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INCREASING TRENDS OF AIR TEMPERATURE IN URBAN AREA: A CASE STUDY FROM FOUR STATIONS IN ZAGREB CITY AREA

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REZIME

The paper studies different increasing trends of characteristic (minimum, mean and maximum) annual temperatures measured at four meteorological stations in the Zagreb City area. The goal of the analysis is to determine the extent to which the warming trend observed in different part of the Zagreb City area is caused by their locations, i.e. by the urban heat island (UHI) effect. Data from the following four meteorological stations are used: (1) Zagreb Grič (ZG); (2) Zagreb Maksimir (ZM); (3) Zagreb airport (ZA); (4) Puntijarka (PU). The meteorological station ZG is located in the inner city centre, ZM in the suburb exposed to intensive urbanisation in the recent decades, ZA in the suburb exposed to low urbanisation, while the location of PU is near the top of the Medvednica Mountain, far from any influence of urbanisation. The time series of differences between the characteristic air temperatures for all pairs of meteorological stations are calculated during two periods: (1) 1949-2016; (2) 1981-2016. Regression and correlation methods, trend analyses of time series of characteristic air temperatures and their differences, t-test and Mann-Kendal test are used in this paper. The differences in characteristic air temperatures between all pairs of stations showed individual development of temperatures at nearby stations. The stations located in the city and the rapidly urbanised suburb are under a stronger influence of global warming (GW) and UHI effects than the station located in the suburb, less influenced by urbanisation. ZM experiences a higher influence of GW and UHI compared to ZG, and especially ZA and PU. UHI affects the increase in the ZM minimum air temperatures approximately 30% more than at ZG. The most significant increasing trend is observed in the time series of the minimum annual air temperatures. The increasing trend of characteristic air temperatures measured at PU is not influenced by the UHI effect.

Key words: Characteristic annual air temperatures, Air temperature trend, Global Warming, Urban Heat Island, Zagreb City

1. INTRODUCTION

The term urban heat island (UHI) is used to describe the occurrence of higher air temperatures in the urban than in the surrounding non-urban areas as a direct consequence of urbanisation. Today, more than half of the population lives in urban areas, and 1.5 million people are added to the global urban population every week. DESA (2014) reports: "*In 1950, 30% of the world's population was urban, and by 2050, 66% of the world's population is projected to be urban. The planet has gone through a process of rapid urbanisation over the past six decades.*"

Rapid planetary urbanisation provides a substantial number of opportunities, but at the same time it contains many potentially dangerous challenges. One of the rapidly emerging problems is connected with the increasing air temperature caused by the UHI effect. The global warming (GW) and UHI effects co-exist in the rapidly developed cites. It is of particular importance to better understand how they interactively function in different city area warming. This is a very individual process for each urban area. Due to this fact, it is of particular importance to better understand and explain the UHI effect on each individual urban agglomeration. Li et al. (2016) believe that these efforts can help in the improvement of urban ecological environment and the realisation of sustainable urban development.

The number of UHI-related publications has continuously increased since 1991. During the 1991-2015 period, 1822 papers have been published in 352 journals based on the Science Citation Index-Expanded (Huang and Lu 2018). Certainly, the interest in a better understanding of air temperature increase, especially in the urbanised area, and consequently the analysis of the UHI effect, has become a focal topic.

Urbanisation significantly modifies the landscape. It represents a more or less fast-consuming process of simultaneous removal of natural land cover and the introduction of urban materials and technologies. UHI is a result of population growth accompanied by the construction of physical properties of buildings and other structures, and the emission of heat by human activities (Parker, 2010). These alterations have resulted in the changes to the energy budget and poor air quality leading to higher temperatures (Xu and Chen 2004). The changes of air temperature in urban areas have a major impact on heating and cooling energy demand.

It seems that the heat waves (HW) have become more frequent and that they last longer over most land areas in the recent decades, which raises serious public health concerns. Urban residents face higher health risks due to synergies between HW and UHIs. Li et al. (2015) suggest that UHIs are higher under HW conditions. Hot temperatures in combination with high humidity cause human discomfort, and may increase morbidity and mortality (Fischer et al. 2012).

This paper investigates the different behaviour of characteristic (minimum, mean and maximum) annual temperatures measured at four meteorological stations located in and near Zagreb City area. The goal of the investigations is to better understand the effect of urbanisation on the increasing trend of air temperatures, and to distinguish it from the existing global warming effect. The paper demonstrates the changes of the relationship between characteristic annual air temperatures (minimum, mean and maximum) at four meteorological stations located in the urban area of Zagreb City (Croatia). The paper attempts to determine the extent to which the warming trend observed in different part of Zagreb City area is caused by the UHI.

2. STUDY AREA

The study area is presented in Fig. 1 shows the locations and distances between four analysed meteorological stations: (1) Zagreb Grič (ZG); (2) Zagreb Maksimir (ZM); (3) Zagreb airport (ZA); (4) Puntijarka (PU). It also presents Zagreb City urban area development from 1857 to present time. Two graphs in Fig. 2 illustrate the expansion of Zagreb City urban area, *A* (km^2), and population, *N*, increase in the past 150 years. The Zagreb City urban area grew from the less than 100 km^2 up to 1700 km^2 and the population increased from 5000 up to 800,000 inhabitants.

The meteorological station ZG operates on a small hill in the inner city centre. It is located beneath the foothills of the Medvednica Mountain (45°49' - 15°59') at elevation of 157 m a.s.l. It has a complete time data series of mean daily air temperature from 1 Jan. 1862, while the time data series of minimum and maximum daily air temperatures exist from 1 Jan. 1881. The location of all analysed stations has not been moved during the entire period of their functioning.

Time series of ZG air temperature have already been studied in many papers at different times (e.g. Šegota 1981, Juras 1985, Penzar et al. 1992, Radić et al. 2004, Ogrin and Krevs 2015). The results of the standard normal homogeneity test reveal that the air temperature time series of ZG and ZM are homogenous for the 1949-1998 period (Likso 2003). Nitis et al. (2005) found that the Zagreb City local topography played an important role in the formation and the evolution of the UHI. Klaić et al. (2002) analysed the modification of the local winds due to the hypothetical urbanisation of the Zagreb surroundings.

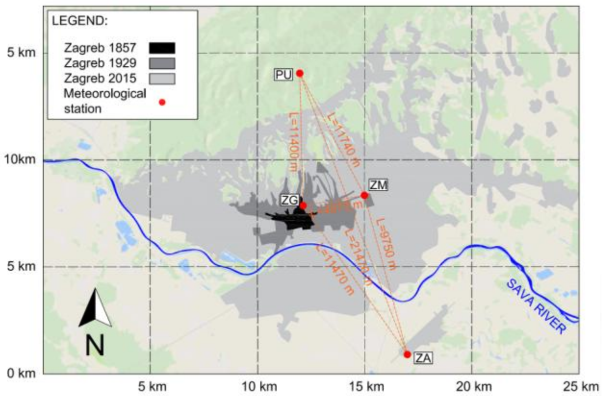

Figure 1. Schematic presentation of Zagreb City urban area development from 1857 to present time indicating the sites of four analysed meteorological stations in Zagreb City area

The meteorological station ZM is located less than 4 km west of the inner city centre (5°49' - 16°02') at elevation of 123 m a.s.l. It has a complete time data series of minimum, mean and maximum daily air temperature from 1 Jan. 1949. The terrain surrounding the station is flat. The area around ZM is influenced by rapid and considerable urbanisation, and even industrialisation. During the past few decades, the processes of urbanisation have been rather intensive in this area.

Urbanisation of the area around the ZM meteorological station is widely recognised as a new housing development built on farmland and rural environment. Hectares of asphalt and roofs in recent decades have been constructed and exposed to the sun.

The meteorological station ZA is located in a plain 10 km south-east of Zagreb centre and 2.5 km south of the Sava River (Fig. 1), near the suburban village of Pleso and Velika Gorica City (45°44' - 15°04'). It has a complete time data series of minimum, mean and maximum daily air temperature from 1 Jan. 1981. The terrain surrounding the meteorological station and airport is considerably flat and predominately covered by grasslands and the elevation of the station is at 106 m a.s.l. Because of the airport expansion and operation, the process of urbanisation in this area is less intensive than around the ZM station area. As a consequence of the vicinity of the Sava River and shallow groundwater, this meteorological station recorded more days with fog than all other three stations analysed in this paper (Brzoja 2012, Zoldoš and Jurković 2016).

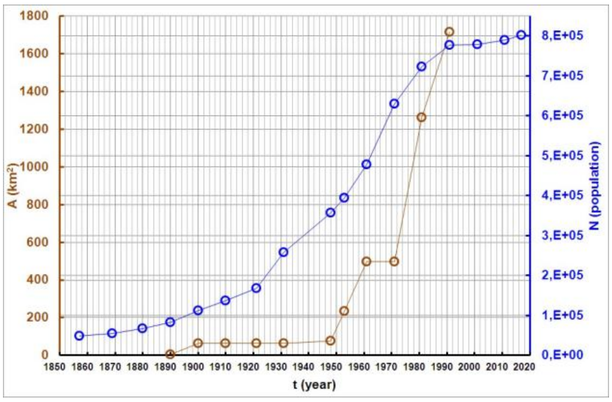

Figure 2. Graphical presentation of Zagreb City urban area expansion, *A* (km^2), and population, *N*, increase in the past 150 years

At all four analysed meteorological stations, air temperature is measured in a thermometric screen, 2 m above the ground. The meteorological station PU is located to the north of Zagreb, near the top of the Medvednica Mountain (45°55' - 15°58') at elevation of 988 m a.s.l. It is surrounded by dense natural woodland. It has a complete time data series of minimum, mean and maximum daily air temperature from 1 Jan. 1981. Its distance from the Zagreb City rapidly developed suburban area on the mountain hill slope is approximately 7 km. Due to this fact, it is realistic to assume that the air temperature of this station is not influenced by UHI, which means that its air temperature increasing trend can be explained by GW effect only.

3. ANALYSED DATA

The values of annual characteristic (minimum, average and maximum) air temperatures measured at four observed stations in two different time periods are provided in Table 1. The minimum annual temperatures are the highest at ZG and lowest at ZM. Table 2 shows the results of the t-test between the pairs of time series of characteristic (minimum, mean, maximum) annual air temperatures, whereas Table 3 provides the results of the Mann-Kendal trend test for the time series of characteristic air temperatures.

Table 1. Characteristic annual values (minimum, average and maximum) air temperatures measured at analysed stations in different time periods

Time period	Station	T_{min} (°C)	T_{av} (°C)	T_{max} (°C)
1862-2016	ZG	-	11.6	-
1881-2016	ZG	-22.2	11.6	40.3
1949-2016	ZG	-19.4	12.0	40.3
	ZM	-27.3	10.9	40.4
1981-2016	ZG	-17.2	12.4	38.8
	ZM	-22.6	11.4	38.6
	ZA	-18.3	11.2	39.1
	PU	-20.8	7.04	32.1

Table 2. Results of t-test between time series of characteristic (minimum, mean, maximum) annual air temperatures in different time periods

Station	Time period	Minimum	Average	Maximum
ZG-ZM	1949-2016	$p < 0.01$	$p < 0.01$	$p = 0.348$
	1981-2016	$p < 0.01$	$p < 0.01$	$p = 0.752$
ZG-ZA	1981-2016	$p = 0.903$	$p < 0.01$	$p = 0.305$
ZG-PU		$p < 0.01$	$p < 0.01$	$p < 0.01$
ZM-ZA		$p < 0.01$	$p = 0.375$	$p = 0.506$
ZM-PU		$p = 0.083$	$p < 0.01$	$p < 0.01$
ZA-PU		$p < 0.01$	$p < 0.01$	$p < 0.01$

Table 3. Results of Mann-Kendal test for time series of characteristic air temperatures

Station	Time period	Characteristic	r	p
ZG-ZAGREB GRIČ	1862-2016	mean	0.514	p<0.01
	1881-2016	minimum	0.416	p<0.01
		mean	0.601	p<0.01
		maximum	0.252	p<0.01
	1949-2016	minimum	0.303	p<0.01
		mean	0.598	p<0.01
		maximum	0.360	p<0.01
	1981-2016	minimum	0.170	p=0.015
		mean	0.709	p<0.01
		maximum	0.550	p<0.01
ZM-ZAGREB MAKSIMIR	1949-2016	minimum	0.366	p<0.01
		mean	0.653	p<0.01
		maximum	0.502	p<0.01
	1981-2016	minimum	0.215	p=0.013
		mean	0.768	p<0.01
		maximum	0.496	p<0.01
ZA-ZAGREB AERODROM	1981-2016	minimum	0.191	p=0.258
		mean	0.739	p<0.01
		maximum	0.414	p<0.01
PU-PUNTIJARKA	1981-2016	minimum	0.216	p=0.068
		mean	0.629	p<0.01
		maximum	0.293	p=0.141

Figure 3 depicts the time data of minimum annual ($T_{ZG\text{-}min}$), mean annual ($T_{ZG\text{-}mean}$) and maximum annual ($T_{ZG\text{-}max}$) air temperatures for the ZG meteorological station. For the mean annual air temperature, the time series cover the 1862-2016 period, whereas for the minimum and maximum temperature, the time series cover the 1881-2016 period. Figure 4 depicts the linear and 2nd-order polynomial trend lines with the coefficient of linear correlation, *r*, and index of nonlinear correlation, *R*. The Mann-Kendall trend test was used for determining the statistical significance of air temperature trends (Mann 1945, Kendal 1975, Hamed and Ramachandra 1998). In all cases, the coefficients of linear correlation, *r*, for mean annual time series are statistically significant (see Table 3). It should be noted that the indexes of 2nd-order polynomial correlation, *R*, are significantly higher than the linear correlations coefficients, *r*. This can be explained by the fact that the behaviour of analysed time series during 155 and/or 136 years is more complex and cannot be explained by using only the linear model. The rescaled adjusted partial sums (RAPS) method (Garbrecht and Fernandez 1994) revealed a statistically significant jump in the Western Balkans region that started in the early 1980s (Bonacci 2012, Bonacci and Željković 2018).

The comparison of long-term air temperature trends of Ljubljana (capital of Slovenia) and Zagreb (capital of Croatia) demonstrated that the warming trends are more pronounced in Ljubljana. The trend of the mean annual Ljubljana air temperature shows an increase by 1.1°C/100 years and in Zagreb by 0.9°C/100 years (Ogrin and Krevs 2015).

Figure 4 represents two time series of the minimum annual air temperature for ZG ($T_{ZG\text{-}min}$) and ZM ($T_{ZM\text{-}min}$) during the 1949-2016 period. The statistically significant increasing trends of the minimum annual air temperature exist at both stations (see Table 3). The increasing intensity is higher at ZM than at ZG.

Figure 5 depicts two time series of mean annual air temperature for ZG ($T_{ZG\text{-}mean}$) and ZM ($T_{ZM\text{-}mean}$) during the 1949-2016 period, and includes the linear and 2nd-order polynomial trend lines with the coefficient of linear correlation, *r*, and index of nonlinear correlation, *R*. In both cases, the increasing trends are statistically significant (see Table 3). Index of 2nd-order polynomial correlation, *R*, for the time series of mean ($T_{ZM\text{-}mean}$) annual air temperature are significantly higher than the linear correlations coefficients, *r*. It is obvious that the substantial increasing trend started in the early 1980s.

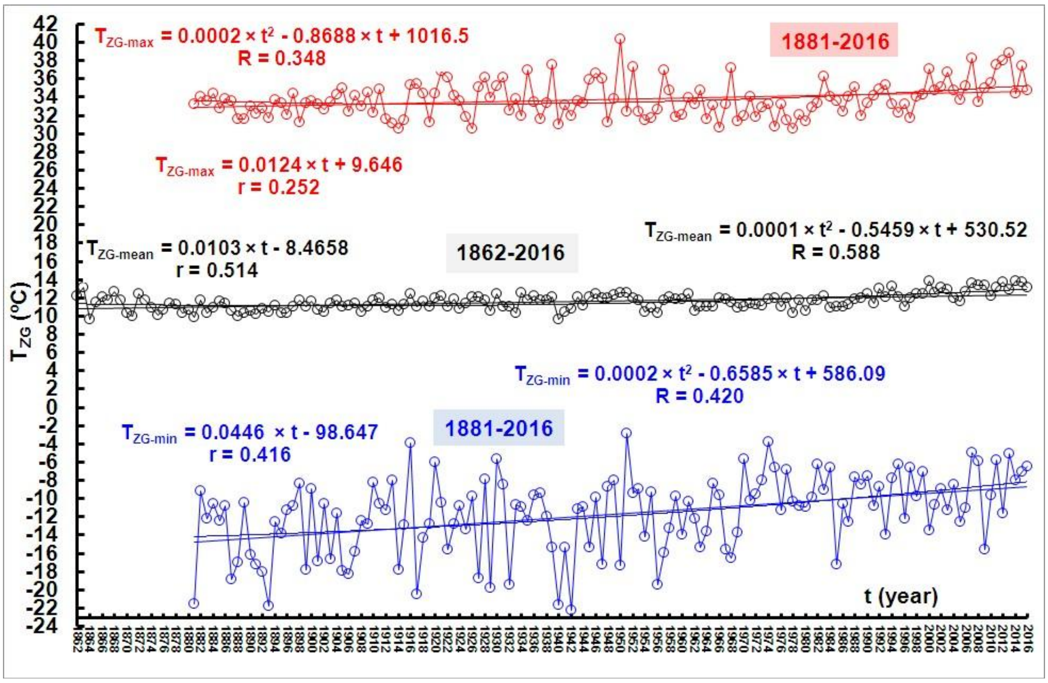

Figure 3. Three time series of minimum, mean and maximum daily air temperature at ZG for the 1862-2016 period (for mean annual air temperature) and 1881-2016 period (for minimum and maximum annual air temperature) with linear and 2nd-order polynomial trend lines and coefficients of linear, *r*, and nonlinear, *R*, correlations

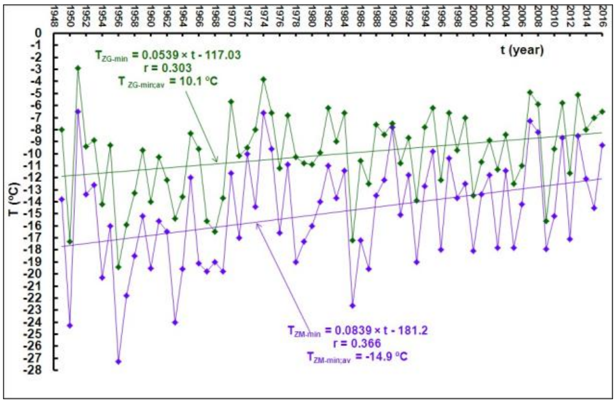

Figure 4. Two time series of minimum annual air temperature at ZG and ZM for the 1949-2016 period with linear trend lines and coefficients of linear correlation, *r*

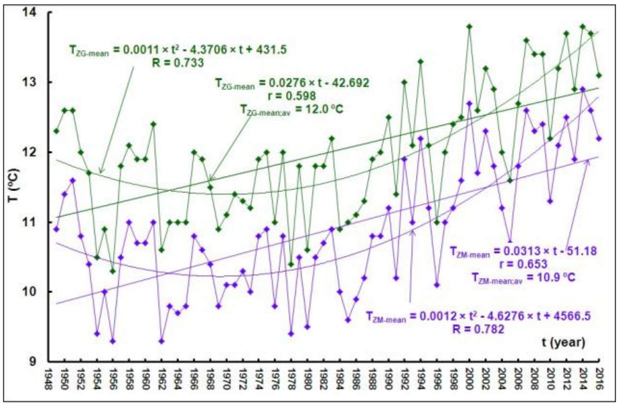

Figure 5. Two time series of mean annual air temperature at ZG and ZM for the 1949-2016 period with linear trend lines and coefficients and 2nd-order polynomial trend lines and coefficients of linear, *r*, and nonlinear, *R*, correlations

Figure 6 indicates two time series of the maximum annual air temperature for ZG (T_{ZG-max}) and ZM (T_{ZM-max}) during the 1949-2016 period, and includes the linear and 2nd-order polynomial trend lines with the coefficient of linear correlation, *r*, and index of nonlinear correlation, *R*. The indexes of 2nd-order polynomial correlation, *R*, for the both time series of the maximum annual air temperature are significantly higher than for the linear correlations coefficients, *r*. The beginning of a significant jump in air temperature increase started in the early 1980s.

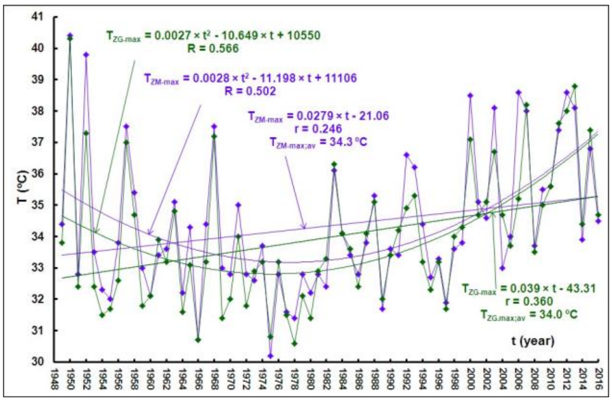

Figure 6. Two time series of maximum annual air temperature at ZG and ZM for the 1949-2016 period with linear trend lines and coefficients and 2nd-order polynomial trend lines and coefficients of linear, *r*, and nonlinear, *R*, correlations

Figure 7 represents four time data series, in the period 1981-2016, of the minimum annual temperature for: (1) ZG (T_{ZG-min}); (2) ZM (T_{ZM-min}); (3) ZA (T_{ZA-min}); (4) PU (T_{PU-min}). During this 36 years long period all four meteorological stations were in operation. There are increasing trends of minimum annual air temperatures at all analysed stations, but they are not statistically significant at the level, $p<0.01$ (see Table 4). The slope of the linear regression line for ZM is the highest with the value of 0.0769ºC per year. The second one is for PU (0.0666ºC per year) and the third for ZA (0.0612ºC per year). For ZG the slope of linear regression (0.0484ºC per year) is approximately 40% lower than for ZM.

Figure 8 depicts four time data series of mean annual temperature for: (1) ZG ($T_{ZG-mean}$); (2) ZM ($T_{ZM-mean}$); (3) ZA ($T_{ZA-mean}$); (4) PU ($T_{PU-mean}$). In the 1981-2016 period, a similar and statistically significant increasing trends of mean annual air temperatures were found at all four analysed stations ranging between $r=0.629$ and $r=0.768$ (see Table 3). The most significant slope of the linear regression line is observed at ZM (0.0659ºC per year), and the weakest at ZA (0.0597ºC per year).

Table 4. Average values of differences between characteristic (minimum. average and maximum) air temperatures measured at all pairs of analysed stations in two different time periods

ΔTi (ºC)	Time period	Minimum	Average	Maximum
$\Delta T1=T_{ZG}-T_{ZM}$	1949-2016	4.81	1.11	-0.354
	1981-2016	4.29	1.06	-0.144
$\Delta T2=T_{ZG}-T_{ZA}$	1981-2016	0.092	1.24	-0.463
$\Delta T3= T_{ZG}-T_{PU}$	1981-2016	5.61	5.41	6.86
$\Delta T4=T_{ZM}-T_{ZA}$	1981-2016	-4.20	0.185	-0.319
$\Delta T5=T_{ZM}-T_{PU}$	1981-2016	1.32	4.35	7.00
$\Delta T6= T_{ZA}-T_{PU}$	1981-2016	5.52	4.17	7.32

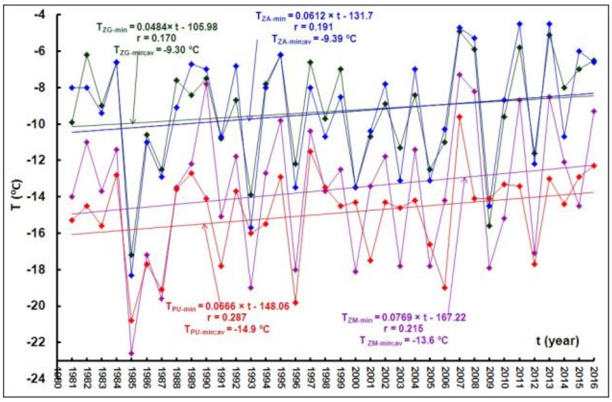

Figure 7. Four time series of minimum annual air temperature at ZG, ZM, ZA and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

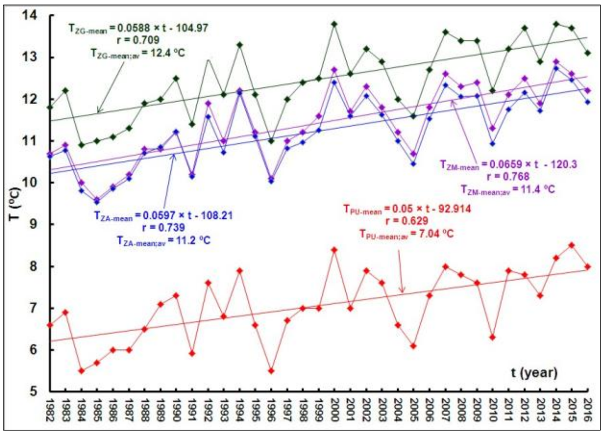

Figure 8. Four time series of mean annual air temperature at ZG, ZM, ZA and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

Figure 9 depicts four time data series of mean annual temperature for: (1) ZG (T_{ZG-max}); (2) ZM (T_{ZM-max}); (3) ZA (T_{ZA-max}); (4) PU (T_{PU-max}). In the 1981-2016 period, a statistically significant increasing trend of the maximum annual air temperatures was not discovered only at PU station (see Table 3). The slope of the linear regression line for ZM is the highest with the value of 0.0966ºC per year. The maximum measured air temperatures vary in the narrow range between 38.6ºC at ZM and 39.1ºC at ZA except for PU when the maximum measured air temperature was 32.1ºC.

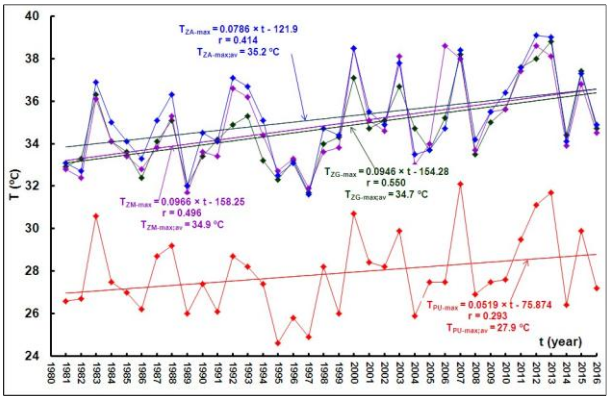

Figure 9. Four time series of maximum annual air temperature at ZG, ZM, ZA and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

4. DIFFERENCES OF CHARACTERISTIC AIR TEMPERATURES BETWEEN ANALYSED STATIONS

By analysing the development during the time series of differences in characteristic (minimum, mean and maximum) annual air temperatures between all pairs of four analysed meteorological stations, we will attempt to better understand the UHI effect in different parts of the Zagreb City area.

Six different values, *ΔT1*, *ΔT2*, *ΔT3*, *ΔT4*, *ΔT5* and *ΔT6,* between the characteristic annual air temperatures measured at four meteorological stations are defined by the following equations:

$$\Delta T1 = T_{ZG} - T_{ZM} \quad (1)$$

$$\Delta T2 = T_{ZG} - T_{ZA} \quad (2)$$

$$\Delta T3 = T_{ZG} - T_{PU} \quad (3)$$

$$\Delta T4 = T_{ZM} - T_{ZA} \quad (4)$$

$$\Delta T5 = T_{ZM} - T_{PU} \quad (5)$$

$$\Delta T6 = T_{ZA} - T_{PU} \quad (6)$$

Where, T_{ZG}, is temperature measured at ZG, T_{ZM}, is temperature measured at ZM, T_{ZA}, is temperature measured at ZA, and T_{PU}, is temperature measured at PU.

The average values of differences between characteristic (minimum, mean and maximum) air temperatures measured at all pairs of analysed stations in two different time periods are provided in Table 4. Table 5 shows the results of the Mann-Kendal test for time series of differences between the characteristic air temperatures. During the both analysed periods (1949-2016 - 68 years and 1981-2016 - 36 years), the time series decreasing trends of differences of mean annual air temperatures between ZG and ZM are statistically significant. It should be noted that the statistically significant trends are discovered for all pairs of differences between mean annual temperatures, except in case of pair ZG-ZA. For all other analysed cases of the difference between the maximum and minimum annual air temperatures (except for differences of maximum annual air temperatures between ZG-PU in 1981-2015 period and minimum annual air temperatures between ZG-ZM in 1949-2016 period) increasing or decreasing trends are not statistically significant.

Figure 10 depicts three time series of differences, *ΔT1*, between minimum, mean and maximum air temperatures of ZG and ZM for the 1949-2016 period with linear trend lines and coefficients of linear correlation, *r*. The most significant decreasing trend is between the mean annual air temperatures. Increasing trend in the time series of the minimum air temperature at the ZG station is less intensive than at the ZM station, as is evident from Fig. 10. During the 1949-2016 period (68 years), the minimum air temperature at ZG increased by 3.67ºC or 0.0539ºC per year, while during the same period at ZM the increase was 5.71ºC or 0.0839ºC per year. It can be concluded that UHI affects the increase ZM minimum air temperatures approximately 40% more than at ZG. The situation with mean annual air temperatures between ZG and ZM is similar. During the 1949-2016 period (68 years), the mean annual air temperature at ZG increased by 1.84ºC or 0.0276ºC per year, while during the same period at ZM the increase was 2.11ºC or 0.0313ºC per year. In case of mean annual temperatures, the UHI effect at the ZM station is approximately 15% higher than at ZG. The difference between the maximum annual air temperatures at ZG and ZM stations has slow increasing trend.

Table 5. Results of Mann-Kendal test for time series of differences between characteristic air temperatures

Difference	Time period	Characteristic	r	p
$\Delta T1 = T_{ZG} - T_{ZM}$	1948-2016	minimum	-0.327	$p<0.01$
		mean	-0.489	$p<0.01$
		maximum	0.270	$p=0.791$
$\Delta T1 = T_{ZG} - T_{ZM}$	1981-2016	minimum	-0.194	$p=0.131$
		mean	-0.508	$p<0.01$
		maximum	-0.0245	$p=0.191$
$\Delta T2 = T_{ZG} - T_{ZA}$	1981-2016	minimum	-0.116	$p=0.870$
		mean	-0.0707	$p=0.713$
		maximum	0.236	$p=0.828$
$\Delta T3 = T_{ZG} - T_{PU}$	1981-2016	minimum	-0.090	$p=0.785$
		mean	0.440	$p<0.01$
		maximum	0.525	$p<0.01$
$\Delta T4 = T_{ZM} - T_{ZA}$	1981-2016	minimum	0.111	$p=0.693$
		mean	0.582	$p<0.01$
		maximum	-0.319	$p=0.300$
$\Delta T5 = T_{ZM} - T_{PU}$	1981-2016	minimum	0.161	$p=0.327$
		mean	0.572	$p<0.01$
		maximum	0.197	$p=0.153$
$\Delta T6 = T_{ZA} - T_{PU}$	1981-2016	minimum	0.024	$p=0.946$
		mean	0.416	$p<0.01$
		maximum	0.378	$p=0.595$

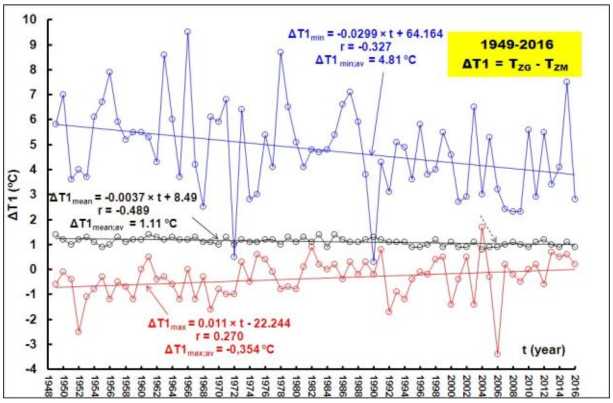

Figure 10. Three time series of differences, *ΔT1*, between minimum, mean and maximum air temperatures of ZG and ZM for the 1949-2016 period with linear trend lines and coefficients of linear correlation, *r*

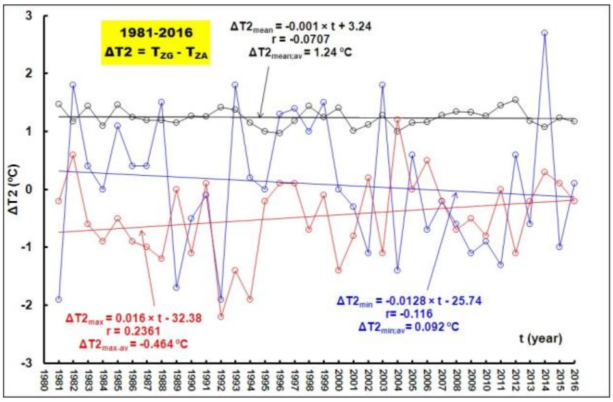

Figure 11. Three time series of differences, *ΔT2*, between minimum, mean and maximum air temperatures of ZG and ZA for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

Figure 11 highlights three time series of differences, *ΔT2*, between minimum, mean and maximum air temperatures of ZG and ZA for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*. There are no statistically significant increasing or decreasing trends in any of three time series of differences in characteristic air temperatures between ZG and ZA. A possible conclusion is that the increase in air temperature at ZA is generally caused by GW, and that UHI does not play a significant role in this process.

Figure 12 represents three time series of differences, *ΔT3*, between minimum, mean and maximum air temperatures of ZG and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*. For the mean and maximum annual air temperatures, the statistically significant increasing trend of differences between ZG and PU exists. For the minimum annual air temperatures, the decreasing trend of differences is not statistically significant. It can be concluded that PU is not influenced by the UHI effect and is less influenced by GW than ZG as well as all other analysed stations. This can be explained by the fact that PU is located at the altitude about 850 m higher than all other stations and is surrounded by dense forested landscape.

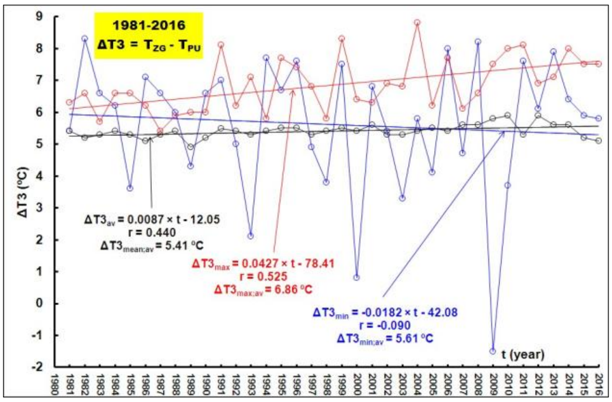

Figure 12. Three time series of differences, *ΔT3*, between minimum, mean and maximum air temperatures of ZG and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

Figure 13 depicts three time series of differences, *ΔT4*, between minimum, mean and maximum air temperatures of ZM and ZA for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*. A statistically significant increasing trend of time series of the mean annual differences proves that the ZM station is exposed to a more intensive UHI influence than ZA. The minimum annual temperature at ZA is in average 4.2ºC lower than at ZM. The increasing trends of time series of the minimum and the maximum annual differences are not statistically significant.

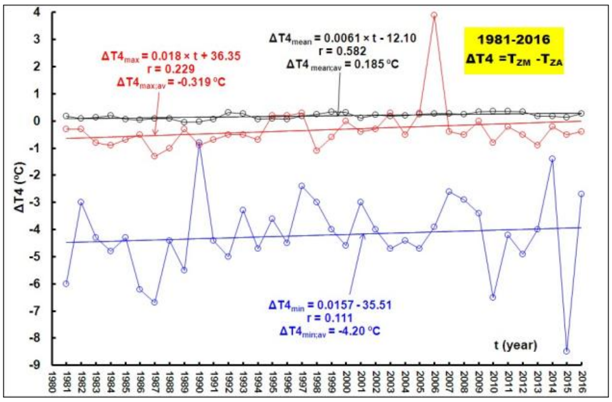

Figure 13. Three time series of differences, *ΔT4*, between minimum, mean and maximum air temperatures of ZM and ZA for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

Figure 14 depicts three time series of differences, *ΔT5*, between minimum, mean and maximum air temperatures of ZM and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*. A statistically significant increasing trend of time series of the mean annual differences proves that the ZM station is exposed to a more intensive UHI influence than PU. For the maximum and minimum air temperatures, the increasing trends of differences between ZM and PU are not statistically significant.

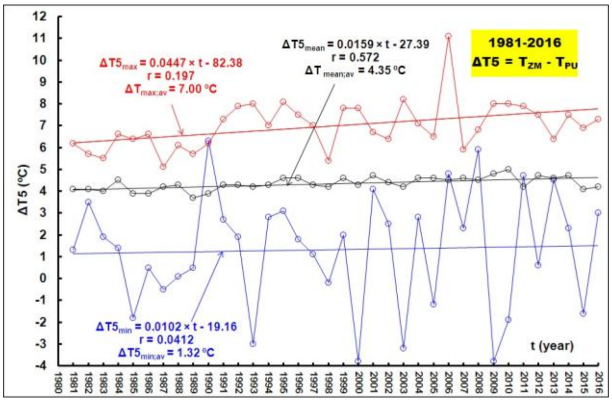

Figure 14. Three time series of differences, *ΔT5*, between minimum, mean and maximum air temperatures of ZM and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

Figure 15 depicts three time series of differences, *ΔT6*, between minimum, mean and maximum air temperatures of ZA and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, r. The conclusions are practically the same as for the comparison of temperatures between: (1) ZG and PU; (2) ZM and PU.

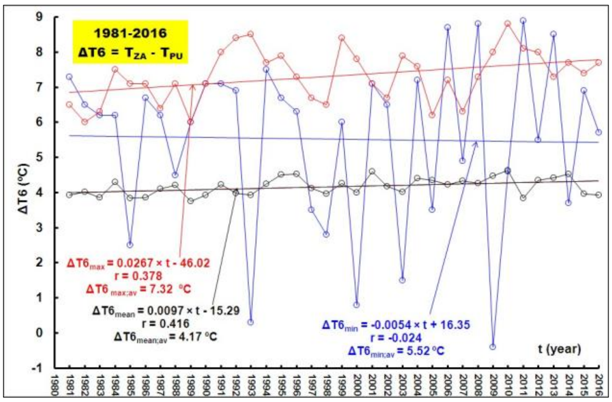

Figure 15. Three time series of differences, *ΔT6*, between minimum, mean and maximum air temperatures of ZA and PU for the 1981-2016 period with linear trend lines and coefficients of linear correlation, *r*

5. CONCLUSION

The analyses conducted herein lead to the conclusion that ZM is subjected to a higher influence of GW and UHI compared to ZG, and especially ZA and PU. The changes of air temperatures in the study area are not equally distributed throughout the analysed period. The station ZM located in the rapidly urbanised suburb are under a stronger influence of GW and UHI effects than all other stations. The most significant increases of high characteristic temperatures occurred in the mid-1980s. The maximum annual air temperatures are very similar at three stations (ZG, ZM and ZA) located at altitudes between 106 and 157 m a.s.l. ZG is the station with the hottest mean annual temperatures, but ZM has a tendency to reach it in the next few decades. The most significant increasing trend is observed in all analysed time series of the mean annual air temperatures. A significant jump in ZG and ZM stations (and most probably in the entire larger area) started in the early 1980s. The definite conclusion is that ZM station is exposed to a more intensive UHI effect than ZA. The average minimum annual temperatures in 1949-2016 period at ZA (-9.39ºC) are 4.2ºC higher than at ZM (-13.59ºC). The minimum temperature measured at ZA (-18.3ºC) is 4.3ºC higher than at ZM (-22.6ºC). The average maximum annual temperature in 1949-2016 period at ZM (34.88ºC) is only 0.33ºC lower than at ZA (35.2 ºC). The average maximum annual temperature at PU (24. ºC) is 7.0ºC lower than at ZA (31.6ºC).

The analyses of UHI should be considered as an exceptionally important topic with many unsolved questions. Peterson (2003) argues that all analyses of the impact of UHIs on in-situ temperature observations suffer from inhomogeneity or biases in the data, which make UHI analyses difficult and may lead to erroneous conclusions. He concluded that a variety of adjustments were applied to the data in order to remove the biases caused by differences in elevation, latitude, time of observation, instrumentation, and nonstandard siting. Wang and Yan (2016) noted that calculated urban warming trends are also influenced by the various sources of temperature data and the size of urban areas. Due to this fact they propose: *"Further understanding and quantification of urbanization-related effects in local climate records is expected through the application of high-resolution regional climate modelling, along with the gathering of high-precision information on the changing underlying surface and improvements in the representation of key urban processes in climate models."* Parker (2006) stresses that UHI-s occur mainly at night and are reduced in windy conditions. Because of that he concludes that the observed overall warming is not a consequence of urban development.

The research presented by Li et al. (2016) attempts to unravel how a global temperature time series created partly from the urban in-situ stations can lead to no contamination from urban warming. They note that some urban stations are warmer than the nearby rural stations, but that almost the same numbers of stations are colder.

Mohsin and Gough (2012) argue that "*UHI intensity for any city is a critical task, and it is imperative to consider some key features such as the physiography, surface characteristics of the urban and rural stations, the climatology such as the trends in annual and seasonal variation of UHI with respect to the physical characteristics of the stations, and also more importantly the objectives of a particular study in the context of UHI effect*."

In order to achieve better special and temporal development of the UHI forecast, it is of crucial importance to improve and extend the understanding of this complex process. It seems that one of the best ways for achieving this goal is a detailed analysis of the UHI effect in many different urban areas. The authors believe that the investigations described in the paper will be useful for other researchers and practitioners who analyse different aspects of UHIs.

It is only with intense and close interdisciplinary cooperation that the researchers will be able to update their understanding of UHIs.

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POVEĆANJE TRENDOVA TEMPERATURE VAZDUHA U URBANIM PODRUČJIM – NA PRIMERU ČETIRI METEOROLOŠKE STANICE U GRADU ZAGREBU

by

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Rezime

U članku se analiziraju razlike u trendovima porasta karakterističnih (minimalnih, srednjih i maksimalnih) godišnjih temperature vazduha izmerenih na četiri meteorološke stanice u području grada Zagreba. Cilj analize je da se odredi kako se razvija trend porasta temperatura u raznim delovima područja koje je različito obuhvaćeno procesima urbanizacije. Porast temperatura u urbanim područjima delimično je uzrokovan globalnim zagrevanjem, a delimično efektom urbanizacije. Za analize su korišteni podaci sa sledećih meteoroloških stanica: (1) Zagreb Grič (ZG); (2) Zagreb Maksimir (ZM); (3) Zagreb Aerodrom (ZA); (4) Puntijarka (PU). Meteorološka stanica ZG se nalazi u centru grada, ZM u predgrađu koje se vrlo intenzivno urbanizuje, ZA u predgrađu koje je slabije zahvaćeno procesima urbanizacije, dok je stanica PU smeštena gotovo na vrhu Zagrebačke gore koji je u celosti izvan uticaja urbanizacije. Vremenske serije razlika između karakterističnih temperatura vazduha za sve parove stanica računate su za sledeća dva perioda: (1) 1949-2016; (2) 1981-2016. U članku su korištene metode korelacije i regresije, analize trendova vremenskih serija i razlika među njima, t-test i Mann-Kendal test. Razlike u karakterističnim temperaturama vazduha između parova stanica pokazuju individualno ponašanje na svakoj od njih. Na porast temperatura vazduha na stanicama smeštenim u gradu i u području koje se naglo urbanizuje snažan uticaj vrši istovremeno globalno zagrevanje i urbanizacija. Stanica ZM ima jači intenzitet porasta od stanice ZG, a osobito satnica ZA i PU. Urbanizacija povećava minimalne godišnje temperature vazduha na stanici ZM približno 30% više nego na stanici ZG. Najjači intenzitet porasta opažen je na serijama minimalnih temperatura vazduha.

Ključne reči: Karakteristične godišnje temperature vazduha, temperaturni trendovi, globalno zagrevanje, urbana temperaturna ostrva, grad Zagreb

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