which increases the UTCI in particular. Waste heat from cars, air conditioning, industry and other sources also contributes to UHI because many forms of pollution change the air properties of the atmosphere [28].

Biometeorological and bioclimatic conditions analysis is becoming increasingly significant in the climate interpretation for various needs, such as spatial planning, tourism, public health, bio-prognosis, etc. Several bioclimatic indices have been developed whose model is based on meteorological and physiological parameters. These are heat budget indices based on the human heat balance, i.e., heat balance between people and their environment, which provides positive feedback on temperature deviations from neutral conditions of the body core and skin like in nature [29]. The analysis of the urban bioclimate conditions and adaptation measures is necessary to improve city residents' biothermal conditions, health and well-being.

The role of human bioclimatology within interdisciplinary research has been steadily growing for the past 20 years. We witnessed a considerable increase in the number of publications containing thermal indices analysis during the past decade, covering large spatial dimensions and conducted in various geographical regions, indicating a prevalent use of the UTCI and PET budget indices in this subject. One of the most frequently implemented bioclimate thermal indices in the past twenty years is the physiologically equivalent temperature (PET) which is used to determine the human thermal comfort [30–32], recently updated as modified physiologically equivalent temperature (mPET) [33–35].

A more recently developed thermal index called the Universal Thermal Climate Index (UTCI) is also frequently implemented in the bioclimatic and biometeorological research. It is based on thermo-physiological modeling of human response to meteorological conditions, including acclimatization. The UTCI is developed under the framework of the International Society of Biometeorology (ISB) and COST Action 730 and is supported by the EU RTD Framework Program [36]. The UTCI index is primarily implemented in Europe [37–49] but also in some other geographical regions, such as Brasil [50], Iran [51,52], India [53], China [53,54], and Japan [55]. According to Jendritzky [36], thermal environment assessment is one of the basic issues in human biometeorology. Being applicable in a wide range of geographic and climatic regions, the UTCI can undoubtedly be implemented in human biometeorology, such as daily forecasting and warnings, urban and regional planning, environmental epidemiology and climate impact research [56].

While some climatology analysis based on individual meteorological parameters was carried out for Belgrade, a human bioclimatic analysis for urban-suburban area based on PET and UTCI indices is still open for urban bioclimate research. This study aims to present the distribution of PET, mPET and UTCI indices and determine their differences in the urban and suburban parts of the city. Another objective of this paper is to show the pattern of each index due to the thermal stress in a mild climate location and examine annual and seasonal PET, mPET and UTCI differences in Belgrade. Furthermore, its goal is to point out the necessity of urban bioclimatological assessment to closely define Belgrade's thermal environment and its thermal hotspots in the context of the human experience of meteorological conditions and outdoor thermal comfort. The study is based on hourly data obtained from urban and suburban weather stations for 43 years. The case study is the city of Belgrade in Serbia, which according to Köppen-Geiger classification, has a temperate climate (Cfa) [57].

2. Materials and Methods

This chapter presents details of the area covered by the research ((i) Study area), data obtained from the meteorological stations ((ii) Data description) and methods used in the analysis ((iii) Methods).

2.1. Study Area

Serbia's capital Belgrade follows the definition of urban heat island (UHI), with a positive thermal balance between the urban area and surrounding rural area [1–7]. The city is faced with an increasing frequency of heatwaves every summer [8]. It is located in South-Eastern Europe or Western Balkans (Figure 1a). According to the Comparative overview of the population carried out in 2011, Belgrade had 1,166,763 residents in the city area and 1,659,440 residents in the overall administrative area. Almost 16% of the Serbian population lives in the city [58]. Belgrade is situated in South-Eastern Europe on the Balkan Peninsula, at the point where the Sava river merges with the Danube river. Its surroundings is divided into two geographic regions, Panonian plain in the north and Šumadija in the south. The broader territory of the city covers artificial ecosystems of wheat and maize in the north and orchards and vineyards in the south. The highest forms of relief are the low mountains Kosmaj (628 m) and Avala (511 m).

According to Köppen–Geiger Climate Classification [59], the territory of Serbia (Figure 1b) is characterized by warm temperate humid climate type with warm summers, Cfb type with maximum precipitation during late spring and early summer. Belgrade's climate has mainly temperate continental characteristics, categorized as Cfa according to the Köppen climate classification [57]. The mean annual air temperature in Belgrade for the period of 1961–1990 was 11.9 °C. It should be noted that this temperature was measured at the observation point located in the very center of the city, where the heat island effects dominate. According to Gburcik [60], the average annual temperatures in the suburbs and the higher locations are around 11.0 °C. The average temperature of the first decade of the 20th century was 11.3 °C, while in the last decade it amounted to 12.5 °C. This growth of the temperature rate can be attributed to the increasing urbanization and the presence of the heat island.

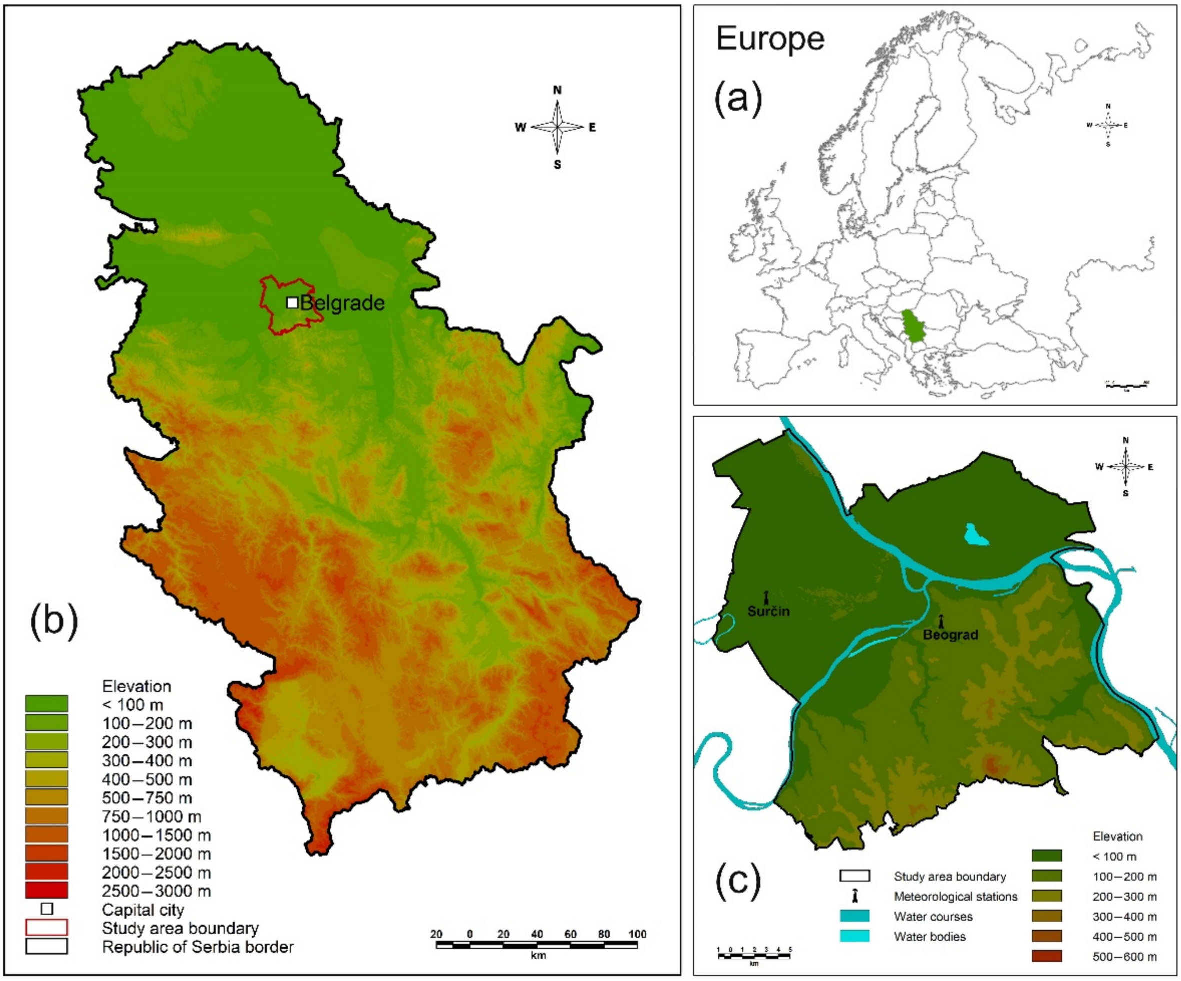

Figure 1. The geographical position of the research area: Serbia's position in Europe (**a**) Relief map of Serbia (**b**) Relief map of Belgrade (**c**).

The total area covered by the research is 779.9 km^2, of which the largest part amounting to 438.4 km^2 (56%) is situated at 100 m above the sea level. An area of 250.9 km^2 (32%) is situated between 100 and 200 m, 85.5 km^2 (11%) are situated between 200 and 300 m above the sea level, while the area of 5.5 km^2 (1%) lies between 300 and 500 m above the sea level. (Figure 1c).

2.2. Data Description

Daily maximum and minimum air temperatures, together with hourly (7 h, 14 h CET) air temperatures, wind speed and relative humidity cloud cover, were collected from a database available from 1976 to 2018. The hours 7 h, and 14 h CET correspond to the most common time for daily minimum and maximum temperature. The data set from 1976 was chosen to follow the rapid urbanization of Belgrade that started in the late 1970s. The observations were obtained from the National Weather Service of Serbia, situated in the Belgrade Meteorological Observatory, located in the city center's park area and at the weather station in Surcin located at the Belgrade airport (Figure 1c). The station in the city center is situated at 132 m above mean sea level (geographical coordinates: $\varphi = 44°48'$ N and $\lambda = 20°28'$ E), while the station at the airport is situated at 99 m above mean sea level (geographical coordinates: $\varphi = 44°49'$ N and $\lambda = 20°17'$ E). Therefore, most of the area studied (88%) is where the stations are located (99 m and 132 m) is up to 200 m above sea level, which allows the comparison of the data obtained.

2.3. Method

This research applied the PET index and its modification mPET index together with the UTCI index for calculating the objective human thermal sensation.

Physiologically equivalent temperature (PET) is one of the most common thermal indices and certificated by the German VDI-Guidelines 3787, Part 2 [61]. According to the definition given by Höppe [32], physiologically equivalent temperature (PET) represents air temperature at which, in a typical indoor setting, the heat balance of the human body is maintained with core and skin temperatures equal to those under the conditions being assessed. It is based on the Munich Energy-balance Model for Individuals (MEMI), a two-node thermo-physiological heat-balance model and the mean radiant temperature (Tmrt). The PET was calculated using the RayMan model [62,63]. The RayMan model was described in VDI Guideline 3787 of the German Engineering Society (Verein Deutscher Ingenieure) as "Methods for the Human-Biometeorological Assessment of Climate and Air Hygiene for Urban and Regional Planning" [61]. Its purpose is to calculate the radiation flux in simple and complex environments on the basis of various parameters, such as air temperature, air humidity, wind velocity, degree of cloud cover, time of day and year and the albedo of the surrounding surfaces' elevation and location. The application of the RayMan model is used to determine thermal comfort conditions from relevant meteorological and human body variables and requires adjustment of the following constants: body surface standardized to 1.9 m^2, which represents a human with a height of 1.75 m, and a bodyweight of 75 kg [30], the rate of metabolic energy transformation (work metabolism) based on 80 W for a standing person and the insulation factor of clothing standardized to 0.9 [61]. Particular ranges of PET are categorized according to thermal stress (Table 1).

The modified physiologically equivalent temperature (mPET) originates from PET (see above), which is a more realistic demonstration of the human thermal comfort in different climate zones. The meteorological input data are similar to PET and for a better correlation, mPET uses the same classification as PET (Table 1) since the results range within the same spectrum. Unlike PET, mPET uses a multi-node heat transport model equal to the Fiala model [64] and a self-adapting multi-layer clothing model, which includes the simulation of water vapor resistance. Hence, mPET integrates clothing behaviors depending on given thermal conditions, which was the main disadvantage of PET [33]. The RayMan model allows the calculation of mean radiant temperature (T_{mrt}), an important variable for the estimation of PET and mPET. The model was established to combine biometeorology with urban climatology and can be used in other fields, like tourism and recreational studies.

Table 1. Thermal perception and stress classification of Physiological Equivalent Temperature (PET) [31] and Universal Thermal Climate Index (UTCI) [65].

PET (°C)	Grade of Physiological Stress	Abbr.	UTCI (°C)	Grade of Physiological Stress	Abbr.
>41	extreme heat stress	EHS	>46	extreme heat stress	EHS
35 to 41	strong heat stress	SHS	38 to 46	very strong heat stress	VSHS
29 to 35	moderate heat stress	MHS	32 to 38	strong heat stress	SHS
23 to 29	slight heat stress	SLHS	26 to 32	moderate heat stress	MHS
18 to 23	no thermal stress	NTS	9 to 26	no thermal stress	NTS
13 to 18	slight cold stress	SLCS	0 to 9	slight cold stress	SLCS
8 to 13	moderate cold stress	MCS	0 to −13	moderate cold stress	MCS
4 to 8	strong cold stress	SCS	−13 to −27	strong cold stress	SCS
<4	extreme cold stress	ECS	−27 to −40	very strong cold stress	VSCS
			<−40	extreme cold stress	ECS

By definition, the UTCI represents the equivalent ambient temperature of the reference environment that would elicit the same physiological response from a reference person as the actual environment [66]. In other words, the heat exchange between a person and the environment depends only on the air temperature, with other meteorological parameters at a constant level [67]. UTCI values are a measure of the thermal stress in a person (Table 1). The development of the UTCI was aimed at the production of an international standard index based on scientific progress in thermo-physiological modeling of human response to meteorological conditions, including the acclimatization issue [36]. The UTCI represents various weather conditions very well and is very sensitive to changes in temperature, humidity, solar radiation and wind speed. This is derived from the multi-dimensional dynamic response of a state-of-the-art multi-node thermo-physiological model of human heat transfer and thermoregulation [68]. UTCI can only be approximated for appropriate use using a regression equation abbreviated from sample calculations performed by computing centers [36,69]. It causes a narrow range of input parameters it can manage with. For the reference environment, the ISB Commission on the UTCI decided to use: (i) a wind speed (v) of = 0.5 m·s^{-1} at 10 m height (approximately = 0.3 m·s^{-1} at 1.1 m), (ii) a mean radiant temperature (Tmrt) equal to air temperature, (iii) vapor pressure (vp) that represents a relative humidity (f) of 50%; at high air temperatures (>29 °C) the reference humidity was taken to be constant at 20 hPa [66]. Physiological parameters, the metabolic rate (M) and the thermal properties of clothing (clothing insulation, permeability) are taken as universal constants in the model due to the evaluation by means of the regression equation. This implies an outdoor activity of a person walking at the speed of 4 km·h^{-1} (1.1 m·s^{-1}), corresponding to heat production of 135 W·m^{-2} (2.3 MET) of metabolic energy [36] and the clothing insulation, which is self-adapting according to the environmental conditions [70]. Clothing insulation, vapor resistance and the insulation of surface air layers are strongly influenced by changes in wind speed and body movement and will therefore also influence physiological responses [67].

The UTCI index has both great advantages and some weaknesses. One of them is a lack of reduce wind speed to human-biometeorological reference height (1.1 m a.s.l.) and estimation of Tmrt (mean radiation temperature) which is calculated on the basis of solar radiation. Since the solar radiation measurements are relatively rare, Tmrt was calculated indirectly considering cloudiness and geographical position of measurement point using BioKlima software package [71]. Particular ranges of UTCI are categorized according to thermal stress (Table 1).

Differences between the incoming parameters used for calculations of PET and UTCI are the following: wind speed for the PET index was reduced to 1.1m a.s.l., which is equivalent to a standing person's body center, while the wind velocity value used for UTCI is 10 m a.s.l. Another important difference between PET and UTCI is that the PET model is always based on the 0.9 clo clothing parameter, while the UTCI index model adjusts the clothing parameter by adapting to the specific exterior conditions [36].

Applied human bioclimatological methods and data collection from the urban and suburban area of Belgrade are essential for evaluations of biothermal conditions. The obtained PET, mPET and UTCI indices are presented with morning PET_{7h}, $mPET_{7h}$ and $UTCI_{7h}$ indices and midday PET_{14h}, $mPET_{14h}$ and $UTCI_{14h}$ indices. These hours correspond to the most common time for daily minimum and maximum temperatures. They are given by months for both stations to identify the general stress classes. The quantification of human bioclimatic conditions in Belgrade and Surcin was designed for each index on a daily basis of each defined stress category. To obtain a better insight into indices values for the investigated period, averaged UTCI, PET and mPET at 7 h and 14 h together with time series and trends was provided for each year. Further, the mean monthly values of all indices, including their mean seasonal and mean annual values for the period observed (1978–2018) were presented. The wind speed was recalculated for a height of 1.1 m above the surface using Hellman's exponential law [72] that correlates the wind speed readings at two different heights as follows in Formula (1)

$$\frac{v}{v10} = \left(\frac{H}{H10}\right)^{\alpha}, \tag{1}$$

where v is the wind speed at height H = 1.1 m, v_{10} is the wind speed at height H_{10} = 10 m and α is the friction coefficient (Hellman exponent). We used α = 0.40 for the urban area and α = 0.30 for the rural area.

The next part of the study examines the differences in PET, mPET and UTCI indices between Belgrade (urban area) and Surcin (suburban area) in order to verify to what extent the differences between the bioclimatic indices ΔPET, ΔmPET and ΔUTCI follow the definition of the urban heat island. Since the minimum temperature has been most powerfully affected by urban heat island, mean monthly minimum and maximum temperatures (tmin and tmax) in the central Belgrade area and in the suburbs are compared with urban-suburban differences of heat budget indices. This is confirmed by the differences between the absolute minimum and absolute maximum temperatures (Δtmin and Δtmax) and differences between the absolute minimum and maximum heat budget indices. Variables ΔPET, ΔmPET, ΔUTCI, Δtmin and Δtmax represent the differences of PET, mPET, UTCI, tmin and tmax between Belgrade and Surcin and are expressed with Formulas (2)–(6):

$$\Delta PET = PET_{BG} - PET_{SU} \quad (2)$$

$$\Delta mPET = mPET_{BG} - mPET_{SU} \quad (3)$$

$$\Delta UTCI = UTCI_{BG} - UTCI_{SU} \quad (4)$$

$$\Delta tmax = tmax_{BG} - tmax_{SU} \quad (5)$$

$$\Delta tmin = tmin_{BG} - tmin_{SU} \quad (6)$$

3. Results

Based on the proposed methodology and the multiyear meteorological data, biothermal conditions were presented in three separate sections: (i) Frequencies of PET, mPET and UTCI thermal stress classes per each month, with a comparison between Belgrade (urban) and Surcin (suburban) area, (ii) average monthly and annual PET, mPET and UTCI and (iii) differences in indices between Belgrade (urban) and Surcin (suburban) areas.

3.1. Frequencies of PET, mPET and UTCI

This section presents monthly frequencies (expressed in percentages) of the represented thermal stress classes of all three PET, mPET and UTCI indices in Belgrade and Surcin areas at 7 h and 14 h (CET).

Based on the 7 h morning observations in Belgrade (urban) area, it is interesting to note the no thermal stress class frequency rate. In PET index, this class is registered from May to September with the range between 42–84%, with the largest percentage in June and almost twice as lower percentage of up to 44% in September (Figure 2). In contrast to PET, the no thermal stress class of mPET is observed in April and October, but with a smaller share of 2.3%, while the highest shares are observed in May and September, 84% and 86%, respectively (Figure 2, left charts). Concerning the UTCI index, no thermal stress class was observed from April (18%) till November (7%), with a 100% share in May and September and a somewhat lower percentage (95%) in April and October (91%). A large percentage difference is notable between no thermal class in April between PET and mPET on the one hand (0% and 2%, respectively) and UTCI (95%) on the other. The highest PET and mPET form of the thermal heat stress appears as the slight heat stress from June until August in the range from 12% to 21% for the PET index and in the range from 23 to 51% for the mPET index. The highest form of the thermal cold stress is extreme cold stress which for the PET index is observed during the winter months, from 9 to 23% and in March (5%), while for the mPET index, it is only observed in January (2%). The highest form of the UTCI index thermal heat stress is moderate heat stress, which also appears from June to August in the range from 35 to 63%. The highest form of the UTCI cold thermal stress is moderate cold stress which was observed during the winter months within the range from 56 to 70% as well as in March (9%) and November (7%).

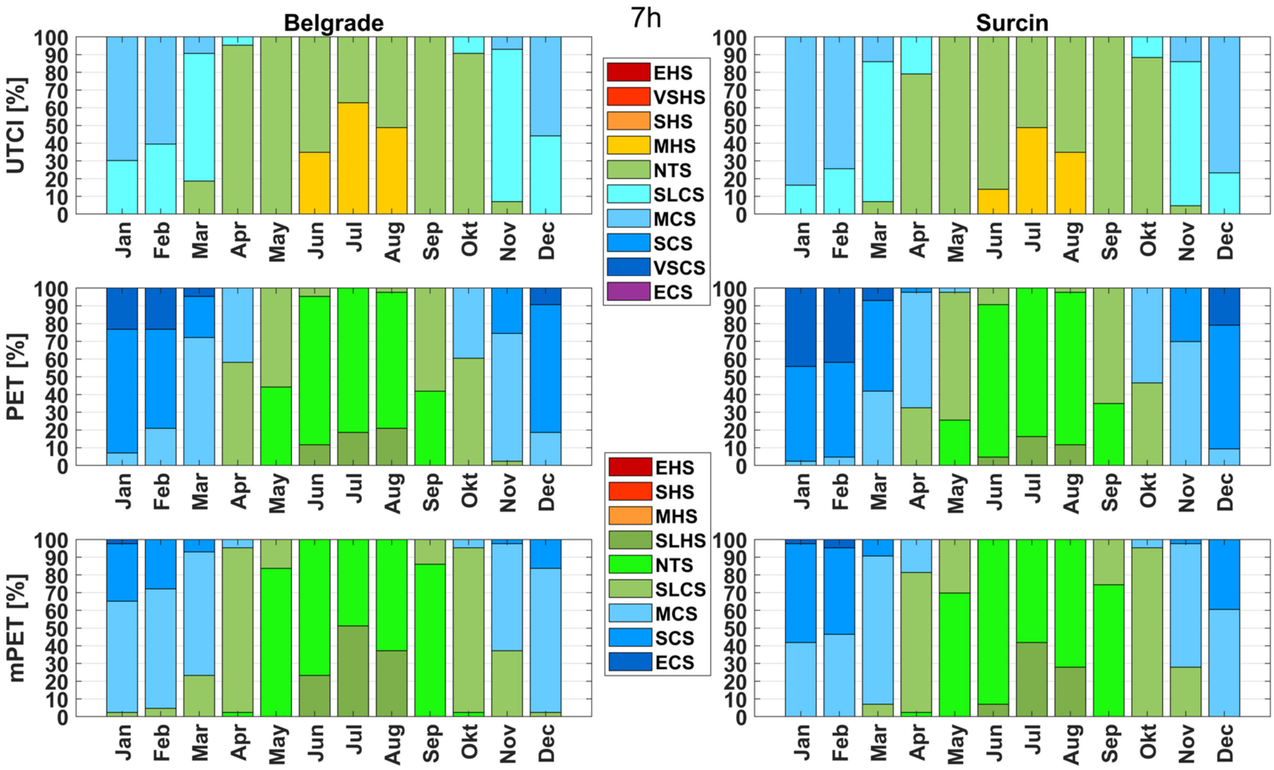

Figure 2. Monthly frequencies (expressed in percentages) of the represented thermal heat stress classes of all three PET, mPET and UTCI indices in Belgrade and Surcin areas at 7 h and 14 h (CET).

In Surcin (suburban area), the 7 h no thermal stress class has an almost identical monthly distribution, with the exception of October when this class was not observed for mPET index, in contrast to Belgrade, where it amounted to 2%. However, during the summer, a higher percentage of PET index no thermal heat stress was observed in Surcin than in Belgrade, with the exception of May and September. In May and September, no thermal stress PET index ranges from 26% to 35%, respectively. In the mPET index, the greater share of no thermal stress during the summer months (JJA) is also characteristic for Surcin compared to Belgrade, which is expected due to a distinct heat island in the city's urban area. No thermal heat mPET index is apparent from April until September and it ranges from 2% in May (as in Belgrade) to 74% in September. However, in May and September, no thermal heat stress periods are more distinctive in Belgrade than in Surcin. This may be explained by the lack of sunshine at the weather station caused by the distribution pattern of the buildings in the central part of town. In addition, this weather station is located in the park, which evidently creates a microenvironment very different from the one of the weather stations located at the airport on an open plateau. Concerning the UTCI index, May and September were 100% no thermal heat stress months, both in Belgrade and Surcin. No thermal heat stress percentage during the summer months (June, July and August) is again greater in Surcin than in Belgrade compared to April and October, when the percentage of no thermal heat stress periods is higher in Belgrade than in Surcin (Figure 2, right charts).

When it comes to 14 h CET observations, the thermal heat stress situation is considerably different in a sense that no thermal heat stress share is lower in all three indices in favor of the moderate heat stress and moderate cold stress bordering classes. This is absolutely expected in the context of the daily radiation flow in the spring, summer and autumn months (Figure 3). In both stations, PET and mPET slight heat stress is dominant at 14 h CET observations, ranging from 72 to 95% during the summer months (JJA), with an insignificant difference between Belgrade and Surcin. The PET index slight cold stress is prevalent in April and October, ranging from 55 to 66%. In Belgrade, the mPET index slight cold stress appears in March and November, with close to 75% share, while in Surcin, it occurs in April and November within a range from 70 to 72%. It should be noted that May, September and October are months with the highest no heat stress percentages out of the whole year (14 h CET observations).

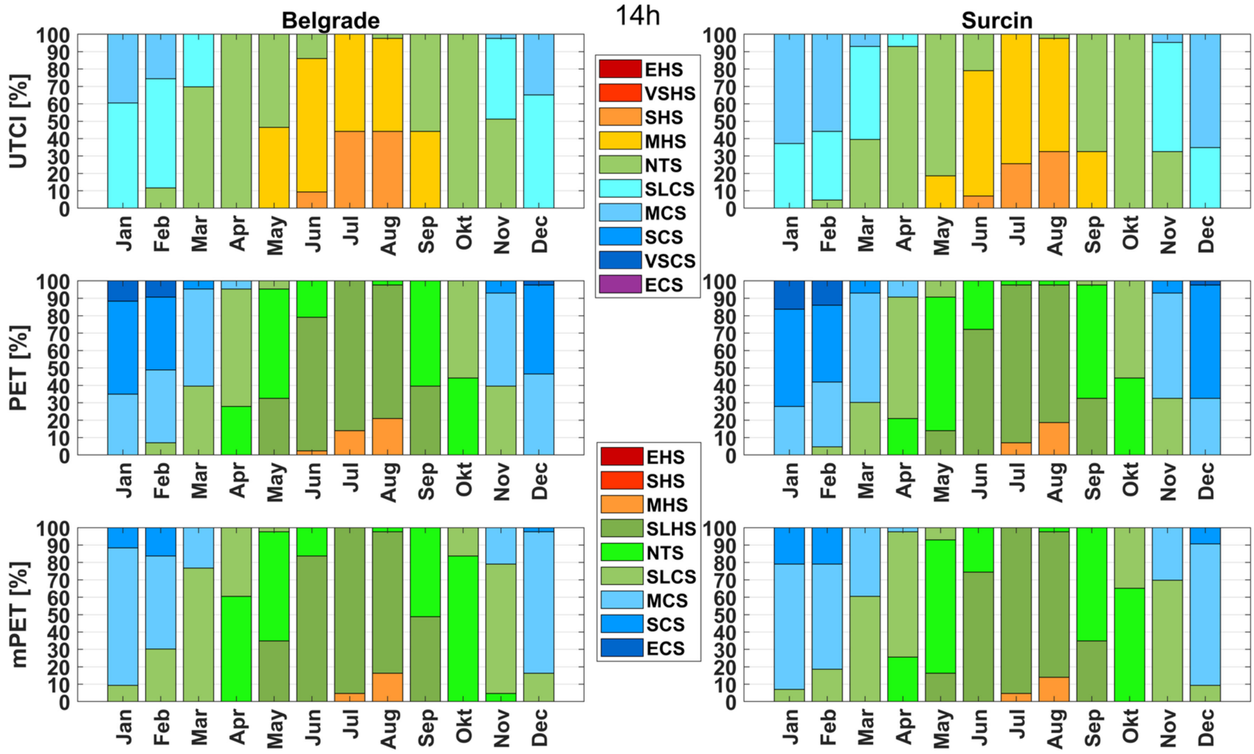

Figure 3. Monthly frequencies (expressed in percentages) of the represented thermal stress classes of all three PET, mPET and UTCI indices in Belgrade and Surcin at 14 h.

With regard to the UTCI index, the 14 h CET observations during the summer months show that the dominant thermal heat stress is moderate heat stress and ranges from 53% to 77%, with insignificantly higher stress during July and August in Surcin than in Belgrade. In October, in both Belgrade and Surcin, only no thermal heat stress period was observed (100%). In April, no heat stress percentage was slightly lower in Surcin (93%), while in Belgrade, it remained at 100% no thermal heat stress. When it comes to the cold thermal stress, the highest percentage observed was the PET slight cold stress (41–65%) in the winter months (DJF) and mPET moderate cold stress (53–81%), with a slightly greater percentage of the cold stress recorded in Surcin. In the case of the UTCI index, the highest percentage of the cold thermal stress was recorded from November to February as the slight cold stress and it was more significant in Belgrade than in Surcin, while the moderate cold stress was prevalent in Surcin, compared to the Belgrade data.

To obtain a better insight into indices values for the investigated period, averaged UTCI, PET and mPET at 7 h and 14 h together with trends was provided for each year. The averaged values are presented in Figure 4, together with the trends and deviation of each index in order to see how much they fluctuated in relation to the yearly value. The results show a significant increase in values of the UTCI, PET and mPET over the last 46 years. A series of peaks can be observed in the years 1990, 1998, 2000, 2007, 2012, 2015 and 2017 that have been marked as extremely warm according to previous investigation [11–14,16–18,21,22,25]. In addition, there is a growing trend of each index in both stations, i.e., a series of peaks with successively higher values during the investigated period (1976–2018).

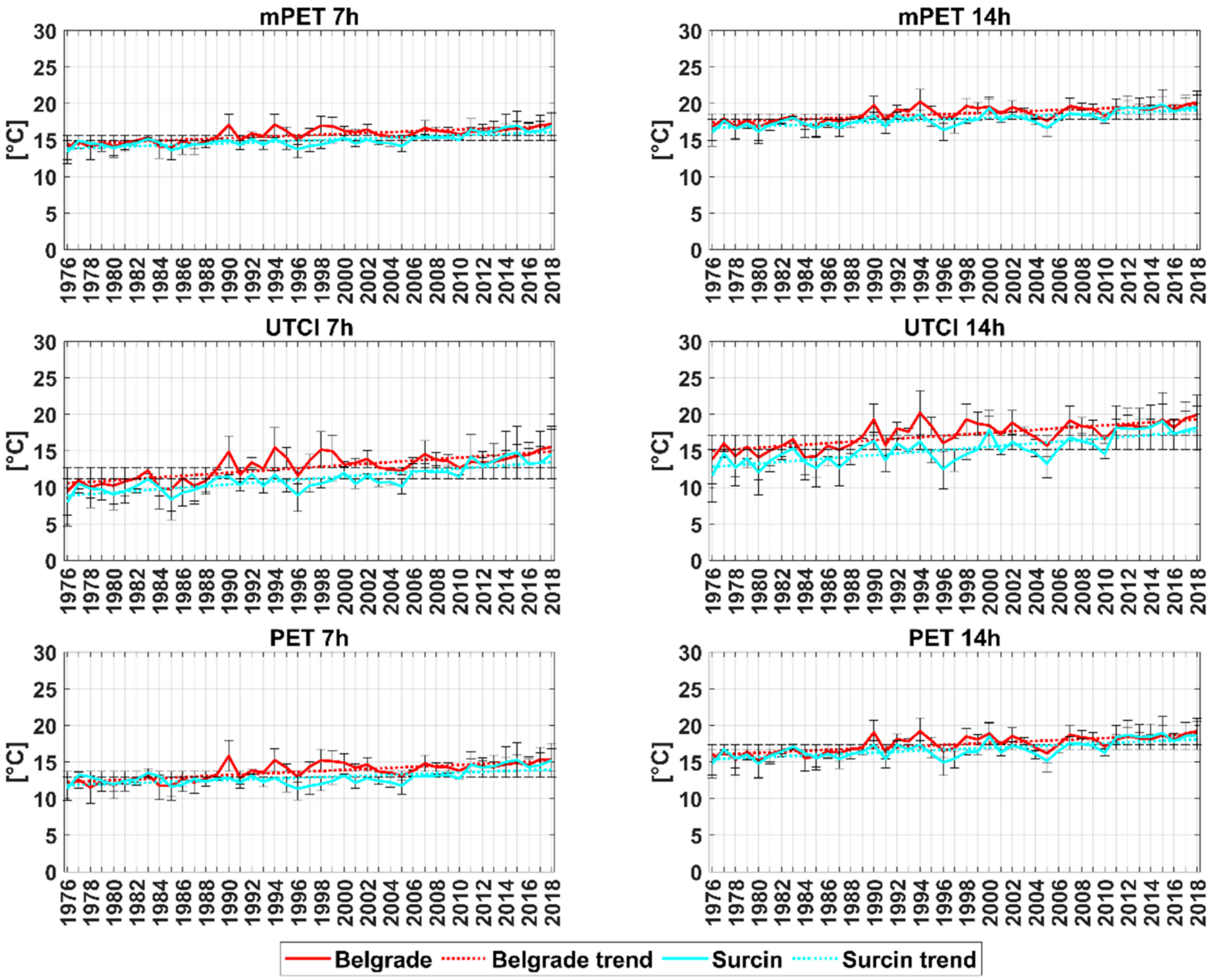

Figure 4. The average annual UTCI, PET and mPET at 7 h and 14 h CET during the period (1976–2018). Red lines and red dotted lines: Belgrade and trend, blue lines and dotted blue lines: Surcin and trend.

3.2. Average Monthly, Seasonal and Annual PET, mPET and UTCI

This chapter gives mean monthly PET, mPET and UTCI at 7 h and 14 h (CET) for the 1976–2018 period. Table 2 shows annual fluctuations of all three indices for the morning observations. The largest difference between the three indices is evident for the winter period. All three indices show annual variations typical for the moderate continental climate, with one July maximum and one January minimum. The PET maximum mean value is 21.9 °C in Belgrade and 21.5 °C in Surcin, which falls under the no thermal heat stress category, while the minimum mean value for Belgrade was 5.2 °C and 4.4 °C in Surcin. The mean annual PET for the period observed was 13.5 °C in Belgrade and 12.7 °C in Surcin. Compared to PET, slightly higher values of mPET were recorded. The maximum mPET value in Belgrade was 22.9 °C and 22.5 °C in Surcin (no thermal stress), while the minimum values for Belgrade and Surcin were recorded at 8.6 °C (moderate cold stress) and 7.8 °C (strong cold stress), respectively. The mean annual mPET value for the period observed (1976–2018) was 15.7 °C in Belgrade and 15 °C in Surcin. UTCI has negative values during the winter period, −2.1 °C in Belgrade and −4.1 °C (moderate cold stress) in Surcin. Additionally, UTCI maximum values are higher than those of PET and mPET and amount to 26.6 °C and 26 °C (moderate heat stress) for Belgrade and Surcin, respectively. The mean annual UTCI in Belgrade was 12.7 °C, while in Surcin, it was 11.2 °C. The difference between all three indices is evident here. According to Matzarakis et al. [42], direct comparison of PET and mPET indices with UTCI index are not possible due to the difference in a scale that defines the UTCI index no thermal heat stress. However, the difference between mean annual and mean seasonal (spring, summer and winter) values of all three indices is not large. A more significant difference was recorded for the winter period which can be seen in the seasonal analysis below.).

Table 2. Average monthly and annual PET, mPET and UTCI in Belgrade (BG) and Surčin (SU) for the period 1976–2018 at 7 h (CET).

Index/Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
PET_BG	5.2	5.7	8.7	13.3	17.7	20.7	21.9	21.5	17.9	13.5	9.4	6.5	13.5
PET_SU	4.4	4.3	7.5	11.9	16.9	19.9	21.5	21	17.4	13	8.8	5.3	12.7
Index/Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
mPET BG	8.6	9	11.6	15.5	19.2	21.8	22.9	22.5	19.4	15.8	12.3	9.8	15.7
mPET SU	7.8	7.7	10.5	14.3	18.5	21.2	22.5	22.2	19.1	15.3	11.7	8.7	15
Index/Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
UTCI BG	−2.1	−0.5	5.7	13.8	20.7	25.2	26.6	25.7	20.3	12.8	5	−0.4	12.7
UTCI SU	−4.1	−3.4	3.2	11.3	19.4	23.9	26	25.3	19.8	11.9	3.7	−3	11.2
Index/Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
tmin BG	−1	0.2	3.9	8.4	12.9	16	17.6	17.6	13.6	9.1	4.4	0.4	8.6
tmin SU	−2.6	−1.4	2.3	6.8	11.6	14.7	16.2	16	12.2	7.6	2.9	−1.1	7.1

Table 3 presents annual variations of all three indices observed at 14 h CET. Compared to the prior case, a smaller difference between mean values of the three indices was observed at 14 h CET. A particularly small difference was recorded between PET and mPET indices in all months except those in the winter months. In contrast to mean index values observed at 7 h, which were at their highest in July, maximum annual mean values at 14 h were recorded in August. The maximum monthly mean PET was 27.2 °C in Belgrade and 26.7 °C in Surcin, while maximum monthly mean mPET were 26.9 °C and 26.4 °C, respectively. The difference between PET and mPET in relation to UTCI is smaller during the warmer part of the year and considerably larger during the winter. The maximum mean UTCI in Belgrade was 31.7 °C and in Surcin, it was 30.8 °C. Mean maximum values of all three indices fall in the moderate heat stress category. Mean minimum PET values of 7.2 °C in Belgrade and 6.6 °C in Surcin are within the strong cold stress category, while mean minimum mPET values of 10.2° in Belgrade and 9.6 °C in Surcin belong to the moderate heat stress category. Mean minimum UTCI also belongs to the moderate cold stress category. Despite the evident differences between PET, mPET and UTCI in individual months, annual mean index values show the same difference between PET, mPET as in 7 h morning measurements, while the difference of the UTCI index is larger in 14 h morning measurements (Table 3).

Mean seasonal PET, mPET and UTCI values for both observation times are given in Table 4. Values of all mean seasonal indices are also higher in urban than in suburban city areas. Differences between indices are smallest in the summer months and highest in the winter months. The difference between PET and mPET indices is the largest in winter and runs from 1.1 °C in Belgrade to 1 °C in Surcin. Spring and autumn are similar for all three indices, although slightly higher values were observed for the autumn, particularly at 14 h.

Table 3. Average monthly and annual PET, mPET and UTCI in Belgrade (BG) and Surcin (SU) for the period 1976–2018 at 14 h (CET).

Index/Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
PET BG	7.2	8.3	12.6	17.3	22	24.9	27	27.2	23.1	18.2	12.4	8.2	17.4
PET SU	6.6	7.4	11.6	16.3	21.2	24.2	26.4	26.7	22.4	17.7	11.9	7.4	16.6
Index/Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
mPET BG	10.2	11.1	14.5	18.3	22.3	25	26.7	26.9	23.4	19.3	14.5	11.1	18.6
mPET SU	9.6	10	13.4	17.3	21.6	24.3	26.1	26.4	22.7	18.7	14	10.3	17.9
Index/Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
UTCI BG	0.7	3	10.4	18.3	25.3	29.3	31.7	31.7	26.2	18.7	9.1	1.9	17.2
UTCI SU	−1.5	0	7.1	15.5	23.7	27.9	30.6	30.8	24.8	17.1	7.3	−0.4	15.2
Index/Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
BG tmax	4.8	7.1	12.7	18.1	23.3	26.3	28.6	28.7	23.9	18.4	11.3	6	17.4
SU tmax	4.2	6.7	12.5	17.8	22.9	26.1	28.4	28.5	23.8	18.2	11	5.4	17.1

Table 4. Average seasonal PET, mPET and UTCI in Belgrade (BG) and Surcin (SU) for the period 1976–2018 at 7 h and 14 h (CET).

Index/Season 7 h	PET BG	PET SU	mPET BG	mPET SU	UTCI BG	UTCI SU	tmin BG	tmin SU
Winter	6.5	5.4	9.7	8.7	1	−1.4	1	−0.6
Spring	17.2	16.2	18.8	18	19.9	18.2	12.4	11
Summer	21.4	20.4	21.6	21.3	24.2	23.7	16.3	14.8
Autumn	9.8	9	12.6	11.9	5.8	4.2	4.6	3.1
Index/Season 14 h	**PET BG**	**PET SU**	**mPET BG**	**mPET SU**	**UTCI BG**	**UTCI SU**	**tmax BG**	**tmax SU**
Winter	9.4	8.5	11.9	11	4.7	1.9	8.2	7.8
Spring	21.4	20.6	21.9	21.1	24.3	22.4	22.6	22.3
Summer	25.8	25.2	25.7	25.1	29.9	28.7	27.1	26.9
Autumn	12.9	12.3	15	14.3	9.9	8	11.5	11.5

3.3. Urban-Suburban Differences (ΔPET, ΔmPET, ΔUTCI)

Due to the complex urban impacts on the atmosphere, it is indisputable that cities have a higher temperature than their surroundings. Records of the mean monthly and annual values of all three indices of the Belgrade urban area and the Surcin suburban area clearly demonstrate a difference consistent with the definition of the urban heat island (UHI). The value of this difference is given in this unit, while its consistency with the urban heat island research is presented in the Discussion unit. Mean monthly and mean annual PET, mPET, UTCI, tmax and tmin differences between Belgrade and Surcin for the morning and midday measurements are given in Figure 4. Mean monthly differences of the PET morning observation (ΔPET_{7h}) time range from 0.4 °C in July to 1.4 °C in February. ΔPET_{7h} differences larger than one degree Celsius are recorded in February, March, April and December. Slightly smaller mPET mean monthly differences ($\Delta mPET_{7h}$) range from 0.3 °C in, August September and October to 1.3 °C in February. $\Delta mPET_{7h}$ differences larger than one degree Celsius are recorded in February, March, April and December. The largest mean monthly difference that was observed for the UTCI ranges from 0.4 °C in August to 2.9 °C in February. Apart from the mentioned summer months and October, significantly higher $\Delta UTCI_{7h}$ differences were recorded in other months than ΔPET_{7h} and $\Delta mPET_{7h}$.

Measurements undertaken at 14 h demonstrate smaller ΔPET_{14h} and $\Delta mPET_{14h}$ mean monthly differences compared to the morning measurements, which is expected. ΔPET_{14h} mean monthly difference ranges from 0.5 °C to 1 °C. March and April are the only months with a 1 °C difference, while this difference is smaller in other months. Likewise, the

$\Delta mPET_{14h}$ mean monthly differences range from 0.5 °C to 1.1 °C. The results obtained for the $\Delta UTCI_{14h}$ mean monthly difference are not in line with this. Differences at 14 h daily measurements are larger than the morning measurements and range from 0.9 °C in August to 3.3 °C in March (Figure 5). By comparing mean monthly differences of extreme temperatures, nearly equal values are observed ranging from 0.2 °C to 0.6 °C in maximum air temperatures and from 1.3 °C to 1.6 °C in minimum air temperatures. It is noticeable that averaged monthly differences of PET and mPET are between averaged monthly differences of tmax and tmin in both observation periods, while averaged monthly differences of UTCI vary more, especially in the colder period of the year. One of the reasons for this may be the UTCI sensitivity to other meteorological parameters, such as wind velocity and air humidity.

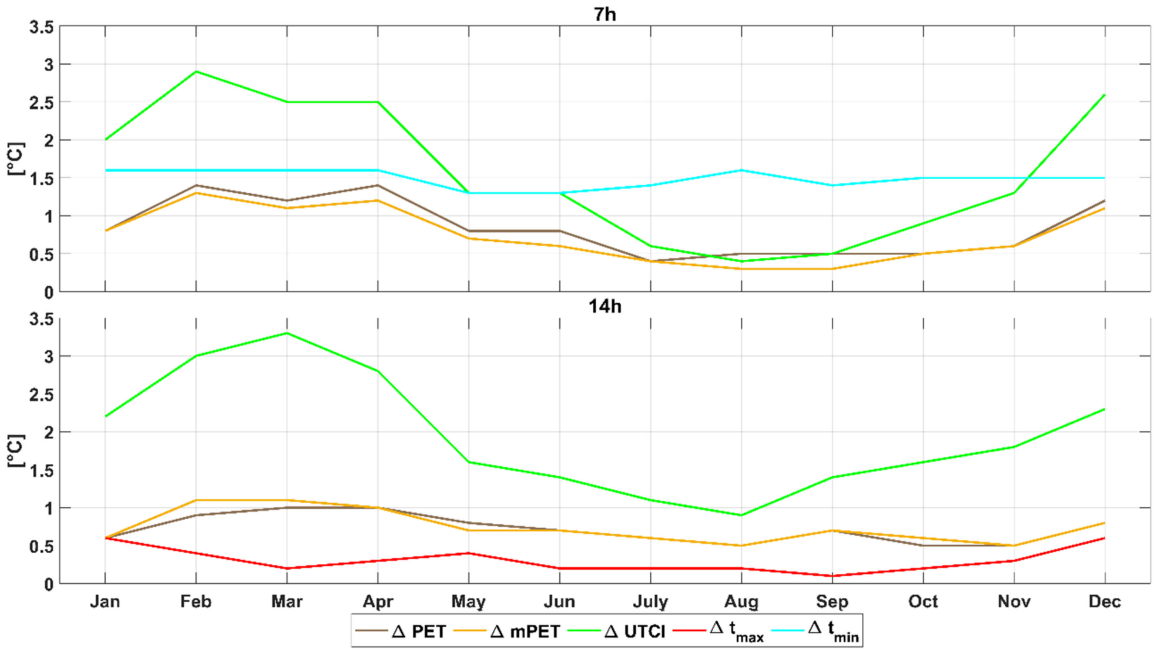

Figure 5. Average monthly and annual differences of PET, mPET, UTCI, tmax and tmin at 7 h and 14 h between Belgrade BG (urban) and Surcin SU (suburban) for the period 1976–2018.

The smallest difference between urban and suburban area indices is observed during the seasons (Figure 5). The slightest is observed during the summer and autumn and the largest during the winter. In terms of indices, ΔPET mean seasonal differences during winter and spring are larger in the morning than the mean seasonal differences measured at 14 h, while there is no difference recorded during summer and autumn (Figure 6). For mPET, the difference between morning average monthly differences ($\Delta mPET_{7h}$) and daytime mean monthly differences ($\Delta mPET_{14h}$) was recorded in all seasons. The UTCI shows considerable differences between the 7 h and 14 h measurements in all seasons, with the morning mean monthly differences ($\Delta UTCI_{7h}$) from 0.2 to 0.6 °C being larger than the daytime mean monthly difference ($\Delta UTCI_{14h}$). Mean annual differences of maximum and minimum temperatures between urban and suburban area are 0.3 °C and 1.5 °C. Further, the mean annual difference of ΔPET_{7h}, $\Delta mPET_{7h}$ and $\Delta UTCI_{7h}$ amounts to 0.8 °C, 0.7 °C and 1.5 °C, respectively, while the mean annual difference of ΔPET14h and ΔmPET14h amounts the same as in morning measurements and $\Delta UTCI_{14h}$ amounts to 2 °C. $\Delta UTCI_{7h}$ and $\Delta UTCI_{14h}$ most closely follow the difference between urban and suburban minimum temperatures (Figure 5).

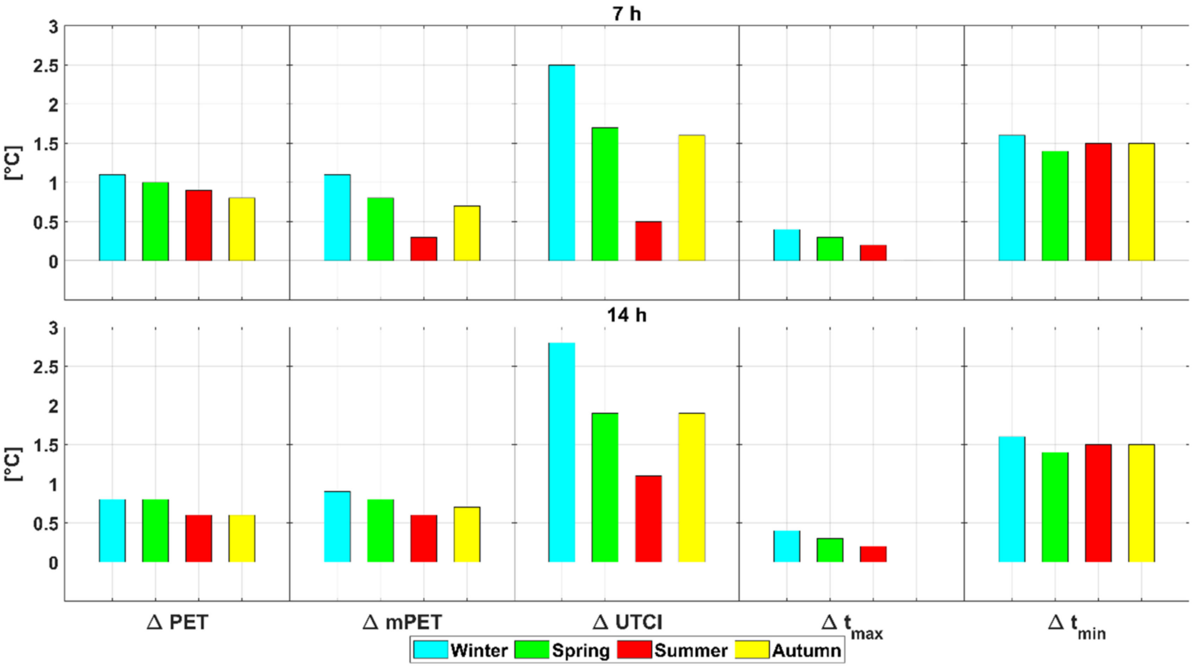

Figure 6. Average seasonal differences of extreme temperatures between Belgrade BG (urban) and Surčin SU (suburban) for the period 1976–2018.

While mean monthly maximum temperatures do not show significant differences, ranging from 0.2 °C in the summer to 0.6 °C (Figure 4) in the winter, mean monthly minimum temperatures are significantly higher in central Belgrade area than in the suburbs and their differences are mostly constant, ranging from 1.3 °C to 1.6 °C (Figure 5). A similar situation is with differences between the absolute minimum and absolute maximum temperatures (Δtmin and Δtmax) of the observed period, which are 7.8 °C and 0.4 °C, respectively. The lowest minimum temperature in Belgrade is −18.2 °C and in Surcin −26 °C amounting the difference of 7.8 °C. The lowest maximum temperature of the observed period is −10.6 °C in Belgrade and −12.3 °C in Surcin, which again gives a significantly smaller difference (1.7 °C) than in the case of the lowest minimum temperatures. However, the absolute maximum temperature in Belgrade is 43.6 °C and 43.2 °C in Surcin, which yields the smallest difference of 0.4 °C between urban and suburban areas. Regarding the differences between the absolute minimums and absolute maximums of the heat budget indices, the situation is as follows: The PET_{7h} absolute minimum amounts to −12.1 °C and −17.3 °C in Surcin, which amounts to 5.2 °C difference between urban and suburban parts of town. According to day observations, the difference between the PET_{14h} absolute minimum of the Belgrade urban area (−10.9 °C) and the suburban Surcin area (−11.9 °C) amount to considerably less, 1 °C. The difference between PET_{7h} absolute maximums in Belgrade (31.5 °C) and the Surcin suburban area (31.6 °C) in the morning observations and the differences between the PET_{14h} absolute maximums during the day observations in Belgrade (42.7 °C) and Surcin (40.6 °C) is significantly smaller amounting to −0.1 °C for 7 h and 2.1 °C for 14 h. The difference between the urban and suburban areas mPET absolute minimum is insignificant and amounts to 2.6 °C at 7 h and 2.7 °C at 14 h. For UTCI, the difference between the urban and suburban areas' absolute minimum is 3.5 °C at 7 h and 9.1 °C at 14 h, while the difference of the absolute maximums of $UTCI_{7h}$ and $UTCI_{14h}$ amounts to 0.6 °C and 1.8 °C, respectively.

4. Discussion

Applied human bioclimatological methods and data of 43 years are considered for temporal analysis of urban (Belgrade city center) and suburban (Surcin airport) distribution of heat budget indices PET, mPET and UTCI. The biothermal evaluation for the period 1976–2018 shows high temporal resolution of hourly observation at 7 h and 14 h identifying the annual and seasonal distribution of each index in the capital of Serbia, together with differences between urban and suburban areas. The analysis of a 43-year-long data sequence (air temperature, max and min air temperature, wind speed, relative humidity, cloud cover) in the context of mean monthly, mean seasonal and mean annual PET, mPET and the UTCI makes it evident that all three indices point to a typical annual flow of a moderate climate with one maximum in July and one minimum in January at the morning observation time. The only exception were the minimum annual values of PET and mPET recorded in Surcin in February.

Thermal indices indicate different evaluations of thermal conditions in Belgrade during the winter, where the estimation of PET showed a higher number of cold stress events in Belgrade and Surcin than the evaluation of mPET did. In Belgrade, the highest cold stress form of the PET index—extreme cold stress—was recorded within 9 to 23% range and even of 5% in March, while the mPET index extreme cold stress was recorded only in January with 2%. Moreover, PET evaluations show classes of moderate cold stress occurring in May in Surcin, but the mPET evaluations of the same months did not. The reason for this is the impact of clothing, which corresponds to thermal conditions implemented in the model of mPET. Similar results were obtained by Matzarakis et al. [35] and Chen and Matzarakis [28] for Freiburg. According to Chen et al. [31], in the neutral zone, where PET and mPET are between 18 and 23 °C, mPET changes slightly when the air temperature changes. Outside the neutral zone, mPET grows similarly to PET, but is much slower in the hot stress zone where PET and mPET are >23 °C. However, in the cold stress zone where PET and mPET < 18 °C, mPET decreases more slowly compared to PET when temperatures rise. Multiyear measurements of UTCI at 14h show that the thermal heat stress dominantly occurs as moderate heat stress during summer months and ranges between 53% and 77%.

Regarding mean seasonal and mean annual PET, mPET and UTCI at 7h, the UTCI is larger than PET and mPET only in the spring and summer. During autumn and winter, mPET and PET have higher values than UTCI, where mPET has higher values than PET. This pattern has already been reported by Blazejczyk et al. [67], Matzarakis et al. [42] and Chen et al. [33]. This is because the two thermal indices have different evaluating processes for radiation parameter. The reason for the differences between these two thermal indices regarding cold conditions compared with the other seasons is that PET has fixed clothing insulation (0.9 clo) which is one of the mean shortcomings of the PET model. As stated by Chen et al. [35] regarding clothing insolation, PET has almost no performance on the variation of clothing insolation while the mPET has significantly different performance on the variation of clothing insolation. An increasing tendency of mPET is involved by the changing of the clothing insolation in the cold conditions. The role of clothing is important in the prevention of the human body latent heat loss, particularly in the winter. As Jendritzky et al. [36] reported, heat stress is the stress that affects the human thermoregulatory system due to the exchange of the heat between the body and its thermic environment, which includes clothing. Unlike PET, the mPET model does not have fixed clothing insulation, which allows it to reflect a more realistic biothermal state of the environment and mitigate the difference compared to UTCI. Another notable difference of PET and UTCI models is the physical activity corresponded by the metabolic energy flux in the form of the constant value of 135 Wm^{-2} for the UTCI model and of 80 wm^{-2} for the PET model. However, Kruger et al. [73] suspect that the clothing insulation effect is overestimated in the UTCI model for air temperatures above 20 °C in Great Britain and Brazil. General comparison between PET and UTCI is acceptable at the mean seasonal and mean annual values level. However, direct comparison between the thermal comforts and especially cold thermal conditions are not possible due to unequal configurations of clothing insulation. At midday measurements, the differences between PET and mPET are slightly smaller, around 1 °C, compared to morning measurements, especially during summer and autumn. The UTCI shows a slightly larger difference of 1 °C compared to morning measurements.

Results obtained for Belgrade urban and Surcin suburban area of all mean monthly and mean annual values of all three indices clearly indicate the difference, which follows the definition of the urban heat island (UHI). Particularly PET and mPET show the same differences for morning and midday observations (0.8 °C and 0.7 °C), while in the case of UTCI, the differences between the urban and suburban zone are 1.5 °C for morning and 2 °C for midday observations. The largest difference between the urban and suburban areas is shown by the $UTCI_{14h}$ index, 3.3 °C in March and the smallest, 0.9 °C in August. Compared to UTCI, PET and mPET show a significantly smaller difference between the urban and suburban zones. Seasonal ΔPET, ΔmPET differences are larger at the morning observation times compared to daytime observations, especially during winter and spring, while seasonal ΔUTCI differences are smaller at the morning observation compare to midday observation. Summer ΔPET, ΔmPET and ΔUTCI difference during daytime observations have the smallest value compared to other seasons, especially summer differences at $\Delta UTCI_{7h}$ and $\Delta UTCI_{14h}$ (Figure 5). This situation may be due to increased radiation on the Surcin plateau compared to the central Belgrade area, where the weather station is shaded by the buildings and situated in a park. Additionally, air humidity is usually higher in the suburbs as reported by Unkasevic [8] for the Belgrade territory. Similar differences in air humidity between urban and suburban areas are reported by Liu et al. [74] in Beijing. Higher radiation and higher humidity levels have an indisputable impact on biothermal heat stress increase. A larger amount of biothermal stress in the suburban area is not necessarily unusual, especially in the summer. From another point of view, wind speed on the Surcin plateau is known to be higher due to the open Panonian terrain configuration, a condition to which the UTCI index is very sensitive, leading to its significantly decreased subjectivity of the biothermal stress. As stated by Chen and Matzarakis [33], the influence of wind speed on UTCI may be more intense than mPET. This explains a dominantly lower UTCI index value in the suburban areas than in the central parts, which is in line with the definition of the urban heat island.

A research based on air temperatures conducted by Milovanovic [4] report that Belgrade follows the definition of urban heat island (UHI), with annual air temperatures higher by around 1.1 °C than temperatures of the surrounding area due to a group of factors, such as changes in the radiation balance during the summer and anthropogenic heat emission during the winter. This is shown by the annual differences of all three indices between the urban and suburban part of the city together with the annual differences of maximum and minimum temperatures. Therefore, the annual difference of minimum temperatures (Δtmin) and UTCI index ($\Delta UTCI_{7h}$, $\Delta UTCI_{14h}$) between urban and suburban is most powerfully affected by urban factors. In this context, while mean monthly maximum temperatures do not show significant differences, ranging from 0.2 °C in the summer to 0.6 °C in the winter, mean monthly minimum temperatures are significantly higher in central Belgrade area than in the suburbs and their differences are mostly constant, ranging from 1.3 to 1.6 °C. This is also confirmed by the differences between the absolute minimum and absolute maximum temperatures (Δtmin and Δtmax) of the observed period, which are 7.8 °C and 0.4 °C, respectively.

The differences of all three indices between urban and suburban may result from anthropogenic heat emission, air pollution and city center geometry. For example, construction materials cause an increase in heat capacity, which leads to a rise in temperature. Air pollution increases the absorption and re-emission of gases, increasing air temperature and impacting the cloud condensation cores, leading to increased air humidity. A noticeably larger difference between urban and suburban areas in the UTCI index may be contributed to higher wind speeds in the area of the Surcin plateau during the winter and autumn (especially to the influence of the local northeast wind Kosava), to which the UTCI index is particularly sensitive in a negative sense, which is then manifested by the decrease of the UTCI values compared to the city center. Therefore, both the air temperature increase and the air humidity increase strongly stimulate the growth of biothermal conditions defined by UTCI, explaining their differences larger than differences of the extreme temperatures (tmin and tmax). A particularly large difference in the UTCI index between urban and suburban area may be justified by these facts considering that the UTCI is, apart from the air temperature, also very sensitive to air humidity and wind speed and, in contrast to PET, focuses on radiant and sensible heat loss. As stated by Błażejczyk et al. [65], the UTCI represents various weather conditions very well and is very sensitive to changes in temperature, humidity, solar radiation and wind speed, whereas the others, including PET, are more related to air temperature. Air speed increase strongly stimulates the decrease of the biothermal conditions defined by UTCI, while in some cases, the geometry of the urban core may cause the wind speed to be lower than in the town's periphery. Consider these circumstances, it is difficult to clearly define the spatial dimension of urban heat island (UHI), taking only two measuring spots. Andjelković [2] similarly concludes that an urban heat island (UHI) is not a homogeneous or a fixed category because its intensity usually grows by rule in developing cities, increasing the area it covers.

However, some potential limitations of this study should be pointed out in order to improve future research. For a more comprehensive analysis of the outdoor thermal comfort spatial distribution, a more concentrated network of urban and suburban automatic micrometeorological measurements would be of considerable significance. One such approach with the establishment of a universally applicable system of categories that describes measurement sites for the purpose of site classification is the well-known system of local climate zones (LCZ) proposed by Stewart and Oke [75]. The advantages of this approach are clearly seen in the example of local measurements in Novi Sad (Serbia) described by Savic et al. [76] and Milošević et al. [77]. That would show the differences between urban and suburban areas may not be necessarily homogenous, but rather, spatially differentiated, which is partly caused by the structure of the city's geographical space, such as green and water areas, relief, types of ground, building density and heights of buildings. Thus, the study would benefit from analyzing the mean diurnal cycle of all relevant weather parameters (air temperature, humidity, wind speed and cloud cover). These are certainly some of the future research goals. This would lead to a more accurate interpretation of the human biometeorological prognosis and a more accurate analysis of favorable or less favorable biothermal conditions of certain city areas and consequently, to a more accurate bioclimatic mapping. Further, more concentrated spatial measurements would provide hourly weather data sufficient for a more sensitive analysis of outdoor thermal discomfort for healthcare purposes. It should be emphasized that each model of PET, mPET and the UTCI is limited by a fixed metabolic rate that approximates light physical activity. This means that the heat stress classes of all three indices fail to give realistic biothermal indicators of the heat stress for an intensive physical activity; otherwise, they should be higher. In addition, adaptability to the existing biothermal conditions should be excluded. Nevertheless, the research results of this study highlight the importance of heat budget indices PET, mPET and UTCI as indicators for biothermal conditions, particularly for urban climate research. They are in an appropriate relation for general research in warm conditions.

5. Conclusions

The present research of the human bioclimatic evaluation based on PET, mPET and UTCI in Belgrade is considered important due to the identification of (i) annual and seasonal biothermal conditions and (ii) biothermal differences in urban and suburban area. The positive trend and the increase in the value of each index for the observed period indicate an increase in subjective thermal stress and thermal discomfort in Belgrade. However, the annual indices difference between the urban and suburban parts of the city is slightly decreasing. Obtained PET, mPET and UTCI indices presented with morning and midday indices correspond to the most common time for daily minimum and maximum temperatures. Of all three indices, the $\Delta UTCI_{7h}$ most closely follow the difference between urban and suburban minimum temperatures, while the ΔPET_{14h} and $\Delta mPET_{14h}$ closely follow the difference between urban and suburban maximum temperatures. Seasonally significant difference in each index between the urban and suburban part of the city is in winter, a slightly smaller in the spring and autumn and the lowest in summer. Observing the indices mutually, their compatibility is highly noticeable in the warmer period of the year, mainly in the summer weather condition of high temperatures and lower humidity. Certainly, the changes that supplemented the physiologically equivalent temperature relate to thermo-physiological modifications (sensitivity to humidity) and modifications of the clothing insulation in the model which is the main difference between mPET and PET. Thus, the advantage of the UTCI index over PET has been significantly suppressed in certain circumstances. In this regard, mPETs show more comprehensive thermal characteristics for assessing all thermal impacts on the outdoor thermal comfort, especially during the winter season when radiation fluxes are lower and during the spring or autumn seasons when the humidity is higher. The evaluation aims at providing a comprehensive assessment in the context of the human experience of meteorological conditions and outdoor thermal comfort. However, the results of the research stress the applicability of PET, mPET and UTCI indices as bioclimatic indicators of the relevant biothermal conditions for the advancement of the biometeorological prognosis, urban planning, public health systems, tourism and recreation purposes.

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