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AN ANALYSIS OF THE INFLUENCE OF AIR TEMPERATURE AND HUMIDITY ON OUTDOOR THERMAL COMFORT IN BELGRADE (SERBIA) USING A SIMPLE HEAT INDEX

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ABSTRACT

The main objective of this paper is to study the outdoor thermal comfort of the central urban zone of Belgrade during summer season in order to examine how different bioclimatic conditions affect human body. For this purposes Humidex, a simple heat index was applied. The research involved analyzing different Humidex values, the so-called “sub-indices” calculated based on hourly (7:00 and 14:00), mean daily and maximum values of meteorological parameters (air temperature and humidity) that were recorded at the meteorological station Belgrade - Vračar.), for the period 1999-2018. Outdoor thermal comfort in Belgrade is generally more adverse in July and August, resulting in most days belonging to the categories of “some discomfort” (30-39) and “great discomfort” (40-44), with periodic recording of the most severe categories of heat stress, as a category “very dangerous”(Humidex>55). Category of “very dangerous” heat stress shows linear increase during July, with positive trend of 0.03 days/10 years. The findings also show that from 1999 to 2018, mean index value gradually rose and values of sub-indices $Humidex_{14h}$ and $Humidex_{Tmax}$ have exceeded thresholds 40 for great discomfort and 45 for dangerous heat stress more often then in the previous decades.

Key words: *Humidex, outdoor thermal comfort, urban areas, Belgrade*

INTRODUCTION

Changing of the bioclimatic conditions of the local environment influenced by climate change as a global phenomenon, combined with densely built urban areas, results in a number of negative effects, such as: more adverse bioclimatic conditions, heat islands effect, severe heat waves etc. [1]. The main target of this paper is to describe and analyze the meteorological conditions and its consequences on the life and different activities of inhabitants of the central urban area of Belgrade, through the simple heat index.

Potentially unfavorable climatic conditions, discussed here, indicate a problem for the urban sustainability in general. Therefore, the study of bioclimatic conditions of urban areas is attracting an increasing number of authors. Humidex, as a simple thermal comfort index based on just two meteorological parameters, gives reliable insight in extreme heat conditions which are caused by high air temperature and humidity. Its results are directly comparable with temperature in degrees Celsius and its values are associated with the corresponding degrees of thermal comfort, rendering the index "widely understandable" according to Geletič and others [2].

Today Humidex application can be found in numerous studies. Heidari et al. in 2016 [3], applied this index in order to evaluate heat stress in the outdoor jobs in arid and semi-arid climates of Iran. Alfano and others in 2011 [4] studied thermal environment assessment reliability using temperature – humidity indices. Burke et al. in 2006 [5], in one part of research, have applied Humidex in order to examine the influence of environmental factors include topography and climatic variables such as heat and humidity, precipitation and daylight availability on a person's propensity to walk in Brisbane, Australia. Study conducted by Zhang et al. [6], estimated the impact of Humidex on HFMD (Hand, Foot, and Mouth Disease) in Guangdong Province (South China) and its variability across socio economic status and age groups was. Other good examples of the application of Humidex in testing of thermal comfort of urban areas which need to be stated are: Geletič et al. in 2018 [2] employed this index to assess thermal comfort of the city of Brno (Czech Republic), using air temperature and relative humidity data; Oleson and others [7] used five indices of heat stress (NWS Heat Index (HI), Apparent Temperature (AT), Simplified Wet Bulb Globe Temperature, Humidex, and Discomfort Index) to analyze interactions between urbanization, heat stress, and climate change, in the wider area of the U.S. and southern Canada. Hamdi et al. in 2016 used Humidex with a 1-km resolution dynamic downscaling technique to perform simulations within the A1B scenario of the ARPEGE-Climate global climate model for Brussels, Belgium [8]. Ho and others in 2016 [9] demonstrated an empirical approach to map apparent temperature (Humidex) at the local scale, which relies on publicly available weather station, observations and spatial data layers combined in a random forest regression model, for Greater Vancouver, Canada. Mekis et al. [10] have studied trends in severe conditions in Canada during the period of 60 years. Giannopoulou et al. [11] analyzed Humidex on the territory of Athens (June–August 2009) with the aim of determining if air temperature and humidity have urban thermal comfort. The assessment of outdoor environmental bioclimatic conditions for the purposes of smart urban planning, which was carried out by means of Humidex in the area of the city of Hardec Karlove (the Czech Republic) for the period from June to August 2011–2014, shows that July is the most adverse month, with the highest rate of "great discomfort" category, according to Středová et al. [12].. An application of Humidex for determining thermal comfort was presented in a research conducted by Rana et al. [13].

Close environment of Belgrade and Serbia was study area for several examples for of applying Humidex in the assessment of bioclimatic conditions. First was bioclimatic assessment of weather condition of Banja Luka (Republic of Srpska) for recreational purposes conducted by Pecelj and others [14]. Recently, Lukić et al. [15] investigated the bioclimatic conditions of the central part of Niš, based on the use of Humidex. The purpose of this research was to observe the index change on a daily basis during the hottest part of the year over the period from 1998 to 2017.

STUDY AREA

Belgrade is a city of international importance with the highest level of urbanization in the Republic of Serbia. It is the administrative center of Serbia, acting as the center of economy, tourism, transport, education, culture and history. The city is located on the Sava and Danube River, near the Mountain Avala (511m a.s.l.). According to the 2011 census [16] 1 659 440 permanent residents live in the wider Belgrade area (Belgrade Agglomeration), while the Belgrade settlement, which includes downtown and more urbanized part has a population of 1 166 763 inhabitants. City is located in a continental climate region where the maximum mean daily temperature occurs in July or August, while the minimum temperature occurs most frequently in January [17]. It is scientifically proven that Belgrade, as the largest urban area in Serbia, has specific bioclimatic conditions, such as an urban heat island with unfavorable conditions [18].

As the main objective of the paper is to study the outdoor thermal comfort of the central urban area of Belgrade during summer season, daily meteorological data from the meteorological station Belgrade - Vračar for the period 1999-2018 have been considered. Based on the climate record of this station, relevant meteorological parameters were used. The station is situated at an altitude of 132 meters and its geographical coordinates are 44° 48' N and 20° 28' E. This meteorological station was chosen because it is located in the most densely populated part of Belgrade and best reflects the bioclimatic conditions that occur in central urban areas. The city municipality of Vračar covers an area of 3 km^2, inhabited by 57 483 inhabitants, which means that the population density is 19 161 inhabitants/km^2 (data by Statistical Office of the Republic of Serbia).

METHODOLOGY

In this study author have conducted a bioclimatic analysis for the hottest part of the year - summer months (June, July and August), which is based on the data obtained at the Belgrade weather station (44° 48' N, 20° 28' E), located in territory of city municipality Vračar. The meteorological data used in this research are taken from the Meteorological Yearbook for the period 1999-2018 [19]. The objective of the research is to observe daily changes in the values of the index discussed during the hottest part of the year during the period of 20 years (1999-2018). The research involved analyzing different Humidex values, the so-called “sub-indices” which were calculated on the basis of the hourly, daily and maximum values of meteorological parameters that were recorded (Table 1). The Humidex index was calculated by applying the BioKlima 2.6 software package [20].

Table 1. Definition of indices used in the study

Abbrevations	Definition of sub-incices
$Humidex_{07h}$	Calculated on the basis of the hourly (07h) values of meteorological parameters
$Humidex_{14h}$	Calculated on the basis of the hourly (14h) values of meteorological parameters
$Humidex_{Tmax}$,	Calculated on the basis of mean daily temperature and humidity values
$Humidex_{daily\ value}$	Calculated on the basis of the maximum daily temperature (Tmax)

Humidex (°C) is defined as a heat index that represents the subjective outdoor temperature that a human feels in a hot and humid environment. In other words, it is used as a measure of heat resulting from the combination of excessive humidity and a high temperature [12,13,14,21,22]. The human body has the ability to respond to environmental conditions and acclimatize to it, but exposure to extreme heat may overcome the resistance of the human body and be harmful for human health [23]. Extreme heat conditions occur when Humidex exceeds specific thresholds (Humidex >30).

If the Humidex value reaches ≥35, we can say that the environmental conditions are becoming potentially dangerous. Therefore, we can expect that the feeling of discomfort will occur in the outdoor environment, as well as various medical problems and even some more serious health disorders, such as severe fatigue and heatstroke [24]. This model was first proposed during the 1960s and it was called Humiture [25]. Later it was established by the Canadian meteorologists [21].

Using the two main dimensions of heat stress, the Canadian meteorologists devised the Humidex range (Table 2) and proposed a formula for calculating this index, which was adopted later. It is calculated as follows:

$$HUMIDEX = t + 0.5555 \cdot (vp - 10)$$

Where, vp is air vapour pressure (hPa) and $vp = 6.112 \cdot 10^{(7.5 \cdot t/(237.7+t))} \cdot f/100$

Here, t is air temperature expressed in Celsius degrees (°) and f is relative humidity expressed in percent (%). According to Environment Canada, Humidex-related hazards are as follows table 2.

Table 2. The scale of Humidex and the degree of comfort, source: [21,22]

Range of Humidex	Degree of comfort	
<29	Comfortable	A little discomfort, fatigue with prolonged physical activity is possible
30–39	Some discomfort	Exhaustion due to heat is possible with prolonged physical activity
40–44	Great discomfort	Avoid strenuous physical activity, possible heat cramps or heat exhaustion
45–54	Dangerous	Prolonged physical activity can lead to heat stroke
>55	Very dangerous	A heat stroke is unavoidable if physical activity continues

RESULTS AND DISCUSSION

Under the influence of climate change, the climate and microclimate of Serbia and its surroundings, especially urban areas are subject to constant change, and adverse weather conditions are becoming more frequent. Minimizing their effects, establishing sustainability and improving living conditions in urban areas is becoming a true challenge for urban planners, architects, ecologists, climatologists and other experts who are dealing with spatial and ecological development. As a result, an increasing number of studies are emerging related to the observation of heat waves and their frequency, outdoor thermal comfort, the occurrence of extreme temperatures in the hotter part of the year and drought across the region etc. [15,18,23,26,27,28,29,30]. The findings of numerous studies exploring different aspects of the weather conditions in Serbia indicate a steady increase in the average annual air temperature and show that these changes are especially noticeable during the summer season [15]. According to Unkašević and Tošić [27] in terms of duration, intensity and the heat wave severity in the hottest summers occurred in the period from 1946 to 1952, 1988 to 1998 (particularly from 1992 to 1995) and from 2000 to 2003. The longest heat waves were recorded in 1952, with 53 days in Belgrade and 62 days in Niš (out of the total number of the days in the year). In other work, Unkašević and Tošić [31] particularly singled out the heat wave that occurred in Serbia in 2007 and lasted from 14^{th} July to 27^{th} July.

The findings that have been obtained in this paper are in keeping with the above studies. Figure 1, 2, and 3 show the ratio of the total number of days for each category of heat stress during the investigated period (June – August, 1999–2018). The graph clearly shows that June in Belgrade is the most favorable month from the bioclimatic point of view during warm, summer season. The pleasant feeling of being outdoors is especially present during the morning hours, at 7 a.m. In the morning the prevalent category is the one defined as “comfortable” (Humidex <29). Similar results were obtained based on the mean values of meteorological parameters ($Humidex_{daily\ value}$) (Figure 1). Apart from the comfortable category of outdoor thermal comfort, days in which Humidex belongs to the category of “some discomfort” (30-39) on a daily level are to some extent represented. According to the representation of the category “some discomfort” on a daily level, 2003 and 2012 stand out. The highest reached heat stress category in June during this 20 years is “dangerous” (45-54) was recorded on June 12^{th} 2010, when index value was 45.1.

Outdoor thermal comfort in Belgrade is generally more adverse in July and August and this especially refers to the values recorded at 14:00 ($Humidex_{14h}$) and during the part of the day when maximum temperature ($Humidex_{Tmax}$) was measured (Figure 2 and 3). Analyzing the results, it can be concluded that the weather conditions during July and August lead to unfavorable bioclimatic conditions, resulting in most days belonging to the categories of “some” (30-39) and “great discomfort” (40-44), with periodic recording of the most severe categories of heat stress (dangerous and very dangerous). Under these conditions, the human body temperature rises and it can cause certain medical problems such as rash, thermal cramps, fatigue accompanied by nausea, dizziness, headache, a sudden rise in body temperature (sunstroke) and finally heatstroke [22]. There are some anthropogenic sources of heat that additionally reinforce adverse bioclimatic conditions, for example traffic, lighting, reduced wind speed etc. [11].

The increasing temperature at Belgrade is also related to heat island processes, enhanced aerosols, and probably, the greenhouse effect, so these records may serve as a valuable tool to monitor potential greenhouse warming [17]. What should be highlighted in this paper is the fact that there is an increasing frequency of extreme temperatures and increasing index values over a 20-year period. During the first decade of the investigated period (1999-2008) maximum index values ranged most frequently around 43, with three cases when sub-index $Humidex_{Tmax}$ exceeding threshold value of 45 (dangerous). That was recorded in 2001 ($Humidex_{Tmax}$=47.01, August 11^{th}), 2003 ($Humidex_{Tmax}$=45.20, July 4^{th}) and 2007 ($Humidex_{Tmax}$=45, August 24^{th}). The second decade (2009-2018) proved to be more bioclimatically unfavorable, which confirms assertions that weather and bioclimatic conditions in Serbia have been changing year by year. Maximum values were ranged between 44 and 45, noting that the threshold of 45 for the category “dangerous” (45-54) was exceeded

5 times (in 2010, 2011, 2015, 2016 and 2017). The highest recorded value during the whole period covered by the study was 55.07 (July 20th 2011).

Apart from the goal of observing the change in the index value on a daily basis from year to year, the second part of the research was dedicated to separate observation of the first (1999-2008) and second decades (2009-2018) to gain insight into what long-term changes can be expected. The results obtained showed that all sub-indices record decline in the number of days defined as "comfortable". On the other hand, there was an increase in all the other categories characterized by a lower or higher degree of discomfort. The most noticeable changes were recorded in $Humidex_{07h}$ sub-index values during July and August. If we look at the data obtained in July for $Humidex_{07h}$, we can see that the number of days with "some discomfort" rose from 61 (1999–2008) to 79 (2009–2018) which means by a one-third (almost 30% of increase). In August, $Humidex_{07h}$ in the category of "some discomfort" records the constant tendency of growth from 26 to 51 that is, the number of such days increased by almost 50% over a ten-year period. The smallest increase was recorded during June, only three days in the mentioned category (from 38 to 41). When it comes to the month of June, comparing the two decades of the study period, the changes that occurred with the $Humidex_{14h}$ are much more interesting. An increase can be observed in the values of $Humidex_{14h}$, where there is a positive trend of rose in the number of days with "great discomfort" from 8 (1999–2008) to 16 (2009–2018). Comparing the two decades, during July and August, $Humidex_{14h}$ index recorded similar results: a positive change trend in July from 23 to 32 days in the category "great discomfort", and in August from 22 (1999-2008) to 30 (2009-2018) in the same heat stress category. The changes do not only refer to the hottest part of the day, but also the mean daily values. Findings of Unkašević et al. [17] show that the mean summer temperature at Belgrade increased at rate of 0.1316°C/yr. On a daily average, ie. sub-index $Humidex_{daily\ value}$, the most pronounced changes were recorded in August. Number of days in the category "comfortable" was reduced from 213 (1999-2008) to 176 (2009-2018) – over 17%, whereas the number of days with "some discomfort" rose from 97 (1999–2008) to 134 (2009–2018).

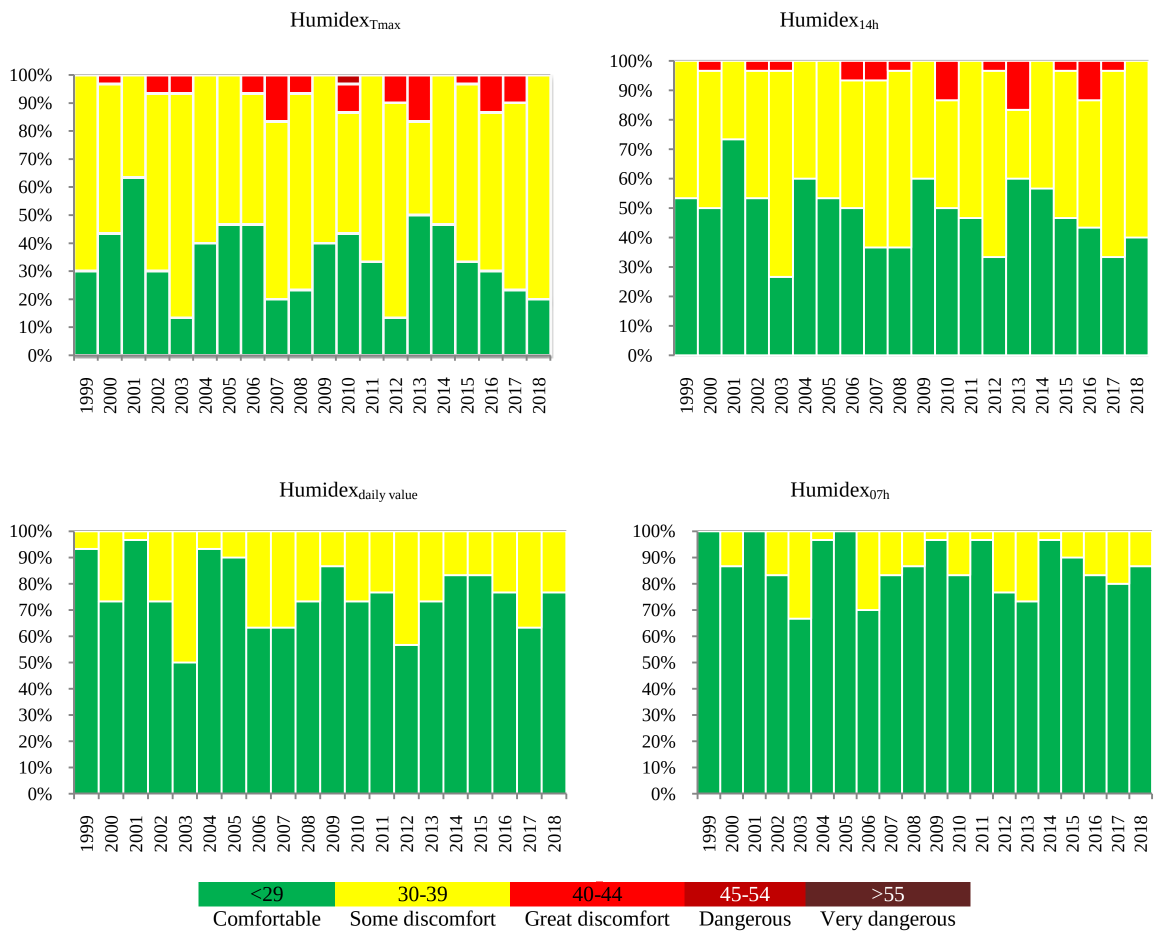

Figure 1. Humidex heat stress categories in total, Belgrade, June, 1999-2018

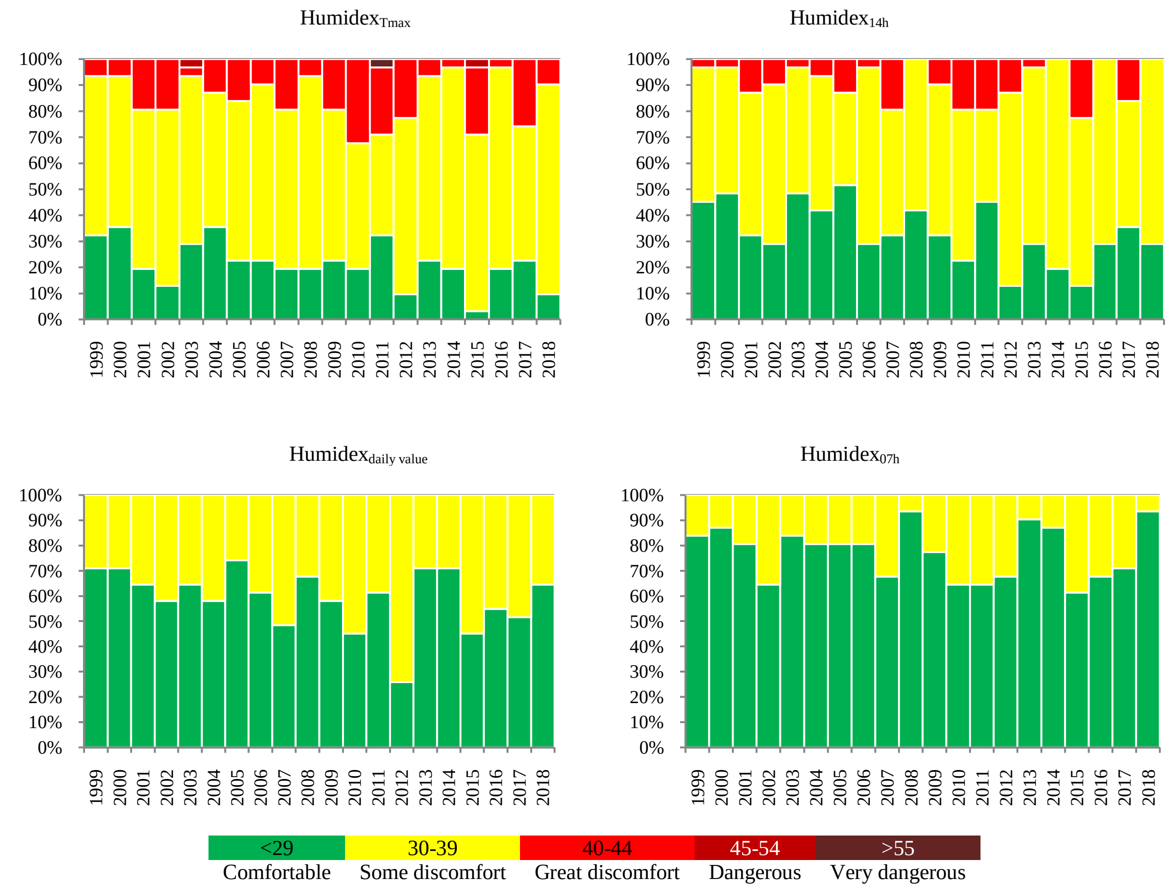

Figure 2. Humidex heat stress categories in total, Belgrade, July, 1999-2018

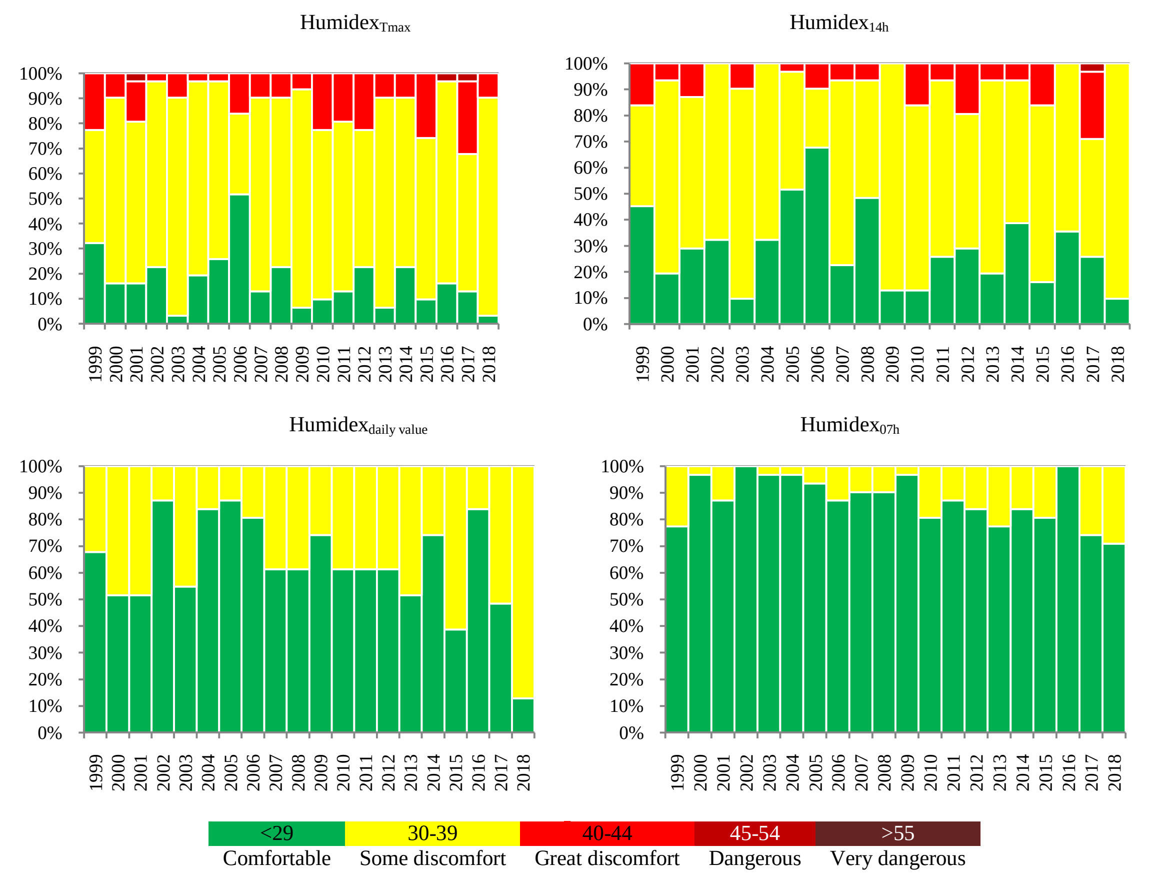

Figure 3. Humidex heat stress categories in total, Belgrade, August, 1999-2018

Since the mid-1980s the incidence of heat waves in Belgrade has increased and they occur on average every year, while before the 1980s, the average incidence of heat waves was once in every three years [26]. As Đorđević claims [30], in observed period (1957-2006) the rise of mean, maximum and minimum annual air temperature in Belgrade was prominent. Unkašević et al. [17] have been investigated trends in extreme temperatures for the Belgrade in the period 1975-2003 to assess how an increase in the mean summer temperatures is related to changes in the extreme maximum and minimum temperatures. They concluded that the rising mean summer temperatures at Belgrade are associated with a substantial increase in the occurrence of extreme maximum temperatures.

Temperature extremes are a key aspect of any climate change because ecosystems and societal responses are most sensitive to them [17]. That is why in the last part of the research special attention was paid to the maximum values of the heat index. Figure 4, 5 and 6 show time series of the number of days for each heat stress category according to $Humidex_{Tmax}$ for the all three months in the 20-years period. Linear graphs show that the most significant changes in outdoor thermal comfort are related to the category of “comfortable”.

There was a linear decrease in the observed heat stress category: in June (1999-2018) it was -1.6 days/10 years, in July it was – 2.41 days/10 years, and in August declining trend was -2.14 days/10 years. As for the other categories of heat stress that present less or greater thermal discomfort, all categories (some discomfort, great discomfort, dangerous and very dangerous) are characterized by positive trend of linear increase. The highest growth trend shows category of “some discomfort” (30-39) in July and it was 1.54 days/10 years, then it followed by August (1999-2018) with positive trend of 1.12 days/10 years. Category of “very dangerous” heat stress shows linear increase just during July, with positive trend of 0.03 days/10 years.

These findings indicate that July is the most adverse month in terms of the bioclimatic conditions on the territory of Belgrade during the summer. It is important to single out the fact that a similar changes were observed in August, as well, during the two decades of investigated period. From 1999 to 2018, mean index value gradually rose, according to $Humidex_{14h}$ and especially $Humidex_{Tmax}$. Values of these sub-indices have exceeded threshold 40 more often then in the past.

Secondly, it has been observed that heat waves defined as prolonged periods of very high air temperatures [23], occurred more and more frequently during the second decade (2009-2018), with three or more consecutive days belonging to the “great discomfort” category (40–44). Considering the tendency of increasing daily temperatures and values of Humidex in August, it can be expected that in the coming decades a higher representation of the highest thermal stress category will occur.

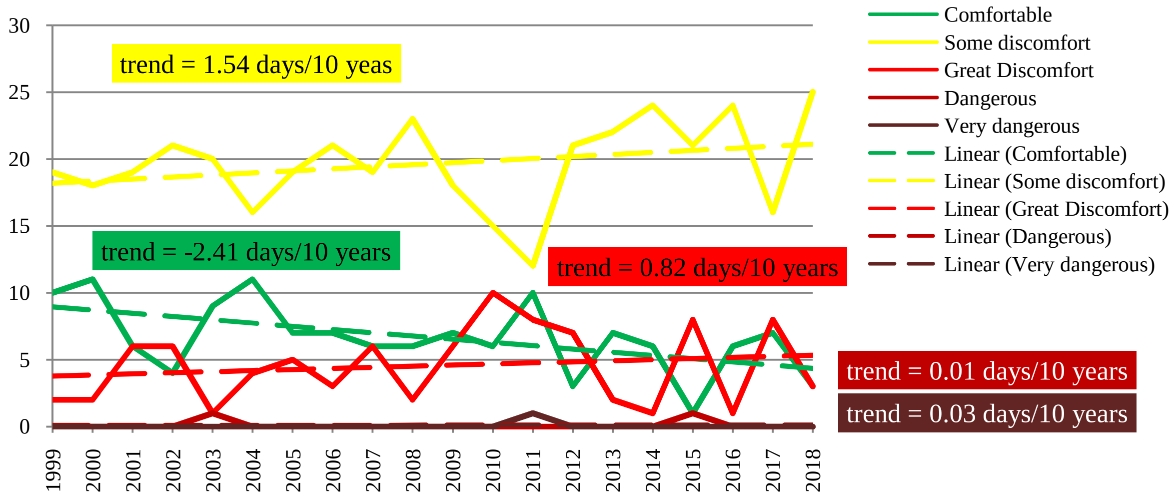

Figure 4. Time series of the number of days for categories of heat stress of $Humidex_{Tmax}$, in June, for the period 1999-2018

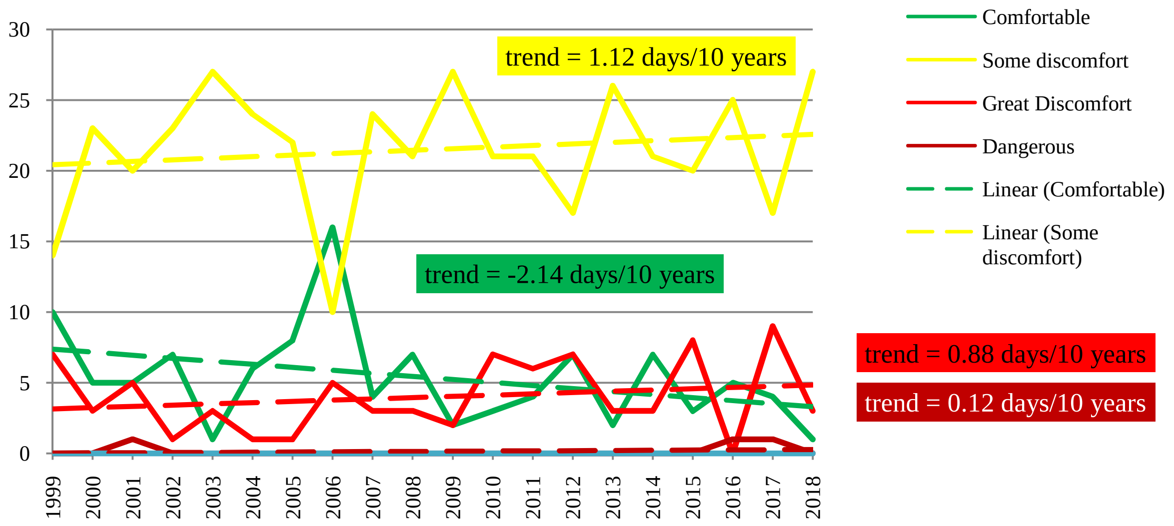

Figure 4. Time series of the number of days for categories of heat stress of Humidex_{Tmax}, in July, for the period 1999-2018

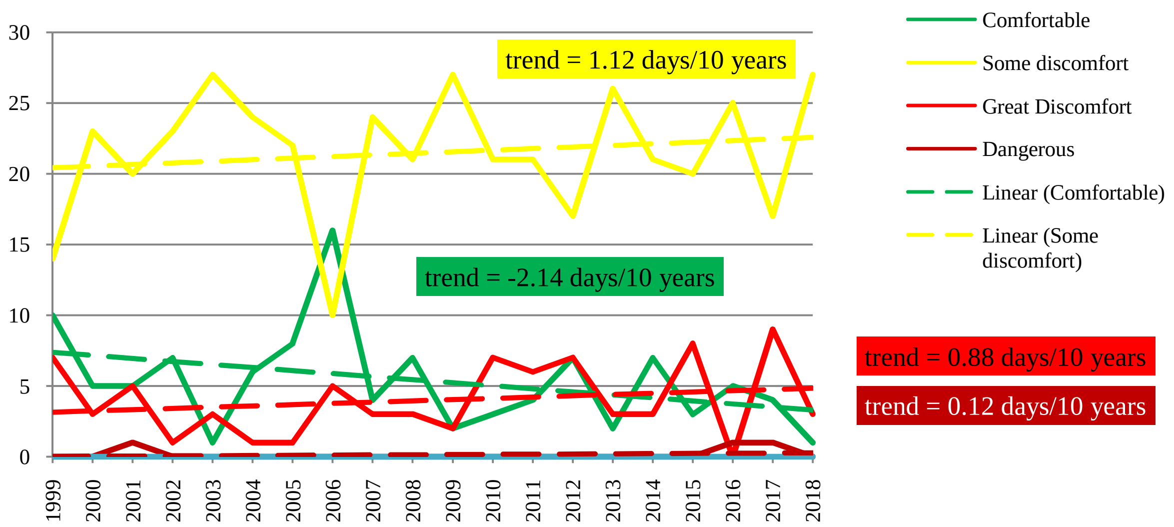

Figure 4. Time series of the number of days for categories of heat stress of Humidex_{Tmax}, in August, for the period 1999-2018

CONCLUSION

The main goal of this study was to conduct analysis of bioclimatic conditions that occur in central urban area of Belgrade during the hottest part of the year - summer months (June, July and August). The research was based on climate record of the meteorological station Belgrade - Vračar for the period 1999-2018. This meteorological station was chosen because it is located in the most densely populated and built up part of Belgrade and best reflects the outdoor thermal comfort of central urban zones. For this purposes Humidex, a simple heat index was applied. Humidex, index based on just two meteorological parameters, gives reliable insight in extreme heat conditions which are caused by high air temperature and humidity.

The results in this study help us to better understand the process of climate change, its impact on local bioclimatic conditions and how it affects human beings and ecosystems in urban environment. Outdoor thermal comfort in Belgrade is generally more adverse in July and August and this especially refers to the values of sub-indices Humidex_{14h} and Humidex_{Tmax}. Under these conditions, the human body temperature rises and it can cause certain medical problems. Those risks are higher in urban areas, as a consequence of a combination of natural factors (weather conditions) combined with anthropogenic influences. The increasing temperature and extreme phenomena at Belgrade are also related to heat island processes, enhanced aerosols, and probably, the greenhouse effect.

The results obtained were analyzed at two levels: first was observing the change in the index value on a hourly and daily basis from year to year, and second was separate observation of the first (1999-2008) and second decades (2009-2018) of the investigated period to gain insight into long-term changes. The results showed that all sub-indices record decline in the number of days defined as "comfortable" (Humidex <29) during all three months, which leads to constant increase in all the other categories of lower or higher degree thermal discomfort. The most pronounced decline in the number of "comfortable" days occurred during July and August, and especially with the sub-index $Humidex_{14h..}$ Number of days in the category of "comfortable" was reduced from 124 (1999-2008) to 83 (2009-2018), ie. over 33% of decrease in July, and in August it was was reduced from 111 (1999-2008) to 70 (2009-2018), which means almost 37% of decrease. Trend lines for each month presented in this paper also confirm that the most significant changes in outdoor thermal comfort in Belgrade during a twenty-year period are related to the category of "comfortable", with a negative trend in July of -2.41 days/10 years.

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