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ANALYSIS OF LONG-TERM AIR TEMPERATURE TRENDS OF THE BELGRADE CENTRAL URBAN ZONE

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ABSTRACT

This paper analyzes long-term air temperature trends in the central urban zone of Belgrade over the period 1991–2020. The research is based on a dataset obtained from the principal meteorological station Belgrade - Observatory, using daily minimum, maximum, and mean air temperature values, as well as measurements recorded at 07:00h, 14:00h, and 21:00h CET (6 different air temperature variables). Trends were examined at annual and seasonal levels as well as through the mean 30-year and mean 10-year values, for each decade of the research period (1991-2000; 2001-2010; 2011-2020) in order to identify changes in local climatic conditions within Belgrade's densely urbanized environment. The results indicate a consistent increase in all analyzed temperature variables during the observed period. Positive trends were detected in mean daily, minimum, and maximum temperatures, as well as in seasonal and annual values, ranging from 0.064°C/year to 0.084°C/year at the annual level, and for seasons from 0.053°C/year to 0.079°C/year (spring), from 0.055°C/year to 0.084°C/year (summer), from 0.076°C/year to 0.091°C/year (autumn) and from 0.069°C/year to 0.082°C/year (winter), with the most pronounced warming occurring after 2011. The strongest increase was observed in evening temperatures (21:00 CET), especially during summer and autumn.

Keywords: Air temperature, Trends, Urban climate, Belgrade, Central urban zone.

INTRODUCTION

According to United Nations (UN) data, about 55% of the world's population lives in urban areas, and projections show that this share will increase to 68% by 2050. According to the IPCC (2021), by 2030 almost 60% of the world's population is expected to live in urban areas. Similar trends are also present in the Republic of Serbia, where the level of urbanization reached almost 60% in 2011, with only the city of Belgrade housing about 27.3% of the urban population (without Kosovo and Metohija) (Draft SPRS 2035; Lukić, 2025). Due to the growing population, increasing pressure on natural resources, complex social, economic, and ecological processes, urban environments have become particularly sensitive to the consequences of climate change. In order to adequately approach sustainable urban development, planning and management of urban environments, protection of public health and safety, improvement of quality of life, preservation of urban ecosystems, etc., experts and urban planners must understand local microclimatic conditions (Lukić, 2025).

Climate change at the global level directly and indirectly affects the urban microclimate. One of the most significant characteristics of the urban microclimate is the urban heat island (UHI) effect. Anđelković (2002; 2003) identified the urban heat island (UHI) effect in Belgrade almost two decades ago, comparing air temperature values measured at two meteorological stations: Belgrade - Observatory (urban) and Surčin (suburban). The mean annual air temperature measured in Surčin in the period 1971-1990 was 11.2°C, while the mean annual temperature at the Belgrade - Observatory was 11.9°C. Thus, Anđelković (2002, 2003) showed that in the given period the UHI intensity was 0.7°C. So, Belgrade's climate is strongly influenced by the UHI, the significance of which was confirmed by Milovanović et al. (2020). Through a comparative analysis of mean monthly and seasonal air temperatures recorded during 1949–2008 in Belgrade and at 22 additional meteorological stations across Serbia, the authors demonstrated that Belgrade was warmer than nearly all other stations in all four seasons (with the exception of Prizren and Negotin, owing to their local geographic characteristics). The largest differences were observed in winter, when Belgrade was almost 1.4°C warmer than the national average, and in autumn, when the difference reached up to 1.2°C. Although somewhat smaller, the differences in summer and spring were still notable, amounting to 0.9°C and 1.0°C respectively.

What is certain is that the values of the mean annual air temperature in Belgrade have been increasing over the past few decades. According to Anđelković (2002), during the period 1941-1990, the mean annual air temperature in Belgrade was 11.9°C. After the 1990s, and especially after 2000, there was a noticeable trend of growth in the mean annual temperature, so according to Tošić et al. (2019) its mean value in the period from 2000 to 2017 was 13.4°C. These findings are particularly relevant in the context of developing more effective responses to altered climatic conditions, implementing adaptation strategies and climate-conscious urban design, mitigating the impacts of the UHI, etc.

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In addition, such studies are also significant in the context of public health and well-being, which will be discussed more in the next chapter.

Air temperature and public health in Belgrade

Belgrade's urban population, especially residents of central urban zones, where the UHI effect is most pronounced, faces elevated health risks. Climate change and extreme events, such as heat waves, are associated with adverse health risks that disproportionately affect vulnerable population groups, including the elderly, individuals with chronic illnesses, women, children, outdoor workers, and socioeconomically disadvantaged populations (Lukić, 2025).

The extent to which extreme temperatures and heat waves may affect human health, in the most serious cases resulting in increased mortality, was demonstrated by Stanojević et al. (2014a). Their study examined the relationship between daily mortality and high summer temperatures in Belgrade over the period 2000–2010, identifying clear associations between elevated temperatures and mortality outcomes. During this period, the year 2007 stands out as the year in which the highest air temperature ever recorded in the Republic of Serbia was observed: 44.9°C (Smederevska Palanka, Central Serbia, 24th July 2007). In Belgrade, the maximum temperature recorded that summer reached 43.6°C (Tošić & Unkašević, 2013; RHSS). Notably, the same date on which the maximum air temperature was measured in Belgrade (24th July 2007) also corresponded to the highest daily mortality, with 94 deaths, substantially exceeding the expected average daily mortality of 55 deaths per day (Stanojević et al., 2014a).

The impact of extreme weather conditions during the July 2007 heat wave on daily mortality in Belgrade was further examined by Bogdanović et al. (2013). Their findings indicated that the number of deaths recorded between 16th and 24th July 2007 was 38% above the expected average for that period. The most severely affected population group comprised individuals aged over 75 years, who accounted for 90% of total deaths. Excess mortality among women was twice as high as that among men (54% vs. 23%). With respect to chronic conditions, mortality among patients with diabetes increased by 286%, among those with chronic kidney disease by 200%, among patients with respiratory diseases by 73%, and among individuals with nervous system disorders by 67%.

Findings of Stanojević et al. (2014b) show that a 1°C increase in mean daily temperature is associated with a 4.6% increase in cerebrovascular mortality, 2.2% in cardiovascular mortality and 1.6% in respiratory mortality. Combining data on daily mortality and weather conditions, intensity and duration of heat waves in the three largest urban centers of Serbia (Belgrade, Novi Sad and Niš) during 2000-2015, Allen et al., (2024) observed "excess" mortality in all three cities and significantly high health risks occurring on the hottest days. The authors emphasized the need to establish an "early warning heat system" in these urban areas.

It is clear that monitoring temperature trends is necessary to better understand the microclimatic conditions of the environment we inhabit as a community, in order to protect public health from increasingly pronounced climate risks, especially vulnerable groups.

THEORETICAL BACKGROUND

Analyses of temperature trends, microclimatic and bioclimatic studies of urban areas of Serbia, but also of wider regional areas, are increasingly becoming the subject of research by domestic authors. The areas from which these studies come to us are diverse: from climatology and bioclimatology, spatial and urban planning, green architecture, bioclimatic design, through public health, tourism, etc. Their diversity indicates the wide application of temperature and bioclimatic indices. Analyses of temperature trends, temperature indices and general climatic conditions were carried out for the area of Novi Sad (Lazić et al., 2006; Vasić et al., 2022), Belgrade (Anđelković, 2002; 2003; Drljača et al., 2009; Đorđević, 2008; Čegar et al., 2023a; Milovanović et al., 2020), Mačva District (Milentijević et al., 2020), Nišava river valley (Prokić, 2018), Nišava District (Milutinović, 2024) and Niš (Drljača et al., 2009; Unkašević & Tošić, 2009a) and the wider area of Serbia (Bačević et al., 2021; Bačević et al., 2026; Anđelković, 2007; Đurđević et al., 2018; Milovanović, 2023; Tošić & Unkašević, 2013; Tošić et al., 2019, 2023; Unkašević et al., 2005; Unkšević & Tošić, 2013, 2015; Vuković et al., 2018; Vuković-Vimić & Vujadinović-Mandić, 2024a, 2004b).

Several studies from other countries in the region should also be highlighted: Zagreb, Croatia (Bonnaci et al., 2018; Nimac, et al., 2021), Banja Luka and Sarajevo, Bosnia and Herzegovina (Gnjato et al., 2021; Popov et al., 2023), Podgorica, Montenegro (Bačević et al., 2020), etc. The increase in air temperature values has a positive effect on the increase in the values of various bioclimatic and thermal indices, which can be seen in the studies of the following authors: (Đurđević et al., 2023; Čegar et al., 2023; Lukić, 2019; Lukić & Milovanović, 2020; Lukić et al., 2021; Lukić & Đurić, 2023; Lukić & Filipović, 2024; Lukić, 2025; Malinović-Milićević, 2023; Milenković & Lukić, 2025; Milošević et al., 2023; Pecelj et al., 2020; Pecelj et al., 2025; Savić et al., 2024; Vasić et al., 2022), etc.

EXPERIMENTAL PART

Study area

The City of Belgrade is the capital and the largest urban area of the Republic of Serbia (Southeast Europe, Western Balkans) (Figure 2). It is situated at the confluence of the Sava and Danube rivers, within the Pannonian macro-region, at 44°48' N latitude and 20°28' E longitude, with an average elevation of 130 m (Figure 1). Belgrade, more precisely its central urban zone, was selected as the study area due to several characteristics: the city's distinct morphological structure, high population and building density, intensive urbanization, deficit of green urban spaces, specific microclimatic conditions, and a pronounced urban heat island (UHI) effect (Lukić, 2019; Lukić & Milovanović, 2020; Lukić & Đurić, 2023; Lukić, 2025; Savić et al., 2024).

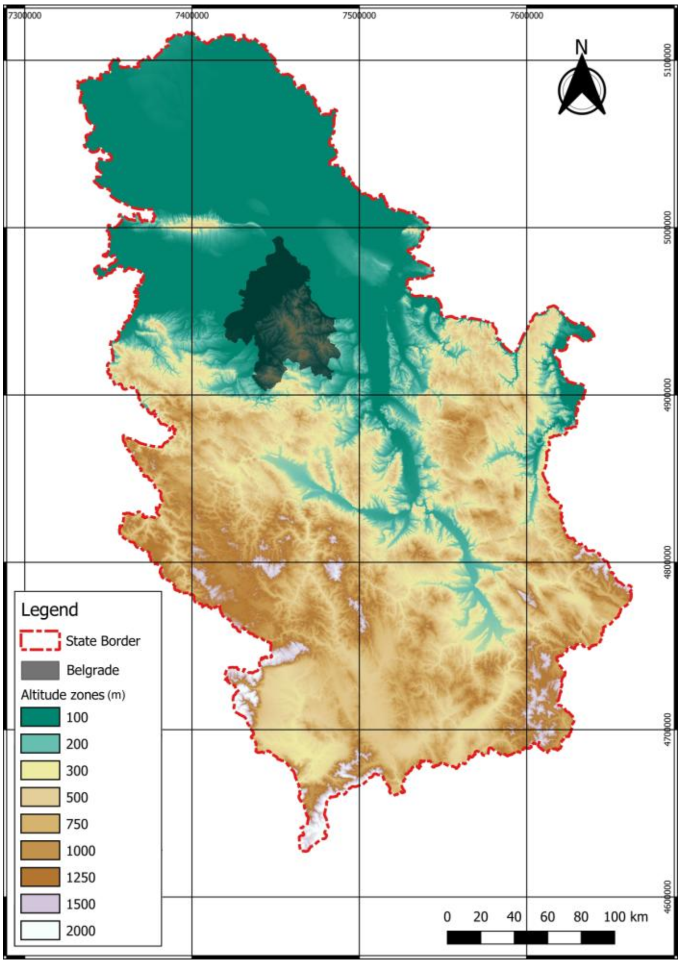

Figure 1. Relief map of Serbia with the studied area – the City of Belgrade. Map was created using the QGIS 3.40.6 software.

According to the Köppen - Geiger climate classification, Belgrade's climate is categorized as Cfb, characterized by a warm, temperate, and humid regime with warm summers and maximum precipitation occurring in late spring and early summer (Mihajlović, 2018; Lukić et al., 2021; Lukić, 2025). The mean annual air temperature in Belgrade during the 1991–2020 period was 13.2 °C, compared to 11.9 °C in the 1961–1990 period. The average annual precipitation total for the 1961–2020 period was 691.8 mm, while in the 2000–2020 period it amounted to 704.3 mm (Čegar et al., 2023a; Lukić, 2025). Belgrade lies within the "Košava" wind region; the Košava typically occurs during the autumn and winter months in intervals lasting 2 - 3 days (occasionally longer). The mean annual number of sunshine hours recorded in Belgrade over the 2000 - 2020 period was 2212 h (Lukić, 2025).

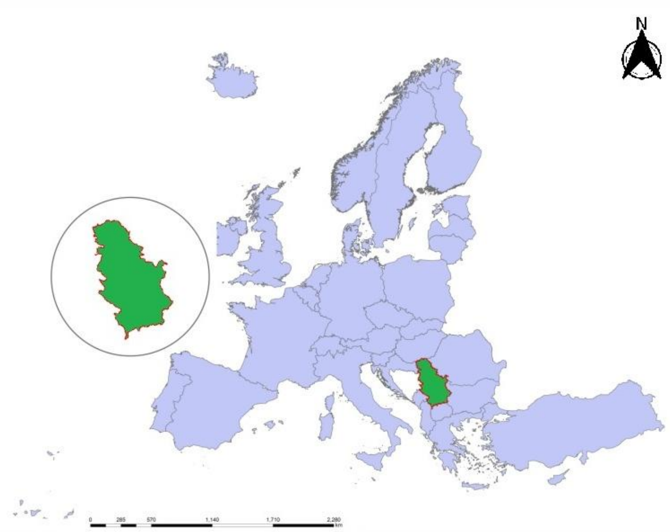

Figure 2. Geographical location of Serbia in Europe. Map was created using the QGIS 3.40.6 software.

Materials and methods

The research was based on climatological data available in the Meteorological Yearbooks published by the Republic Hydrometeorological Service of Serbia (RHSS), for the period 1991-2020 (a standard 30-year timeframe - reference climatological period, in accordance with the World Meteorological Organization - WMO). The data set used on this occasion referred to a set of daily, hourly, minimum and maximum air temperature values that were recorded at the principal meteorological station Belgrade – Observatory 44°48', 20°28', 132 m (Figure 3).

Figure 3. Principal meteorological station Belgrade – Observatory. Source: Author.

Since this meteorological station is located within the territory of the Vračar city municipality, the most densely populated municipality in Belgrade, with a population density of 18 647 inhabitants per km² (according to the 2024 estimates of the Statistical Office of the Republic of Serbia, i.e., 55 942 inhabitants living within an area of approximately 3 km²) in the area characterized by a high density of the built urban fabric and a pronounced deficit of green spaces (only 15.06 ha or 0.15 km^2 of urban greenery have been recorded in this municipality, as noted in the Elaborate for early public inspection for the General Urban Plan of Belgrade 2041), it is evident that the meteorological data recorded at this station are representative for describing the climatic and microclimatic characteristics of Belgrade's central urban zone. The location of the meteorological station Belgrade - Observatory is shown in Figure 4 and Figure 5.

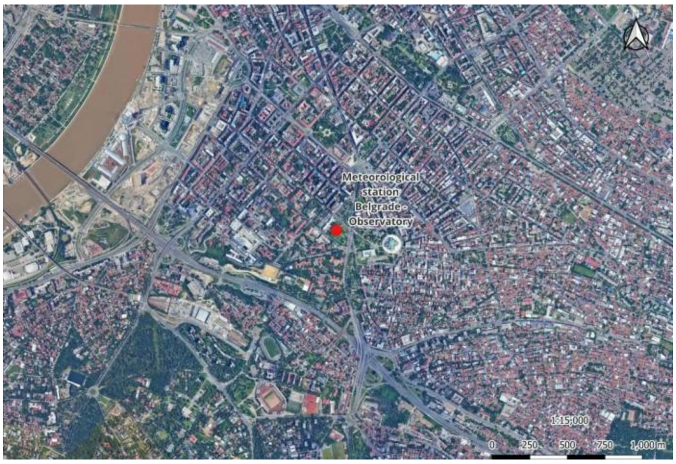

Figure 4. Local-scale location of the meteorological station Belgrade - Observatory (broader view). Source: Google Maps Satellite Imagery. Available at: https://maps.google.com (accessed: 28th January 2026).

Figure 5. Local-scale location of the meteorological station Belgrade - Observatory (detailed view). Source: Google Maps Satellite Imagery. Available at: https://maps.google.com (accessed: 28th January 2026).

The data set on air temperatures is considered homogeneous, complete, and verified, considering its source: the RHSS is the reference national institution that bears full responsibility for the collection and presentation of meteorological data. Based on the aforementioned air-temperature dataset, trends were determined at both seasonal and annual level. Warming corresponds to a positive (or increasing) linear trend, while cooling corresponds to a negative (or decreasing) trend (Zohuri et al., 2022). Linear-regression analysis was applied for trend analysis (i.e. linear trend). It is a widely used statistical technique that serves as a basis for understanding the relationships between variables. Its simplicity and interpretability render it the preferred choice in many studies (Roustaei, 2024). The statistical significance of regression slopes was evaluated using standard t-tests, and p-values were calculated to assess whether the identified trends differ significantly from zero. Apart from the annual level, the results were also analyzed at the decadal level (10-year intervals). Differences in mean annual temperature between decades were tested using one-way analysis of variance (ANOVA) (Sinharay, 2010). The analysis was performed using the Data Analysis Toolpak in Microsoft Excel.

For the seasonal analysis, the meteorological classification of the seasons was applied: spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). This criterion was selected due to its practicality and its widespread use in meteorological analyses. Since, in the meteorological sense, winter spans the period from 1st December to 28/29th February, the determination of seasonal trends during winter required the inclusion of air temperature data recorded in December 1990, as well as in January and February 2021. The air temperature (°C) variables used in this study are presented in Table 1.

Table 1. Air temperature (°C) variables.

Air temperature (°C) variables	Abbr.
Temperature (°C) measured at 07:00h (CET)	T_{07h}
Temperature (°C) measured at 14:00h (CET)	T_{14h}
Temperature (°C) measured at 21:00h (CET)	T_{21h}
Daily mean temperature (°C)	T_{mean}
Maximum temperature (°C)	T_{max}
Minimum temperature (°C)	T_{min}

NUMERICAL RESULTS

Annual air temperature trends in Belgrade (1990-2020)

In this chapter, the research results are presented in detail, both on an annual and seasonal level. Table 2 shows the thirty-year mean air temperature values in Belgrade during the reference period 1991-2020. During that period, the mean annual air temperature (T_{mean}) in Belgrade was 13.2°C, while the average annual maximum temperature (T_{max}) was 18°C. The mean annual minimum temperature (T_{min}) for the period 1991-2020 was 9.1°C.

Additionally, brief consideration can be given to the period 1961–1990, which is often cited as "the last thirty-year period before noticeable impacts of intensified climate change". According to the IPCC, the 1961–1990 period is commonly used as a standard climatological reference baseline against which both subsequent decades and future climate scenarios are compared. As reported by data from the Republic Hydrometeorological Service of Serbia (RHSS), the 30-year mean air temperature (T_{mean}) in Belgrade during this period was 11.9°C, while the corresponding values for maximum (T_{max}) and minimum (T_{min}) air temperatures were 16.6°C and 7.8°C, respectively. The comparison between the two climatological periods (1961–1990 and 1991–2020) reveals a clear and consistent warming signal, with increases of +1.3°C in mean air temperature (T_{mean}), +1.4°C in maximum temperature (T_{max}), and +1.3°C in minimum temperature (T_{min}).

Table 3 shows the mean ten-year values of air temperatures in Belgrade, for each of the three decades of the period under research: I decade (1991-2000), II decade (2001-2010), III decade (2011-2020). For all observed air temperature values (T_{07h}, T_{14h}, T_{21h}, T_{mean}, T_{max} and T_{min}), a trend of increasing values was observed. For instance, an examination of the mean ten-year air temperature in Belgrade measured at 07:00h (or 7 a.m.) (T_{07h}) shows a steady increase over the studied periods: the average value was 10.1°C from 1991–2000, rose to 10.8°C from 2001–2010, and reached 11.5°C in the final decade of the analysis (2011–2020). The mean ten-year air temperatures in Belgrade measured at 2 p.m. (14:00h) ie. T_{14h} has also increased over the past 30 years: during the first decade of the research period, this value was 16.3°C, during the second decade, this value was 16.6°C, while during the third decade it was 17.6°C. Positive climate trends are also indicated by the increase in the mean minimum air temperature values: the average T_{min} value in the period 1991-2000 was 8.4°C, during the period 2001-2010 it was 9.1°C, and during the period 2011-2020 it was 9.8°C.

Also, using one-way analysis of variance (ANOVA) the differences in the T_{mean} air temperature variables between three decades were tested. Results indicate statistically significant differences between the analyzed periods ($F = 10.917$, $p < 0.001$), confirming that the most recent decade (2011–2020) is significantly warmer than earlier periods. Similar results were obtained for evening temperatures (T_{21h}), for which one-way ANOVA also indicated statistically significant differences between the three analyzed decades ($F = 14.384$, $p < 0.001$). Statistically significant differences were also observed for mean maximum temperatures variable T_{max} ($F = 7.842$, $p < 0.01$), although the level of statistical significance is lower compared to evening temperatures, indicating a less pronounced but still consistent warming trend.

Table 2. Mean 30-year air temperature (°C) in Belgrade during the reference period 1991-2020.

Mean 30-year temperature (°C) Ref. per. 1991–2020	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
	10.8	16.8	12.6	13.2	18.0	9.1

Table 3. Mean 10-year (decade) air temperature (°C) in Belgrade during the reference period 1991-2020.

Mean 10-year temperature (°C)	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
1991-2000	10.1	16.3	11.8	12.5	17.5	8.4
2001-2010	10.8	16.6	12.5	13.1	17.8	9.1
2011-2020	11.5	17.6	13.5	14.0	18.8	9.8

Table 4 shows the mean annual values of air temperature (°C) for each year during the observed period (1991-2020). An examination of the five warmest years during 30-year period (highlighted in red, Table 4) indicates that the majority of these occurred after 2011, across most observed air temperature variables (T_{07h}, T_{14h}, T_{21h}, T_{mean}, T_{max}, and T_{min}). Within the analyzed period, the years 2012, 2015, 2018, and 2019 stand out as the warmest. During 2019, the following highest average annual air temperature values were measured in Belgrade: T_{07h} = 12.1°C (the same value was recorded in 2018); T_{14h} = 18.5°C; T_{21h} = 14.3°C; T_{mean} = 14.8°C, and T_{max} = 19.8°C. The highest mean annual minimum temperature in Belgrade during the period 1990-2020 was measured in 2018 (T_{min} = 10.5°C). At the same time, the highest positive temperature anomalies relative to the 30-year average were recorded (1991-2020); for instance, the mean annual air temperature in Belgrade (T_{mean}) in 2019 was 1.6°C above the reference-period average. Furthermore, the value of the mean annual maximum air temperature (T_{max}) in 2019 was higher by 1.8°C compared to the average of the reference period. Regarding the average annual values of air temperature in Belgrade for 2019 measured at 21:00h (T_{21}h), the anomaly was 1.7°C, as well as the values measured at 14:00h (T_{14h}), also 1.7°C. The highest anomaly in the mean annual minimum values (T_{min}) in from the average of the reference period, was recorded in 2018, when it amounted to 1.4°C. In addition to the analysis of extreme years (such as 2019 and 2018), deviations from the reference climatological normal (1991–

2020) were considered in order to provide a clearer perspective on long-term variability. Furthermore, a comparison of decadal averages indicates a progressive increase in temperature values, with the most recent decade (2011–2020) showing the largest deviations from earlier periods within the analyzed period. This pattern confirms an intensification of warming and highlights the increasing departure from previously recorded climatic conditions.

As already mentioned, the linear regression method was used to determine the annual and seasonal trends. Barnes & Barnes (2015) have noted that linear regression can be described as unbiased estimator for the trend analysis The positive (increasing) linear trends in the values of observed air temperature variables (T07h, T14h, T21h, T_{mean}, T_{max}, and T_{min}) recorded at the Belgrade - Observatory in the period 1991-2020 are shown in Figure 6.

Table 4. Mean annual air temperature (°C) Belgrade-Observatory, 1991-2020.

Year	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
T_{07h}	9.0	10.3	9.6	11.1	10.0	9.4	9.5	10.3	10.4	11.6
T_{14h}	15.1	17.2	16.5	17.6	16.2	15.0	15.2	16.3	15.9	18.3
T_{21h}	10.8	12.4	11.4	12.8	11.6	10.8	11.2	12.1	11.8	13.4
T_{mean}	11.4	13.1	12.2	13.6	12.4	11.5	11.8	12.7	12.5	14.2
T_{max}	16.1	18.2	17.5	18.8	17.5	16.1	16.4	17.6	17.2	19.4
T_{min}	7.5	8.7	7.8	9.3	8.3	7.7	7.7	8.5	8.7	9.7
Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
T_{07h}	10.5	11.3	10.3	10.3	9.8	10.5	11.6	11.7	11.4	10.9
T_{14h}	16.1	17.4	16.7	15.8	15.1	16.3	17.6	17.6	17.2	16.5
T_{21h}	12.1	13.0	12.2	11.9	11.3	12.1	13.4	13.4	13.1	12.5
T_{mean}	12.7	13.7	12.8	12.5	11.9	12.8	14.0	14.0	13.7	13.1
T_{max}	17.5	18.6	17.8	17.0	16.3	17.4	18.7	18.9	18.4	17.6
T_{min}	8.7	9.6	8.5	8.7	8.1	8.8	9.7	9.9	9.7	9.2
Year	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
T_{07h}	10.7	11.4	11.4	11.8	11.6	11.1	11.2	12.1	12.1	11.4
T_{14h}	16.8	17.8	17.3	17.6	17.7	17.0	17.6	18.1	18.5	17.4
T_{21h}	12.7	13.6	13.3	13.4	13.7	13.0	13.5	14.1	14.3	13.5
T_{mean}	13.2	14.1	13.8	14.1	14.2	13.5	13.9	14.6	14.8	14.0
T_{max}	17.9	19.0	18.4	18.6	18.8	18.2	19.0	19.3	19.8	18.8
T_{min}	9.0	9.6	9.7	10.3	10.0	9.5	9.5	10.5	10.4	9.9

Source: Lukić, 2025; RHSS - Meteorological Yearbooks, 1991-2020.

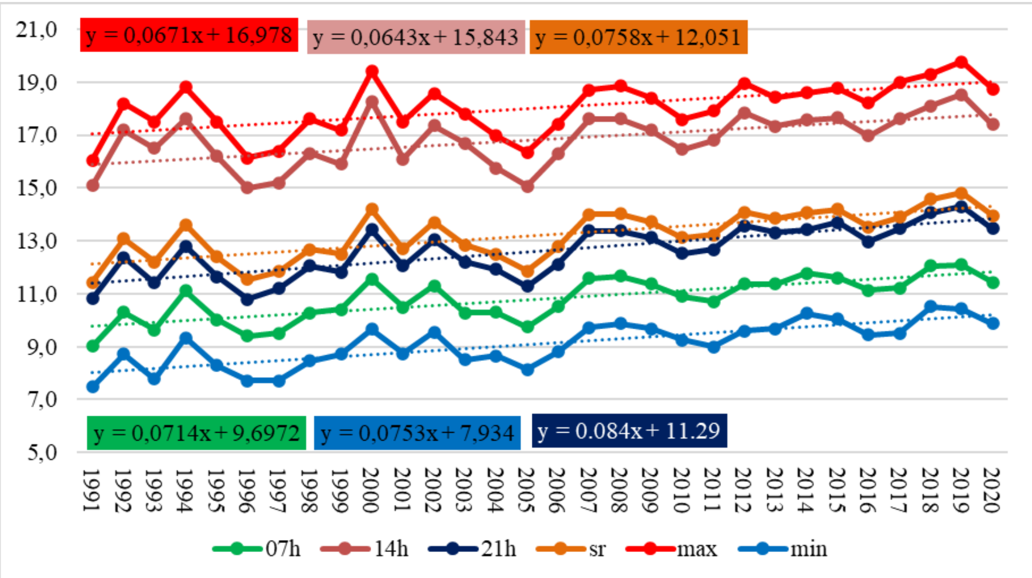

Figure 6. Trend of mean annual air temperatures (°C) in the period 1991-2020, Belgrade – Observatory.

During this period T_{max} values increased at a rate of 0.067°C/year (0.67°C/dec). T_{21h} exhibited the most pronounced positive linear trend whose values increased at a rate of 0.084°C/year (0.84°C/dec). The mean annual temperature (T_{mean}) had a rising trend of 0.075°C/year (0.75°C/dec). Similar results were obtained for T_{min} (0.075°C/year). Morning temperatures in the central urban zone of Belgrade, measured at 07:00h, increased at a rate of 0.071°C/year (0.71°C/dec), while the air temperature values measured at 14:00h had a positive linear trend of 0.064°C/year (0.64°C/dec). To strengthen the reliability of the analysis, linear regression statistics were calculated for all annual air temperature variables during the period 1991–2020. The results (Table 5) confirm statistically significant positive trends for all analyzed parameters ($p < 0.001$). The magnitude of the trends, expressed as slope coefficients (°C/year), shows that the most pronounced increase is observed for evening air temperatures (T_{21h}), followed by mean annual air temperature ($_{Tmean}$) and minimum temperature (T_{min}). The coefficients of determination (R^2) indicate that a substantial proportion of the observed variability in temperature can be explained by the temporal trend, particularly for T_{21h} and T_{min}, suggesting a persistent warming signal in the central urban zone of Belgrade.

Table 5. Linear regression statistics for annual air temperature variables in Belgrade-Observatory (1991–2020).

Variables	Slope (°C/year)	Trend (°C/decade)	R^2	Level of significance, p-value
$\mathbf{T_{07h}}$	0.0714	0.714	0.570	<0.001
$\mathbf{T_{14h}}$	0.0643	0.643	0.326	<0.001
$\mathbf{T_{21h}}$	0.0846	0.846	0.596	<0.001
$\mathbf{T_{mean}}$	0.0758	0.758	0.524	<0.001
$\mathbf{T_{max}}$	0.0671	0.671	0.356	<0.001
$\mathbf{T_{min}}$	0.0753	0.753	0.617	<0.001

Air temperature trends in Belgrade during spring

Table 6 shows the mean seasonal air temperature in Belgrade during the spring (March, April, May) for reference period 1991-2020. During the research period the mean spring air temperature (T_{mean}) in Belgrade was 13.4°C, while the mean spring maximum temperature (T_{max}) was 18.5°C. The mean spring minimum temperature (T_{min}) was 8.7°C. The mean spring air temperature in Belgrade measured at 07:00h (T_{07h}) was 10.7°C, while the mean spring air temperature measured at 14:00h (T_{14h}) was 17.2°C and the mean spring air temperature measured at 21:00h (T_{21h}) was 12.7°C. The highest mean spring values of the observed temperature variables during the research period were recorded during the spring of 2018, when their values were: T_{07h} = 12.7°C, T_{14h} = 19.4°C, T_{21h} = 15°C, T_{mean} = 15.6°C, T_{max} = 20.6°C and T_{min} = 10.8°C. In 2018, the spring in Belgrade was as much as 2°C warmer than the average of the reference period. More precisely, the mean daily temperature in Belgrade ie. T_{mean} during the spring of 2018 was 2.2°C higher than the 1991-2020 average, while the mean maximum spring temperature ie. T_{max} was 2.1°C higher. The air temperature measured at 21:00h (T_{21h}) that spring was higher by as much as 2.3°C compared to the average values of the reference period.

Table 7 shows the mean ten-year spring values of air temperatures in Belgrade central urban zone, for each of the three decades of the period under research: I decade (1991-2000), II decade (2001-2010), III decade (2011-2020). All analyzed air temperature variables (T_{07h}, T_{14h}, T_{21h}, T_{mean}, T_{max}, and T_{min}) exhibited an increasing trend during this period. For example, the mean ten-year spring air temperature measured at 07:00h (T_{07h}) shows increase: the average value was 10°C from 1991–2000, rose to 11°C from 2001–2010, and reached 11.1°C in the final decade (2011–2020). During the first decade of the research period (1991-2000), the average value of spring T_{max} was 17.8°C, and during the third decade of research (2011-2020) it was 19°C. Observing other variables reveals similar patterns: in the period 1991-2000 the average spring 10-year T_{min} value was 7.9°C, in the period 2001-2010 the average value of T_{min} was 9°C, while in the period after 2011 it was 9.3°C. The mean 10-year spring air temperatures in Belgrade measured at 21:00h (T_{21h}) have also increased over the past 30 years: during the first decade of the research period, this value was 11.9°C, during the second decade it was 12.9°C, while during the third decade it was 13.5°C.

Table 6. Mean seasonal air temperature (°C) in Belgrade during spring for the reference period 1991–2020.

Mean spring temperature (°C) Ref. per. 1991–2020	$\mathbf{T_{07h}}$	$\mathbf{T_{14h}}$	$\mathbf{T_{21h}}$	$\mathbf{T_{mean}}$	$\mathbf{T_{max}}$	$\mathbf{T_{min}}$
	10.7	17.2	12.7	13.4	18.5	8.7

Table 7. Mean 10-year (decade) seasonal air temperature (°C) in Belgrade during spring.

Mean 10-year spring temperature (°C)	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
1991-2000	10.0	16.6	11.9	12.6	17.8	7.9
2001-2010	11.0	17.4	12.9	13.5	18.6	9.0
2011-2020	11.1	17.7	13.5	13.9	19.0	9.3

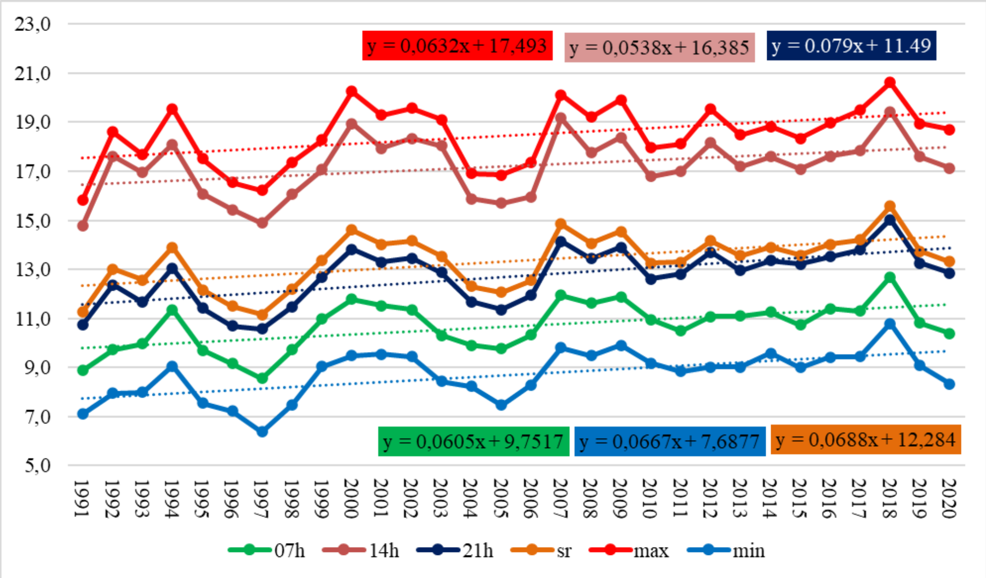

Figure 7. Trend of mean spring air temperatures (°C) in the period 1991-2020, Belgrade – Observatory.

Figure 7 illustrates the positive linear trends of the analyzed spring air temperature variables (T07h, T14h, T21h, Tmean, Tmax, and Tmin) observed at the Belgrade - Observatory during the 1991–2020 period. An examination of the presented results indicates that the mean spring T21h values exhibited the highest rate of increase over the analyzed 30-year period, amounting to 0.079°C/year (0.79°C/dec). A positive linear trend was also observed for spring Tmean, with an increase of 0.068°C/year (0.68°C/dec). Tmin showed a trend of 0.066°C/year (0.66°C/dec), while the corresponding trend for Tmax was 0.063°C/year (0.63°C/dec). These results indicate an overall increase in spring air temperatures in Belgrade.

Air temperature trends in Belgrade during summer

Table 8 displays the mean seasonal air temperature in Belgrade central urban zone during the summer (June, July, August) for the reference period 1991-2020. The mean 30-year summer air temperature (T_{mean}) in Belgrade was 23.2°C, while the average summer maximum temperature (T_{max}) was 28.7°C. The average summer minimum temperature (T_{min}) for the reference period was 17.9°C. The average summer temperature in morning hours in Belgrade (measured at 07:00) T_{07h} was 20.5°C, while the average evening temperature (measured at 21:00) T_{21h} was 22.3°C.

The highest mean summer values of the analyzed air temperature variables during the study period were recorded in the summer of 2012. During this season, the following values were observed: T_{07h} = 22.8°C, T_{14h} = 30.7°C, T_{21h} = 25.3°C, T_{mean} = 26.0°C, T_{max} = 31.9°C, and T_{min} = 19.8°C. Compared to the reference period (1991–2020), the summer of 2012 in Belgrade was 2.8 °C warmer on average. Specifically, the mean daily summer temperature (T_{mean}) exceeded the long-term average by 2.8°C, while the mean summer maximum temperature (Tmax) was 3.1°C higher. Evening air temperatures (T_{21h}) during the summer of 2012 were elevated by 3.0°C relative to the reference period, whereas morning temperatures (T07h) exceeded the long-term mean by 3.2°C. Mean summer minimum temperature (T_{min}) was 1.95°C higher than the reference period.

Table 9 presents the decadal mean summer air temperature values for Belgrade over the three decades of the study period: the first decade (1991–2000), the second decade (2001–2010), and the third decade (2011–2020). An analysis of the presented values for all examined variables indicates an overall increase in air temperatures in Belgrade, particularly after 2011. For instance, the mean summer air temperature (T_{mean}) recorded at the Belgrade - Observatory meteorological station was 22.5°C during the 1991–2000 period and increased to 22.9°C in 2001–2010, reaching 24.1°C in 2011–2020. The mean minimum summer temperatures (T_{min}) also showed an increasing trend when comparing the first decade of the study period (1991–2000) with the third decade (2011–2020): the values rose from 17.1°C to 18.7°C. A similar pattern is observed for the summer maximum temperatures in Belgrade, with the mean maximum temperature (T_{max}) increasing from 28.3°C in 1991–2000 to 29.5°C in 2011–2020.

Table 8. Mean seasonal air temperature (°C) in Belgrade during summer for the reference period 1991–2020.

Mean summer temperature (°C) Ref. per. 1991–2020	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
	20.5	27.5	22.3	23.2	28.7	17.9

Table 9. Mean 10-year (decade) seasonal air temperature (°C) in Belgrade during summer.

Mean 10-year summer temperature (°C)	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
1991-2000	19.9	27.1	21.6	22.5	28.3	17.1
2001-2010	20.4	27.2	22.0	22.9	28.4	17.8
2011-2020	21.3	28.3	23.3	24.1	29.5	18.7

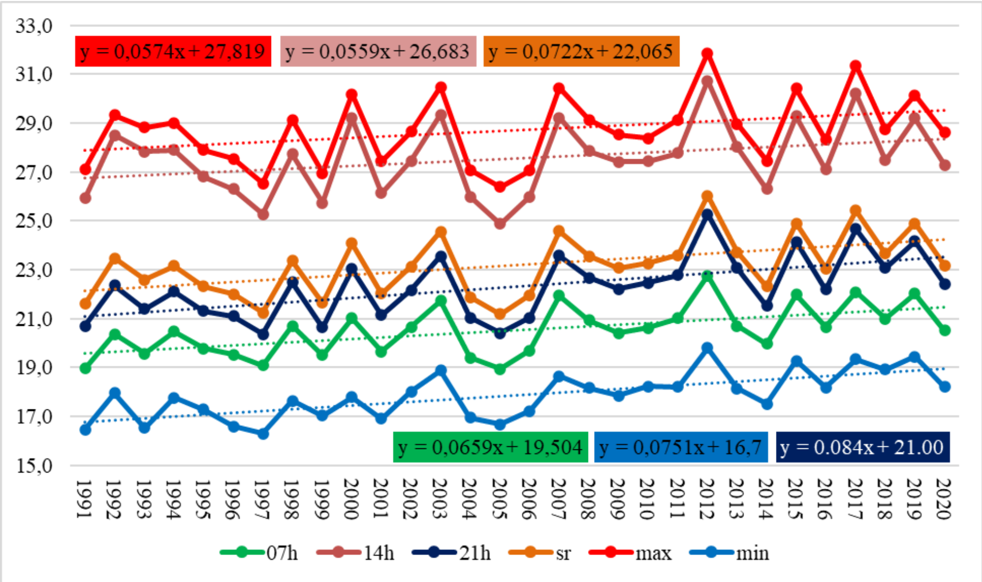

Figure 8. Trend of mean summer air temperatures (°C) in the period 1991-2020, Belgrade – Observatory.

Figure 8 illustrates the positive linear trends of the observed summer air temperature variables (T07h, T14h, T21h, Tmean, Tmax, and Tmin) recorded at the Belgrade - Observatory (principal meteorological station) during the 30-year period. An examination of the presented linear trends reveals a moderate but consistent increase in summer air temperatures in Belgrade. The most pronounced increase in summer values was observed for evening temperatures ie. T21h, with a trend of 0.084°C/year (0.84°C/dec).

This was followed by mean summer minimum temperatures ie. Tmin, which increased at a rate of 0.075°C/year (0.75°C/dec). Mean daily summer temperatures (Tmean) also exhibited a positive trend of 0.072°C/year (0.72°C/dec). Mean summer maximum temperatures (Tmax) showed the lowest rate of increase, amounting to 0.057°C/year (0.57°C/dec).

Air temperature trends in Belgrade during autumn

Table 10 shows the mean seasonal air temperature in Belgrade central urban zone during the autumn (September, October, November) for the period 30-year period (1991-2020). Based on the presented results, the mean daily air temperature (T_{mean}) during the autumn season in Belgrade was 13.3°C. The mean autumn minimum (T_{min}) temperature amounted to 9.5°C, while the mean autumn maximum temperature (T_{max}) was 18.4°C.

The warmest autumn within the analyzed 30-year period was recorded in 2019, when the highest mean values of all examined temperature variables were observed: T_{07h} = 13.1°C, T_{14h} = 20.8°C, T_{21h} = 15.5°C, T_{mean} = 16.2°C, T_{max} = 22.1°C, and T_{min} = 11.8°C. Autumn 2019 was, on average, 2.9°C warmer than the long-term mean: for instance, the mean maximum temperature (T_{max}) was higher by 3.7°C compared to the 30-year average, while the mean temperature measured at 14:00h (T_{14h}) exceeded the long-term mean by 3.5°C. Morning temperatures measured at 07:00h (T_{07h}) were higher by 2.4°C, whereas mean minimum temperatures (T_{min}) were higher by 2.3 °C.

Table 11 shows the mean ten-year autumn values of air temperatures in Belgrade, for each of the three decades of the study period: the first decade (1991-2000), the second decade (2001-2010), and the third decade (2011-2020). The examination of the presented results indicates that the average values of all analyzed variables increased from one decade to the next, particularly after 2011.

For example, the mean morning air temperature (T_{07h}) during the 1991–2000 period was 10.0°C, increased to 10.7°C in 2001–2010, and reached 11.6°C in 2011–2020. A similar pattern is observed for evening temperatures measured at 21:00h: the mean 10-year T_{21h} was 11.8°C in 1991–2000, rose to 12.4°C during the following decade (2001–2010), and further increased to 13.6°C after 2011. This is further supported by the results presented in Figure 9, which illustrates the linear trend of autumn air temperatures in Belgrade over the 1991–2020 period.

The observed linear trends indicate increases in mean, minimum, maximum, as well as all analyzed time-specific temperature values (07h, 14h, 21h). Over the analyzed period, the most rapid increase was recorded for T_{21h}, with a rate of 0.091°C/year (0.91°C/dec), followed by T_{min} and T_{mean}, both exhibiting trends of 0.086°C/year (0.86°C/dec). The T_{07h} variable increased at a rate of 0.081°C/year (0.81°C/dec). These positive trends suggest that autumn seasons in Belgrade are becoming progressively warmer.

Table 10. Mean seasonal air temperature (°C) in Belgrade during autumn for the reference period 1991–2020.

Mean autumn temperature (°C) Ref. per. 1991–2020	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
	10.7	17.3	12.6	13.3	18.4	9.5

Table 11. Mean 10-year (decade) seasonal air temperature (°C) in Belgrade during autumn.

Mean 10-year autumn temperature (°C)	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
1991-2000	10.0	16.7	11.8	12.6	17.8	8.8
2001-2010	10.7	16.9	12.4	13.1	18.1	9.4
2011-2020	11.6	18.3	13.6	14.3	19.3	10.4

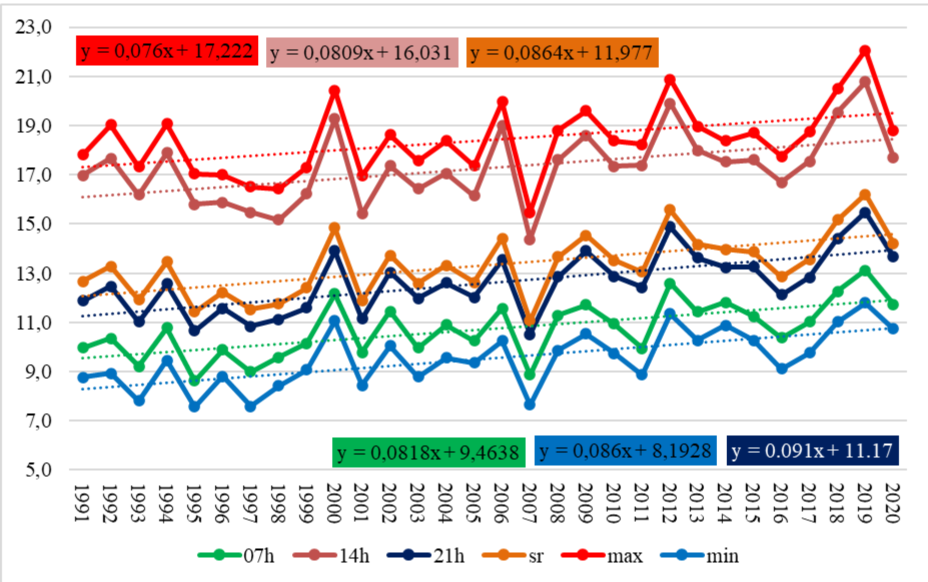

Figure 9. Trend of mean autumn air temperatures (°C) in the period 1991-2020, Belgrade – Observatory.

Air temperature trends in Belgrade during winter

Table 12 displays the mean seasonal air temperature in Belgrade central urban zone during the winter (December, January, February) for the reference period. The mean 30-year winter air temperature ie. T_{mean} in Belgrade was 2.9°C, while the mean winter maximum temperature (T_{max}) was 6.4°C. The mean winter minimum temperature (T_{min}) for the reference period was 0.2°C. The mean winter morning air temperature in Belgrade (measured at 07:00h) ie. T_{07h} was 1.2°C, while the mean evening temperature (measured at 21:00h) ie. T_{21h} was 2.7°C. During the observed 30-year period, the warmest winter was recorded during the 2006/07 season. The highest average winter values of the observed temperature variables recorded during the winter of 2006/07 were: T_{07h} = 4.2°C, T_{14h} = 8.9°C, T_{21h} = 6.1°C, T_{mean} = 6.4°C, T_{max} = 10.0°C, and T_{min} = 3.4°C.

During the season 2006/07, the winter in Belgrade was as much as 3.4°C warmer in average than the mean values of the reference period. For instance, the mean daily temperature in Belgrade (T_{mean}) during the winter of 2006/07 was 3.4°C higher than the 1991-2020 average, while the mean maximum winter temperature (T_{max}) was 3.6°C higher. The mean air temperature measured at 14:00h (T_{14h}) during the winter of 2006/07 was higher by as much as 3.7°C comparing with the average values of the reference period. The average minimum seasonal temperature (T_{min}) in Belgrade during the winter of 2006/07 was 3.2°C higher than the average of the reference period. The results shown in Table 12 and Figure 8 indicate that winters in Belgrade are becoming milder and warmer.

Table 13 represents the mean 10-year winter air temperature in Belgrade during the three decades of the study period, while Figure 10 shows trend of mean winter air temperatures over 30 years. All analyzed air temperature variables (T_{07h}, T_{14h}, T_{21h}, T_{mean}, T_{max}, and T_{min}) exhibited an increasing trend during the researched period. For instance, the mean morning 10-year winter temperature ie. T_{07h} shows an increase in its values: the mean value was 0.4°C from 1991–2000, rose to 1.1°C from 2001–2010, and reached 1.9°C in the third decade (2011–2020). During the first decade of the research period (1991-2000), the mean value of winter T_{max} was 5.9°C, and during the third decade of research (2011-2020) it was 7.2°C. Observing other variables reveals similar patterns: in the period 1991-2000 the mean winter 10-year T_{min} value was -0.5°C, in the period 2001-2010 the average value of T_{min} was 0.1°C, while in the period after 2011 it was 0.9°C. The mean evening 10-year winter air temperature in Belgrade (T_{21h}) also shows an increase in its values over the past 30 years: during the first decade (1991-2000), this value was 2.0°C, during the second decade it was 2.6°C, while during the third decade it was 3.5°C.

The most pronounced increase in winter values was observed for evening temperatures ie. T_{21h}, with a trend of 0.082°C/year (0.82°C/dec). This was followed by mean morning winter temperatures ie. T07h, which increased at a rate of 0.08°C/year (0.8°C/dec). Mean daily winter temperatures ie. T_{mean} also exhibited a positive linear trend of 0.079°C/year (0.79°C/dec). Mean winter temperatures measured at 14:00h (T_{14h}) showed the lowest rate of increase, amounting to 0.069°C/year (0.69°C/dec).

Table 12. Mean seasonal air temperature (°C) in Belgrade during winter for the reference period 1991–2020.

Mean winter temperature (°C) Ref. per. 1991–2020	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
	1.2	5.2	2.7	2.9	6.4	0.2

Table 13. Mean 10-year (decade) seasonal air temperature (°C) in Belgrade during winter.

Mean 10-year winter temperature (°C)	T_{07h}	T_{14h}	T_{21h}	T_{mean}	T_{max}	T_{min}
1991-2000	0.4	4.7	2.0	2.3	5.9	-0.5
2001-2010	1.1	4.9	2.6	2.8	6.0	0.1
2011-2020	1.9	6.0	3.5	3.7	7.2	0.9

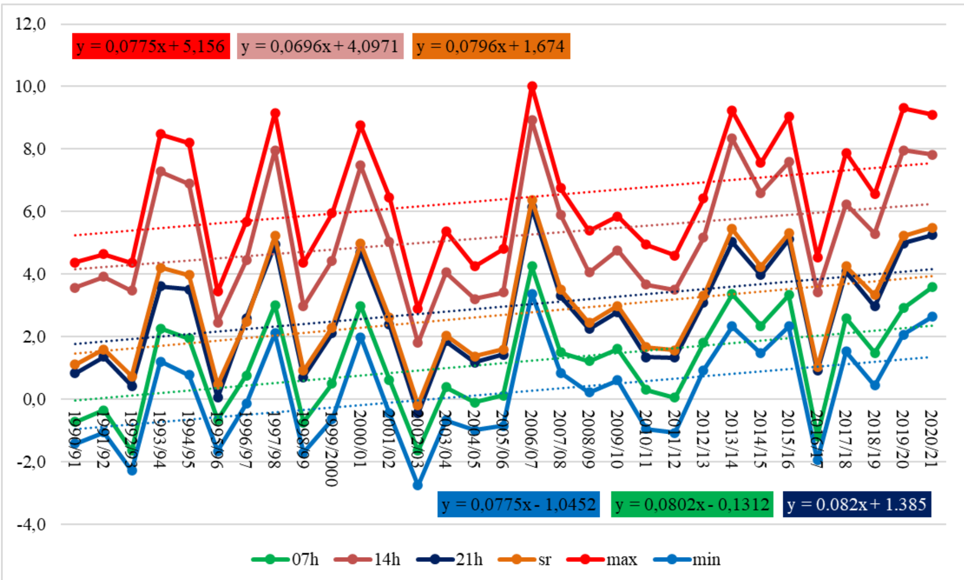

Figure 10. Trend of mean winter air temperatures (°C) in the period 1991-2020, Belgrade – Observatory.

DISCUSSION

The results obtained in this research are consistent with, build upon, and complement the findings of previously conducted climatic and microclimatic studies. Regarding national level, the Republic of Serbia belongs to a group of countries and regions that are warming faster than the global average, i.e. it belongs to the so-called "hot spots", which is why these areas are more often exposed to extreme events (heat waves, droughts, floods, etc.) and extreme temperatures.

In Serbia, during the reference climate period 1961-1990, the mean annual temperature was 10.2°C. According to RHSS data, the mean annual air temperature in Serbia during the period 1991-2020 was 11.1°C. Climate Change Adaptation Programme for the period 2023-2030 highlights that Serbia's climate is warming faster than the global average. According to the IPCC (2021) report, planet Earth is 1.1°C warmer, while the Copernicus Climate Change Service (C3S) data show that global warming caused by human activity has reached approximately 1.2°C above the period 1850-1900. In Serbia the mean annual temperature is already 1.8°C higher, and the mean summer temperature is 2.6°C higher. This trend is also confirmed by the Vuković-Vimić & Vujadinović-Mandić (2024a; 2024b), who state that in the period 2001–2020 the average temperature in Serbia was 1.4°C higher than the average for the period 1961–1990, while in the period 2011–2020 it was higher by 1.8°C. Regarding extreme temperatures, Milovanović et al. (2023) have conducted frequency analysis of absolute maximum air temperatures, using annual maximum series in the period 1961–2010 from 40 climatological stations in Serbia (including Belgrade) and findings indicate the possible occurrence of much higher absolute maximum air temperatures in the future than the ones recorded. Regarding extreme events, frequency of years with drought in Serbia has increased from 1 per decade during 1961–1990 to 5 per decade during 2011–2020 (Vuković Vimić et al., 2022).

Bajat et al. (2014) analyzed mean monthly air temperature values recorded at 64 meteorological stations across the Republic of Serbia. Over the period 1961–2010, an increase in temperature values was observed, particularly after 1989, when a positive trend was registered at nearly all stations, ranging from 0.18°C/dec to 3.63°C/dec. Furthermore, an analysis of daily minimum and maximum temperatures from 15 meteorological stations for the period 1949–2009 indicated a warming tendency in Serbia's climate beginning in the mid-to-late 20th century, with the trend becoming especially pronounced after 2000, i.e., at the start of the 21st century. In addition to the rise in mean daily and extreme air temperature values (minimum and maximum), an increasing trend in the number of summer and tropical days (and nights) was identified, while the number of "ice days" has been decreasing (Unkašević & Tošić, 2013). Vuković et al. (2018) reported that the average increase in mean annual temperature in the Republic of Serbia during 1996–2015 amounted to 1.2°C (relative to the 1961–1980 baseline period), with the most pronounced rise observed in maximum temperatures during the summer season (2.2°C).

Bačević et al. (2021) have investigated spatiotemporal variability of air temperatures in Central Serbia from 1949 to 2018. In this study, based on data from 24 meteorological stations, authors presented the trends for three categories of variables: mean annual, mean maximum and mean minimum air temperatures. The highest increase was recorded in the mean maximum time series of 4.2°C, followed by an increase of 3.5°C in mean maximum air temperatures. The lowest increases were recorded in the mean minimum time series (0.1-0.2°C). A recent study by Bačević et al. (2026) examined air temperature variability during the vegetation period in Central Serbia over 70 years (form April to October). The results obtained indicate a warming trend, which, in addition to affecting local climate conditions, may also affect agriculture and food production.

According to Đurđević et al., (2018) it is expected that air temperature values in the territory of Serbia will continue to rise, and that by the end of the 21st century they will be higher on average by 3°C to 5°C compared to the middle of the 20th century, which will cause an even more significant change in climate conditions, and favor the more frequent occurrence of extreme events in the future. As Vuković-Vimić & Vujadinović-Mandić (2024a) claim for the mid-century period, an expected increase of average air temperature for Serbia is about 3.1°C. Tošić et al. (2023) conducted a comprehensive analysis of changes in mean and extreme temperature indices for Serbia during the period 1951-2020, and the results confirmed the warming trend that dominated for 70 years. The highest increase was observed for „warm nights" ($T_{min} \geq 20°C$) of 7 days/dec during the summer season. All of this affects the climatic conditions in Belgrade, as confirmed by various authors.

Unkašević et al. (2005) investigated the influence of rising mean summer air temperatures in Belgrade during 1975–2003 on changes in minimum (T_{min}) and maximum temperatures (T_{max}). Their results indicated that the mean summer temperature increased by 0.132°C/year, the mean minimum temperature by 0.138°C/year, and the mean maximum temperature by 0.104°C/year. An even more pronounced increase was recorded for the highest summer maximum temperatures, which rose at a rate of 0.164°C/year over the same period. Đorđević (2008) analyzed mean (T_{mean}), minimum (T_{min}), and maximum (T_{max}) air temperature values in Belgrade over the period 1888–2006. For example, the mean winter air temperature exhibited a positive trend of 1.95°C/100 years, while the winter maximum temperature showed an increase of 1.68°C/100 years. The most pronounced rise, however, was observed in winter minimum temperatures, with a trend of 2.97°C/100 years. Overall, across the 118-year study period, minimum air temperatures (T_{min}) increased most rapidly in the remaining seasons as well: minimum spring temperatures showed a trend of 1.92°C/100 years, minimum summer temperatures 1.95°C/100 years, and minimum autumn temperatures 1.69°C/100 years.

In order to comprehensively assess and identify altered climatic conditions, it is necessary to consider studies based on multi-decadal time series. One such investigation was conducted by Unkašević & Tošić (2009a), who analyzed heat waves recorded during the three summer months (June, July, and August) using data on maximum daily temperatures (T_{max}) from Belgrade (1943–2007), Smederevska Palanka (1949–2007), and Niš (1948–2007). Heat waves in Belgrade and Niš were further examined by Unkašević & Tošić (2009b) for the period 1948–2004, during which an increase in the number of "tropical days" ($T_{max} \geq 30°C$) was documented, particularly after 1975. Unkašević & Tošić (2015) extended their analysis of cold and heat waves in Serbia beyond 2007, supplementing their earlier research with a study focused on the seasonal variability of cold and heat waves over the period 1949–2012. This research was based on meteorological data collected from 15 stations across Serbia, including Belgrade. The years 2007 and 2012 were identified as record-breaking. July 2007 was 3.3°C warmer than the long-term average. The extreme maximum temperatures recorded across Serbia led to the exceedance of previously observed absolute maxima at nearly all meteorological stations (Anđelković, 2007; Unkašević & Tošić, 2011). In Belgrade, a temperature of 43.6°C was measured during the summer of 2007, surpassing the prior record by 3.1°C (Unkašević & Tošić, 2011).

A study by Čegar et al. (2023a) showed that the mean annual air temperature in Belgrade during 1961–2020 followed a positive trend of 0.042°C/year, with similar tendencies observed for mean monthly values. The highest trends were identified during the summer months: the mean August temperature increased at a rate of 0.075°C/year, the mean July temperature at 0.060°C/year, and the mean June temperature at 0.046°C/year. Among the winter months (December, January, and February), February stood out, with a positive trend of 0.048°C/year. Within the spring season, the most rapid increases were observed in March and April, with trends of 0.046°C/year and 0.043°C/year, respectively.

Similar trends can also be observed when studies from the region are taken into consideration. Bačević et al. (2020) analyzed air temperature data measured in Podgorica (Montenegro) during the period 1947–2018. The authors found that the mean annual air temperature in Podgorica increased by 1.4°C, the mean maximum air temperature increased by 2.5°C and mean minimum air temperature increased by 0.6°C. Analyzing temperature trends in Banja Luka (Bosnia and Herzegovina) for the period 1961–2022, Popov et al. (2023) reported an increase in air temperature at the annual level of 0.51°C/decade. Regarding seasonal trends, the highest warming rates were observed in summer (0.68 °C/ decade) and winter (0.57°C/decade). Gnjato et al. (2021) analyzed extreme climate indices in Sarajevo during the period 1961–2016 and found that annual T_{max} and T_{min} increased by 0.42°C/decade and 0.32°C/decade, respectively. As Bonacci et al. (2018) reported, during the 68-year period (1949–2016) the mean annual air temperature in Zagreb (Croatia), where the meteorological station is located on a small hill in the inner-city centre, increased by 1.84°C or 0.0276°C/year. Over the same period, the minimum air temperature in Zagreb increased by 3.67°C or 0.0539°C/year.

Finally, it is important to briefly address the period after 2020. Although this study focuses on the 1991–2020 period, it should be noted that 2024 was the warmest year on record in Serbia at all principal meteorological stations, with a mean temperature anomaly of +2.3°C relative to the 1990–2020 reference period. In the same year, record values of the mean annual maximum and mean annual minimum air temperature were also observed in Serbia.

In Belgrade, 2024 was the warmest year since 1888, with a temperature anomaly of +2.7°C. According to data from the Republic Hydrometeorological Service of Serbia (RHSS), at the principal meteorological station Belgrade – Observatory, a total of 67 tropical nights ($T_{min} \geq 20°C$) were recorded in 2024, which is 41 nights above the long-term average, exceeding the previous record of 57 tropical nights recorded in 2012. The second warmest year in Serbia since 1951 was 2023, with a mean air temperature anomaly of +1.5°C, while in Belgrade the anomaly reached +1.7°C. Looking back on this past year, 2025 is ranked as the third warmest year in Serbia since 1951, with a mean annual temperature anomaly of +1.3°C relative to the 1990–2020 average. In Belgrade, 2025 was the fourth warmest year since 1888, with an anomaly of +1.5°C.

Accordingly, these results clearly indicate that the previously identified warming trends are likely to continue in the coming decades.

Urban development, land-use change and implications for urban climate in Belgrade

Urban development, land use, and the urban microclimate are closely related. The way in which the urban fabric is transformed under the influence of excessive urbanization often causes a series of direct and indirect implications that affect the local climate. As Tsoka et al. (2017) noted the gradual transformation of the morphological structure of urban areas, particularly through the expansion of surfaces dominated by artificial materials such as asphalt, concrete, steel, and glass instead of natural land cover increases the amount of heat energy in cities (high heat-absorbing properties). According to Khan et al. (2025) anthropogenic heating (AH) is also a significant factor (heat generated by human activities, primarily industrial processes, transport and energy consumption). The combined effect of these factors contributes to the development of the UHI phenomenon, whereby air temperatures in urban areas are generally higher than those measured in surrounding suburban and rural environments (Gunawardena et al., 2017). This has also been confirmed by IPCC Sixth Assessment Report (WG1), where it is pointed out that urbanization has exacerbated changes in temperature extremes in cities, in particular for nighttime extremes (high confidence).

Similar patterns are observed in Belgrade. Regarding the main challenges of contemporary urban development of Belgrade, many domestic researchers agree that some of them are: land-use change, intensive urbanization, heavy traffic, lack of open public spaces and green areas (Lukić & Lukić, 2022; Lukić, 2025; Mitić-Radulović & Lalović, 2021; Mitić-Radulović et al., 2022a; 2002b), usurpation and questionable management of open public spaces (Živković et al., 2025), ethically unsound urban governance practices, large corporate building projects (Čolić Marković & Sturm, 2025; Ćorović et al., 2025, Graovac et al., 2024), etc. The above also presents a significant challenge for establishing long-term climate-conscious urban planning, sustainable land-use policies, and future adaptation strategies.

As the number of active construction sites grows, Belgrade justifiably holds the title of „the largest construction site in Europe" as Mitić-Radulović et al. (2022a,b) claim. Construction activity in Belgrade has intensified considerably in recent years: as much as 30% of all construction works carried out in Serbia in 2020 took place in Belgrade. Between 2016 and 2020, the annual number of new apartments increased by 70%, the annual value of construction works rose by 105%, while the annual number of square meters of newly built high-rise buildings grew by as much as 350% (Mitić-Radulović, 2022a,b). The most intensive construction takes place in the central city municipalities: Vračar, Savski venac and Stari grad, which are already characterized by dense built-up areas, while green spaces are scarce and unevenly distributed, which makes those parts of the city particularly sensitive to the consequences of climate change (Lukić & Lukić, 2022; Lukić, 2025; Mitić-Radulović, 2022a,b). At the same time, the share of green areas is decreasing, which is confirmed by data available in various planning and strategic documents adopted for the City of Belgrade.

These unsustainable practices of urban planning and management also indirectly affect the city's microclimate and increased levels of thermal discomfort, especially in Belgrade central urban zone. Pronounced increase in evening temperatures (T_{21h}) and reduced nocturnal cooling are not only consequences of global warming, but are also likely intensified by rapid urbanization processes, anthropogenic heat emissions, and limited green infrastructure in densely built urban districts such as Vračar.

According to the Elaborate for early public inspection for the General Urban Plan of Belgrade 2041, Vračar is the city municipality with the least representation of green spaces with only 5% of the total territory (0.15 km^2). Such a densely built environment contributed to the fact that during the summer of 2024, as many as 67 tropical nights were recorded in Vračar (RHSS, 2024). Similar patterns are observed in other highly urbanized districts of Belgrade. For instance, research that dealt with the analysis of tropical nights in Belgrade, which were recorded in the period June-August 2008-2017 shows that the central urban area, which is deficient in green spaces, is also the most affected by the urban heat island effect (Filipović & Đurđević, 2023; Simić, 2023).

To what extent urban greenery in a microlocation can influence the outdoor thermal comfort and air temperature in densely built districts of Belgrade, shows the research conducted by Savić et al. (2024). The study showed that urban greenery can lower the temperature in the hottest part of the day by up to 7°C. Similar study was conducted in Novi Sad (Serbia), where the highest mean air temperature during the observation period was 8 degrees lower in the city park, compared to the main city square. Research on the impact of urban greenery on the microclimate conducted by Bukovetz et al. (2023) with in-situ measurements in Skopje (North Macedonia) showed that the differences in the highest measured air temperatures when comparing the values in the main urban park and the street with no greenery were as much as 7.9°C. This suggest that by changing the approach to urban development towards a climate-conscious planning practice, increasing urban greenery and applying nature-based solutions (NbS), it is possible to contribute to the regulation of thermal stress, urban microclimate, and mitigation of UHI.

Study limitations

To ensure the transparency and scientific rigor of the research process, in addition to presenting the obtained results, it is important to highlight the shortcomings of this study and its methodological limitations, as well as to indicate directions for future research.

Although this study makes a significant contribution to the analysis of long-term air temperature trends in the central urban zone of Belgrade, and to a better understanding of the practical application of microclimatic data in urban planning, its key limitation lies in the restricted availability of meteorological data.

The municipality of Vračar (where meteorological station is located) is a good representative of densely built Belgrade's urban districts that are characterized by a deficit of greenery and are therefore more severely affected by the UHI therefore, the air temperature data collected at this station give us a general insight into the current state and trends.

Still, one of the main limitations is that the analysis relied on data recorded at only one meteorological station (Belgrade - Observatory), which limits the possibility of a precise assessment of the spatial distribution of microclimatic conditions within the urban area of Belgrade. The analysis presented in this paper is based on the existing data of the Republic Hydrometeorological Service of Serbia (RHSS) for the reference period 1991–2020 and on theoretical models, without systematic micrometeorological measurements conducted simultaneously at different locations.

There are no publicly available data on continuous measurements of daily and hourly values of meteorological parameters at multiple locations within the city, which complicates analyses of different urban zones. More precisely, the daily data on hourly measurements (07h, 14h, and 21h) over a longer time period, on which this research is based, and which were taken from the Meteorological Yearbook – Climatological data published by the RHSS, are available for only a few meteorological stations in Serbia, including Belgrade-Observatory.

The directions of the author's future work will be aimed at advocating greater availability of meteorological data collected at meteorological stations throughout Serbia, especially hourly values. It is necessary to ensure the transparency and availability of such data, especially for young researchers, but also for the entire scientific community.

The cooperation of national institutions with the academic community, including RHSS, is a prerequisite for the successful adaptation to changed climatic conditions, and the availability of precise and reliable data is necessary not only for researchers, but also for urban planners and policy-makers. In addition, besides studies based on data provided by the RHSS, it would be valuable to conduct field research using mobile meteorological stations at key points across the wider Belgrade urban area (city center, sub-urban area, riverbanks, green spaces, industrial and business zones, residential areas, etc.). One such study was conducted by Savić et al. (2024), who examined how green spaces in the densely built urban core of Belgrade can contribute to mitigating extreme weather conditions and high temperatures during heat waves. It would be very useful if such studies were more regular, continuous, with systemic support and cooperation from national institutions and research organizations. The author will strive to advocate such research in the context of supporting the development of climate-conscious urban planning, primarily through networking and providing the necessary data on air temperature (but also other meteorological parameters) for future bioclimatic and other studies. Further research could also include the application of time-series decomposition methods (trend, seasonal, and residual components), as well as a more detailed analysis of statistical distributions and variability, in order to provide a more comprehensive understanding of temperature dynamics.

CONCLUSION

This paper tried to offer, at least to some extent, an answer to the complex question why is it important to understand long-term air temperature trends in Belgrade. Also, why is it necessary to deeply understand the urban microclimate in the context of adaptation to climate change. The conducted analysis of long-term air temperature trends in the Belgrade central urban zone for the reference 30-year period (1991–2020) indicates a clear and consistent warming trend across all 6 examined temperature variables. Positive trends were detected in mean, minimum, and maximum air temperatures, as well as in temperatures measured at standard observation times (07:00h, 14:00h, and 21:00h CET), both at annual and seasonal levels. The increase was particularly evident after 2011, when the highest mean values of most temperature variables were recorded, confirming the amplification of warming during the last decade of the analyzed period (2011-2020). At the annual level, in the period 1991–2020, an increase in temperature values was observed, so that the registered positive trend was from 0.064°C/year to 0.084°C/year. Seasonal analysis showed that the warming trend is present throughout the entire year, with especially pronounced increases during summer from 0.055°C/year to 0.084°C/year, and autumn from 0.076°C/year to 0.091°C/year, while winters have become milder compared to the first decade of the study period (1991-2020). The winter increase in temperature variables averaged 0.069°C/year to 0.082°C/year. In most cases, the highest increase in air temperature values was observed during the evening hours (T_{21h}), indicating a reduced nocturnal cooling effect, which is characteristic of densely urbanized environments affected by the urban heat island phenomenon (UHI).

These results are consistent with previous climatic and bioclimatic studies conducted for Belgrade urban area, and the wider region, which also reported a long-term increase in air temperature values. In addition, these findings confirm that the Belgrade central urban zone is experiencing intensified warming, consistent with broader regional and global climate change.

Finally, it should be noted that the results of this research also contribute to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). By identifying long-term warming trends and intensified evening and seasonal temperatures in the central urban zone of Belgrade, the study provides a basis for more climate-resilient and climate-conscious urban planning, including the development of green infrastructure, sustainable land-use strategies, heat-risk reduction measures, and adaptation of densely built urban districts. In addition, the findings support the development of local climate adaptation policies, early warning systems, and public health prevention strategies aimed at reducing the vulnerability of urban populations to increasing thermal stress. Therefore, the understanding of long-term temperature trends at the local scale is essential for different experts and urban planners, decision-makers, institutions responsible for sustainable urban development and climate governance, but also for non-governmental organizations dealing with climate education and action, as well as for the citizens themselves.

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