UDK/*UDC*: 502.3:504.7(497.521.2)
Izvirni znanstveni članek – *Original scientific paper*
Prejeto/*Received:* 26.10.2018
Sprejeto/*Accepted:* 13.11.2018

ANALYSES OF THE ZAGREB GRIČ OBSERVATORY AIR TEMPERATURES INDICES FOR THE PERIOD 1881 TO 2017

ANALIZE INDEKSOV TEMPERATURE ZRAKA NA OBSERVATORIJU ZAGREB GRIČ V OBDOBJU 1881-2017

Ognjen Bonacci[1,*], Tanja Roje-Bonacci[1]

[1] Faculty of Civil Engineering, Architecture and Geodesy, University of Split, 21000 Split, Matice hrvatske 15, Croatia

Abstract

The paper studies time series of characteristic (minimum, mean, and maximum) daily, monthly, and yearly air temperatures measured at the Zagreb Grič Observatory in the period from 1 Jan. 1881 to 31 Dec. 2017. The following five air temperatures indices (ATI) are analysed: (1) absolute minimum yearly, monthly, and daily; (2) mean yearly, monthly, and daily minimum; (3) average mean yearly, monthly, and daily; (4) mean yearly, monthly, and daily maximum; (5) absolute maximum yearly, monthly, and daily. Methods of Rescaled Adjusted Partial Sums (RAPS), regression and correlation analyses, F-tests, and t-tests are used in order to describe changes in air temperature regimes over 137 years. Using the RAPS method the five analysed yearly ATI time series durations of 137 years were divided into two sub-periods. The analyses made in this paper showed that warming of minimum air temperatures started in 1970, mean air temperatures in 1988, and maximum air temperatures in 1998. Results of t-tests show an extreme statistically significant jump in the average air-temperature values in the second (recent time) sub-periods. Results of the t-tests of monthly temperatures show statistically significant differences between practically all five pairs (except in two cases) of analysed monthly ATI subseries for the period from January to August. From September to December the differences for most of pairs (except in six cases) of the analysed monthly ATI subseries are not statistically significant. It can be concluded that the urban heat island influenced the increase in recent temperatures more strongly than global warming. It seems that urbanisation firstly and chiefly influenced the minimum temperatures, as well as that Zagreb's urbanisation had a bigger impact on minimum temperatures than on maximums. Increasing trend in time series of maximum temperatures started 20 years later.

Keywords: minimum, mean and maximum daily, monthly and yearly air temperatures; global warming; urban heat island; trend; jump; Zagreb Grič (Croatia).

Izvleček

Članek obravnava časovne vrste značilnih (minimalnih, srednjih in maksimalnih) dnevnih, mesečnih in letnih temperatur zraka, izmerjenih v Observatoriju Zagreb Grič v obdobju od 1. 1. 1881 do 31. 12. 2017. Analizirali smo pet indeksov temperature zraka: (1) absolutni minimalni letni, mesečni in dnevni; (2) srednji

[*] Stik / *Correspondence*: obonacci@gradst.hr

https://doi.org/10.15292/acta.hydro.2018.05

letni, mesečni in dnevni minimalni; (3) povprečni srednji letni, mesečni in dnevni; (4) srednji letni, mesečni in dnevni maksimalni; (5) absolutni letni, mesečni in dnevni. Za opis sprememb režimov letnih temperatur v obdobju 137 let smo uporabili metodo umerjenih delnih vsot (Rescaled Adjusted Partial Sums – RAPS), regresijsko in korelacijsko analizo, F-test in t-test. Pri uporabi metode umerjenih delnih vsot (RAPS) smo pet analiziranih letnih časovnih vrst indeksa temperature zraka v obdobju 137 let razdelili v dve podobdobji. Analize, opravljene za potrebe tega prispevka, so pokazale, da so minimalne temperature zraka začele naraščati leta 1970, srednje temperature zraka leta 1988 in maksimalne temperature zraka leta 1998. Rezultati t-testov kažejo ekstremno statistično značilno povečanje povprečnih vrednosti temperature zraka v drugem (zadnjem) podobdobju. Rezultati t-testov mesečnih temperatur izkazujejo statistično značilne razlike med praktično vsemi petimi pari (razen v dveh primerih) analiziranih mesečnih podserij indeksov temperature zraka za obdobje od januarja do avgusta. Od septembra do decembra razlike pri večini parov (razen v šestih primerih) analiziranih mesečnih podserij indeksov temperature zraka niso statistično značilne. Zaključimo lahko, da je bil vpliv mestnega toplotnega otoka na naraščanje temperatur v zadnjem času večji kot vpliv globalnega segrevanja. Zdi se, da je urbanizacija vplivala najprej in predvsem na minimalne temperature in da je bil vpliv urbanizacije v Zagrebu večji na minimalne kot na maksimalne temperature. Trend naraščanja v časovnih vrstah maksimalnih temperatur se je začel 20 let pozneje.

Ključne besede: minimalne, srednje in maksimalne dnevne, mesečne in letne temperature zraka, globalno segrevanje, mestni toplotni otok, trend, sprememba, Zagreb Grič (Hrvaška).

1. Introduction

Land surface air temperature is one of the most important parameters in explaining and solving many theoretical and practical geophysical, environmental, biological, agricultural, engineering, social, and health issues (e.g. Piani et al., 2010; Schneider and Breitner, 2016, etc.). It plays a decisive role in climatological, ecological, hydrological, engineering, geophysical, geographical, and many other processes. This makes it of crucial importance to follow and analyse how it changes at different time scales, and what implications trends in the land surface air temperature may have for society as a whole.

Air temperature plays a crucial role in practically all hydrological processes. Its most important influences are on: (1) evapotranspiration as the main element of the water budget; (2) water temperature in rivers and lakes, which affects other physical properties and influences the chemical and biological reactions in its lotic system (Bonacci et al., 2008); (3) soil moisture content; (4) snow and ice melt contributions to floods, etc. Air temperature variations resulting from climate change are an important driving force driving change in hydrologic processes in any watershed ecosystems.

Heat waves and cold spells have both shown adverse effects on practically all human and ecological processes. This fact highlights the crucial importance of extreme (minimum and maximum) air temperature analyses at different time scales from day(s) to years. It is well known that in global temperatures increased over the past two centuries. More detailed conclusions about this extremely important, recent process can be attained through analyses of the time series monitored for a long time, namely longer than 100 years.

Global warming (GW) and urban heat island (UHI) effects co-exist in rapidly developed towns. Understanding better how they interactively function in various urban areas is of crucial importance. UHI describes the occurrence of higher air temperatures in urban compared to surrounding non-urban areas as a direct consequence of urbanisation. This process depends on the interaction between natural and anthropogenic factors, which are very different for each urban area. Urban warming trends are influenced by the various sources of temperature data and the size of urban areas (Wang and Yan, 2016).

This paper outlines the changes in the characteristic (minimum, mean and maximum) annual, month, and daily air temperature measured at the Zagreb Grič Observatory during 137 years and contains an analysis thereof. This observatory operates on a small hill in the inner city centre (Fig.1). It is located beneath the foothills of the Medvednica Mountain (45°49' – 15°59') at an 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. Although the Zareb-Grič Observatory is surrounded by urban areas, its position is on a hilltop and thus the influence of the heat island is reduced. On the other hand, from the beginning of its operation the observatory has been at the same location and with minimum changes in the surrounding area (Ogrin and Krevs, 2015). Scientists analyzing climate change consider air temperature anomalies rather than absolute values, and “constant” influences are thus removed.

Various analyses of mean annual air temperature and other climatological time series measured at the Zagreb Grič Observatory have already been published in a few papers (Šegota, 1981; Juras, 1985; Penzar et al., 1992; Radić et al., 2004; Auer et al., 2007; Pandžić et al., 2009; Pandžić and Likso, 2010; Likso and Pandžić, 2014; Ogrin and Krevs, 2015). Likso (2003) concludes that the standard normal homogeneity test reveals that the air temperature time series are homogenous for the 1949-1998 period. Klaić et al. (2002) analysed the modification of the local winds due to the hypothetical urbanisation of Zagreb’s surroundings. Nitis et al. (2005) found that Zagreb’s local topography played an important role in the formation and the evolution of the urban heat island (UHI). Secular trends observed by Zagreb-Grič (1862-2012) of the annual number of days above the 90th percentile (days fall under the categories very warm and extremely warm) indicate a positive significant trend of 19.0 days/100 years, while for days below 10th percentile (days within the categories very cold and extremely cold) a significant negative trend of -18.1 days/100 years could be observed (Likso and Pandžić, 2014).

Analysing the long-lasting time series we try to explain the various changes of analysed characteristic air temperatures (minimum, mean and maximum) (ATI). 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 following equation for the calculation of mean daily air temperature ${}_{md}T$ (º C) is in use in Croatia as well as in the Northern European countries (Heino, 1994; Bonacci et al., 2013; Bonacci and Željković, 2018):

$${}_{md}T = ({}_{7}T + {}_{14}T + 2 \times {}_{21}T)/4, \qquad (1)$$

where ${}_{7}T$, ${}_{14}T$, and ${}_{21}T$ are the air temperatures measured at 7h, 14h, and 21h respectively. The hours refer to the mean local time.

This paper includes analysis of the following five characteristic air temperatures: (1) absolute minimum yearly, monthly, and daily; (2) mean yearly, monthly, and daily minimum; (3) average mean yearly, monthly, and daily; (4) mean yearly, monthly, and daily maximum; (5) absolute maximum yearly, monthly, and daily.

A time series analysis can detect and quantify trends and fluctuations in records. Methods of regression and correlation analyses, F-test, t-test, and Rescaled Adjusted Partial Sums (RAPS) are used in order to describe changes in air temperature regimes. The RAPS method (Garbrecht and Fernandez, 1994; Bonacci, 2012; Tadić et al., 2016) helps to overcome random changes, errors, and variability in the analysed time series. The value of RAPS is calculated by the expression:

$$RAPS_k = \sum_{t=1}^{k} \frac{Y_t - {}_{m}Y}{S}, \qquad (2)$$

where ${}_{m}Y$ is the mean and S is the standard deviation over the entire values in the time series, while (k=1, 2…, n) is the counter limit of the summation for the k-th member of the time series.

During the last about 150 years Zagreb's 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. The main goal of this paper is to understand and explain the behaviour of air temperature variability in a town as rapidly urbanised as Zagreb is. The air temperature changes in any urbanised area can be governed by GW and by UHI.

2. Year as a time unit

Figure 2 depicts five RAPS time series of yearly ATI for the 1881-2017 period: (1) absolute minimum ${}_{Y.a.m}T$ (dark blue); (2) mean daily minimum ${}_{Y.md.m}T$ (green); (3) average mean daily ${}_{Y.av.md}T$ (black); (4) mean daily maximum ${}_{Y.md.M}T$ (orange); (5) absolute maximum ${}_{Y.a.M}T$ (red). On the basis of the graphical presentations given in Figure 2 the data series of yearly absolute minimum ${}_{Y.a.m}T$ and yearly mean daily minimum ${}_{Y.md.m}T$ was divided into two time subseries: (1) 1881-1969; (2) 1970-2017. The data series of yearly average mean daily ${}_{Y.av.md}T$ is divided into the following two time subseries: (1) 1881-1987; (2) 1988-2017. The data series of yearly absolute maximum ${}_{Y.a.M}T$ was divided into two subseries: (1) 1881-1997; (2) 1998-2017. In all analysed cases during the second subseries shift or jump of temperatures started.

The differences in five analysed ATI can be clearly seen in graphical presentations given in Figures 3, 4, 5, 6 and 7. In these figures time data subseries with their average values, linear trend lines and coefficient of linear correlation are r given.

Results of the Mann-Kendall test (Mann, 1945; Kendall, 1975; Hamed and Ramachandra, 1998) for the time series of ATI are given in Table 1. Cases where the trends are statistically significant are marked in bold. The trends in all five complete time series durations from 1881 (1962) to 2017 are statistically significant. Only in two time subseries (yearly average mean daily ${}_{Y.av.md}T$) are the trends statistically significant. In all other eight analysed cases they are not statistically significant, $p>0.1$.

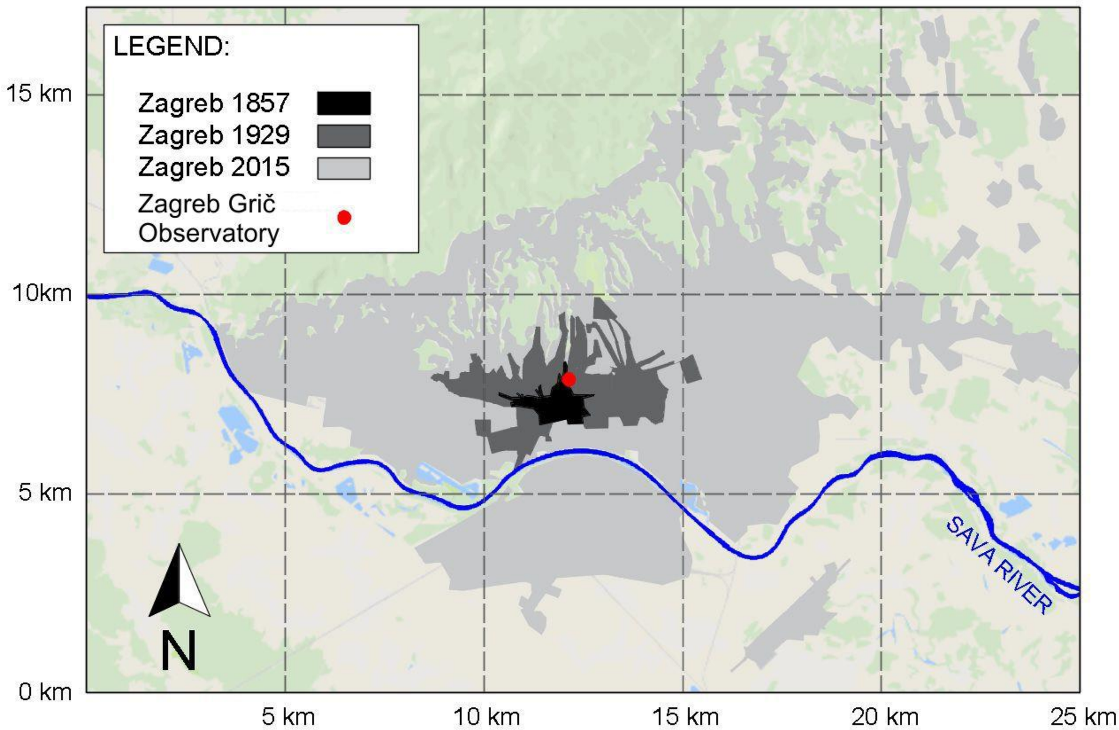

Figure 1: *Development of Zagreb's urban area from 1857 to recent times, with the designated position of the Zagreb Grič Observatory.*

Slika 1: *Razvoj urbanega območja Zagreba od leta 1857 do danes s prikazom lokacije Observatorija Zagreb Grič.*

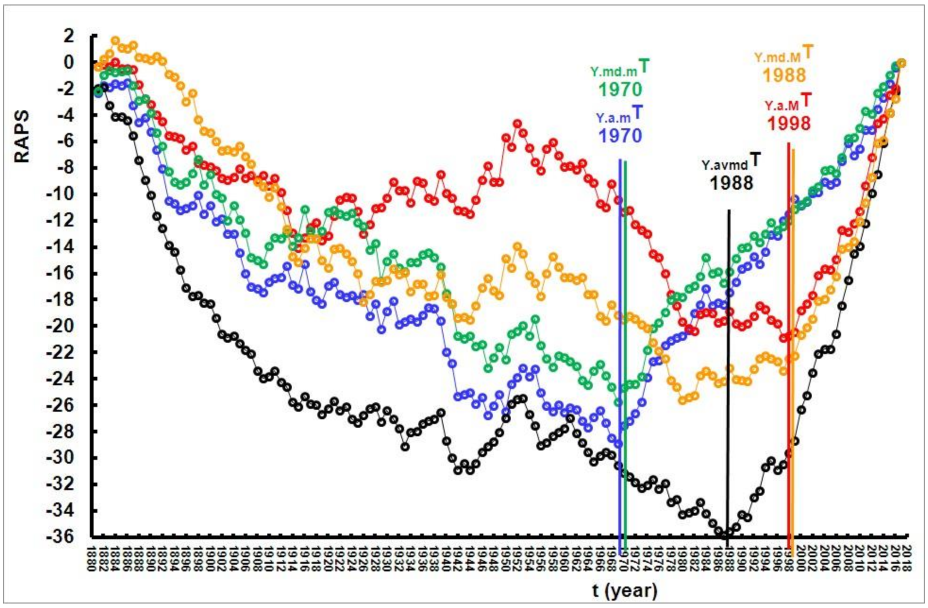

***Figure 2:** Five RAPS time series of characteristic yearly air temperature for the 1881–2017 period: (1) absolute minimum $_{Y.a.m}T$ (dark blue); (2) mean daily minimum $_{Y.md.m}T$ (green); (3) average mean daily $_{Y.av.md}T$ (black); (4) mean daily maximum $_{Y.md.M}T$ (orange); (5) absolute maximum, $_{Y.a.M}T$ (red).*

***Slika 2:** Pet časovnih vrst značilnih letnih temperatur zraka za obdobje 1881–2017, določenih po metodi umerjenih delnih vsot (RAPS): (1) absolutna minimalna $_{Y.a.m}T$ (temnomodra); (2) srednja dnevna minimalna $_{Y.md.m}T$ (zelena); (3) povprečna srednja dnevna $_{Y.av.md}T$ (črna); (4) srednja dnevna maksimalna $_{Y.md.M}T$ (oranžna); (5) absolutna maksimalna, $_{Y.a.M}T$ (rdeča).*

***Table 1:** Results of Mann-Kendall test for time series of characteristic air temperatures (CAT).*
***Preglednica 1:** Rezultati Mann-Kendall testa za karakteristične vrednosti temperature zraka (CAT).*

CAT	period	T (°C)	Mann-Kendall test
	1881-2017	-11.67	8.99E-07
$_{Y.a.m}T_{av}$	1881-1969	-13.05	0.3058
	1970-2017	-9.14	0.9929
	1881-2017	-8.04	3.52E-05
$_{Y.md.m}T_{av}$	1881-1987	-8.95	0.7231
	1988-2017	-6.35	0.9646
	1862-2017	11.60	4.19E-11
$_{Y.av.md}T_{av}$	1881-2017	11.64	5.13E-09
	1881-1987	11.34	0.0034
	1988-2017	12.72	5.38E-04
	1881-2017	27.52	6.78E-05
$_{Y.md.M}T_{av}$	1881-1987	27.21	0.493
	1988-2017	29.32	0.041
	1881-2017	33.78	3.00E-03
$_{Y.a.M}T_{av}$	1881-1997	33.43	0.8303
	1998-2017	35.91	0.0744

Table 2: *Results of F-test and t-test between the values of yearly CATs time subseries.*
Preglednica 2: *Rezultati F-testa in t-testa med vrednostmi letnih CAT pod-serij.*

CAT	sub-period	T (ºC)	F-test	t-test
$_{Y.a.m}T_{av}$	1881-1969	-13.05	0.00403	4.43E-09
	1970-2017	-9.14		
$_{Y.md.m}T_{av}$	1881-1969	-8.95	0.00035	6.23E-08
	1970-2017	-6.35		
$_{Y.avmd}T_{av}$	1881-1987	11.34	0.332	7.58E-17
	1988-2017	12.72		
$_{Y.md.M}T_{av}$	1881-1997	27.22	0.641	1.88E-09
	1998-2017	29.32		
$_{Y.a.M}T_{av}$	1881-1997	33.43	0.796	1.33E-07

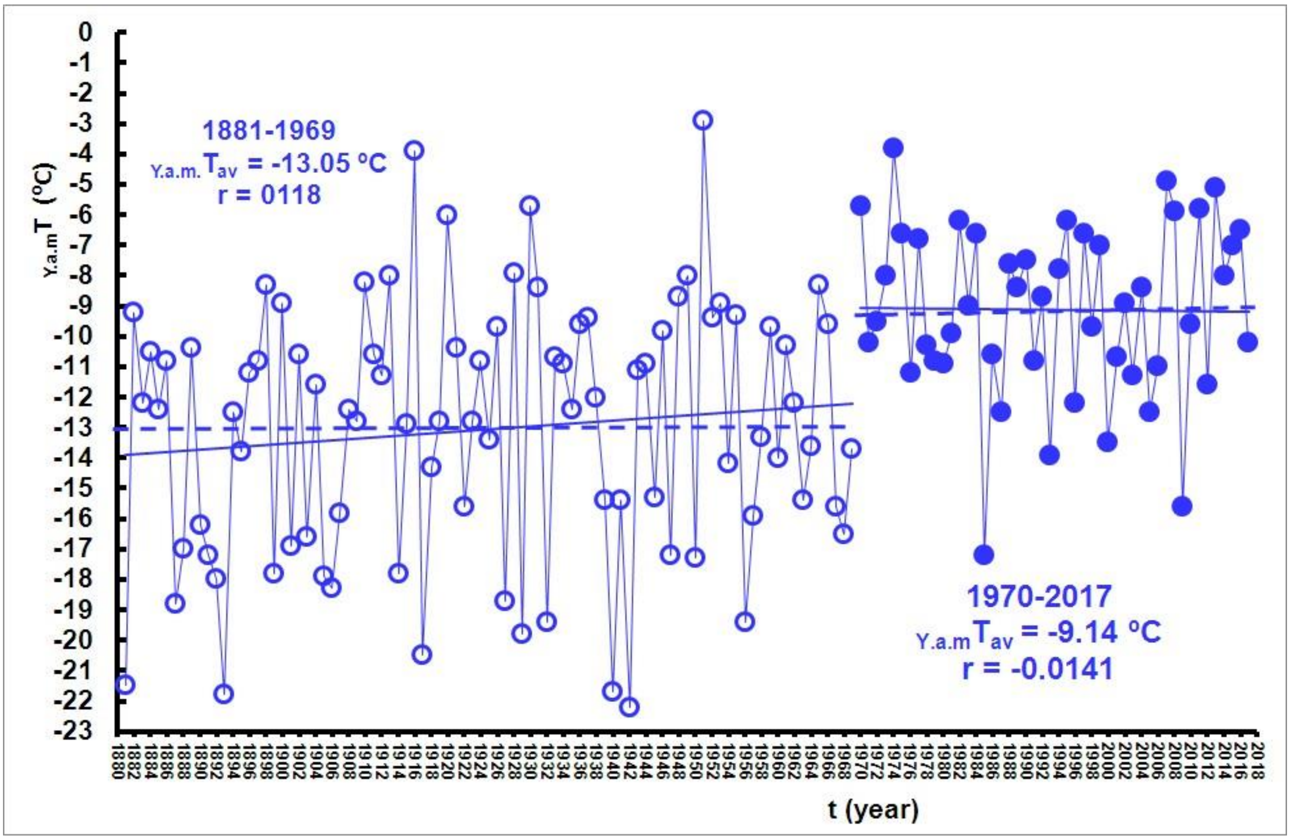

Figure 3: *Time series of yearly absolute minimum air temperature $_{Y.a.m}T$ for two sub-periods: (1) 1881–1969; (2) 1970–2017.*

Slika 3: *Časovne vrste letne absolutne minimalne temperature zraka $_{Y.a.m}T$ za dve podobdobji: (1) 1881–1969; (2) 1970–2017.*

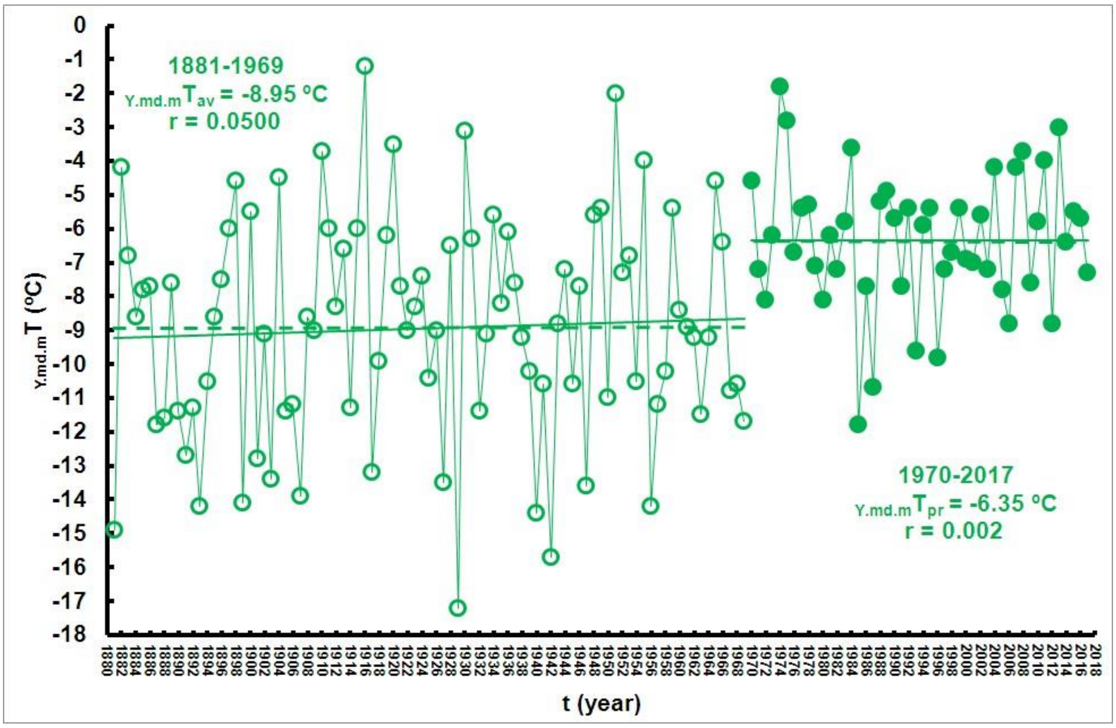

Figure 4: *Time series of yearly mean daily minimum air temperature $_{Y.md.m}T$ for two sub-periods: (1) 1881–1969; (2) 1970–2017.*

Slika 4: *Časovne vrste letne srednje dnevne minimalne temperature zraka $_{Y.md.m}T$ za dve podobdobji: (1) 1881–1969; (2) 1970–2017.*

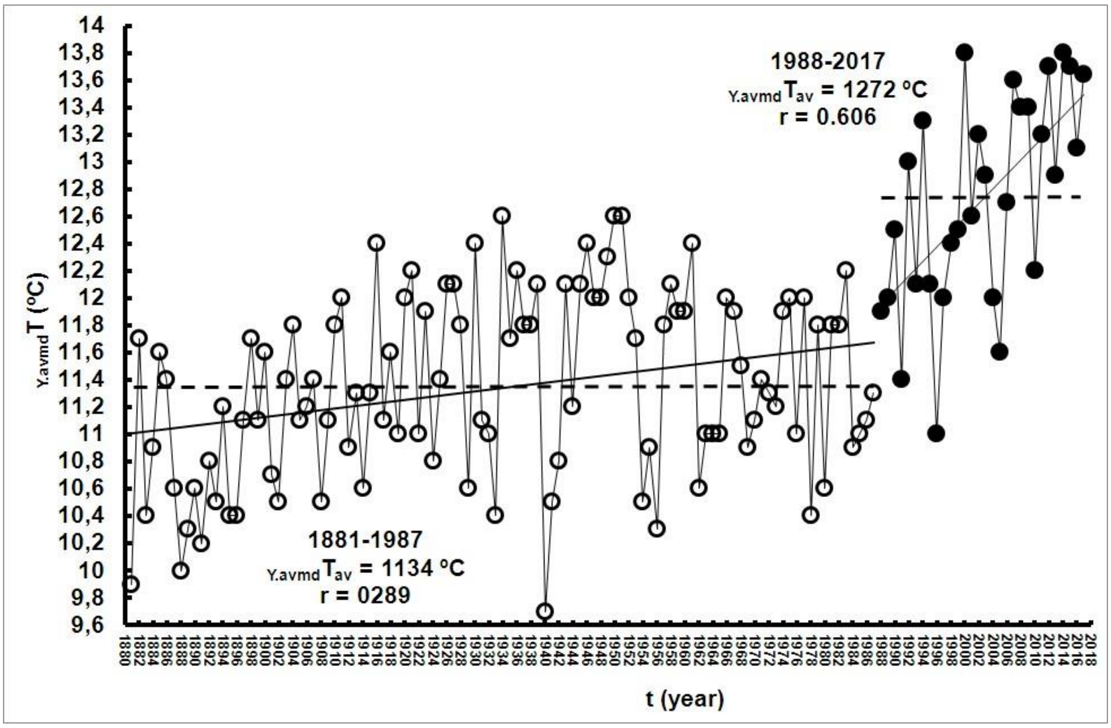

Figure 5: *Time series of yearly average mean daily air temperature $_{Y.avmd}T$ for two sub-periods: (1) 1881–1987; (2) 1988–2017.*

Slika 5: *Časovne vrste letne povprečne srednje dnevne temperature zraka $_{Y.avmd}T$ za dve podobdobji: (1) 1881–1987; (2) 1988–2017.*

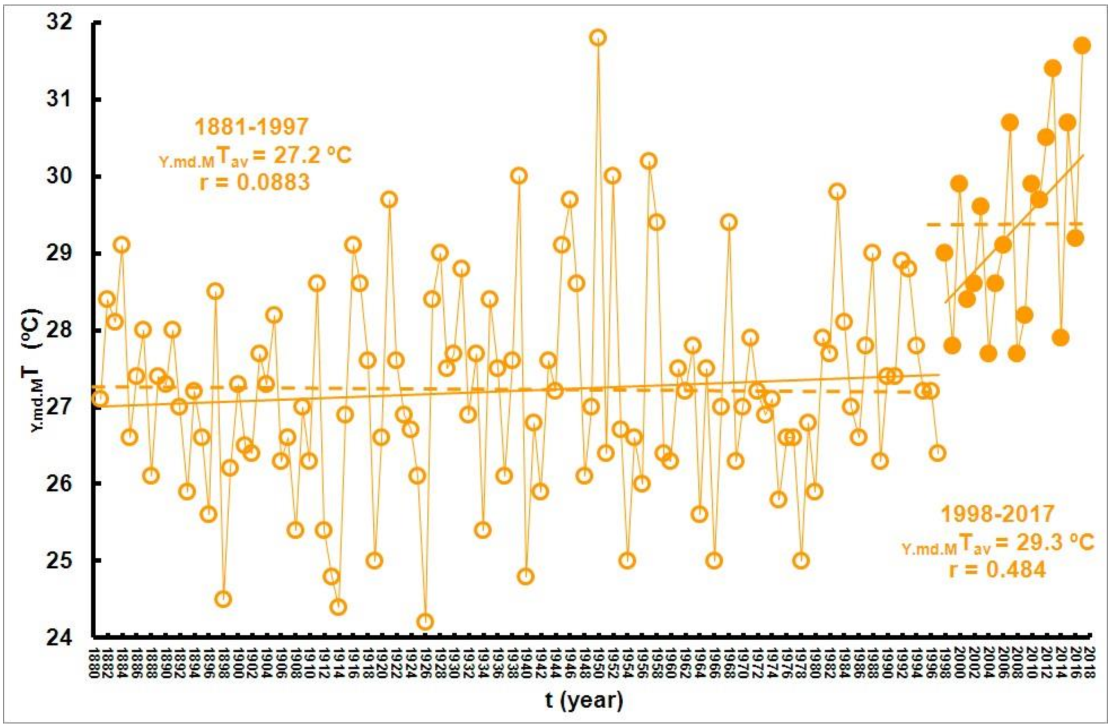

Figure 6: *Time series of yearly mean daily maximum air temperatures $_{Y.md.M}T$ for two sub-periods: (1) 1881–1997; (2) 1998–2017.*

Slika 6: *Časovne vrste letne srednje dnevne maksimalne temperature zraka $_{Y.md.M}T$ za dve podobdobji: (1) 1881–1997; (2) 1998–2017.*

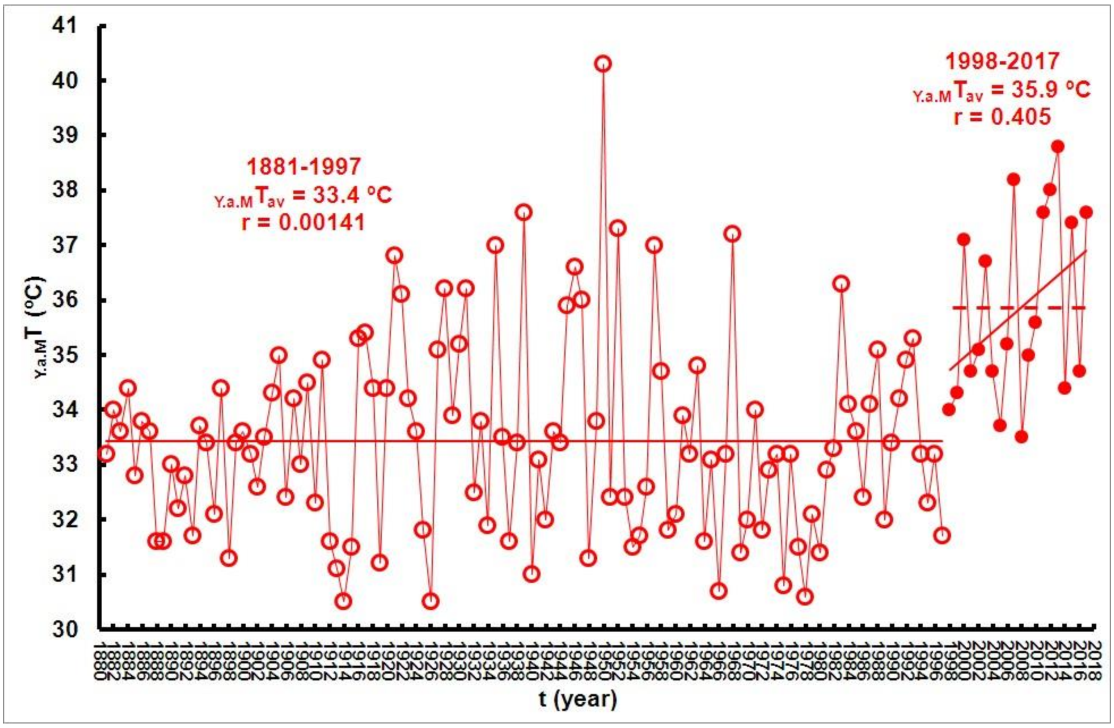

Figure 7: *Time series of yearly absolute maximum air temperature $_{Y.a.M}T$ for two sub-periods: (1) 1881–1997; (2) 1998–2017.*

Slika 7: *Časovne vrste letne absolutne maksimalne temperature zraka $_{Y.a.M}T$ za dve podobdobji: (1) 1881–1997; (2) 1998–2017.*

The results of the F-test and t-test between the values of yearly ATI time subseries are given in Table 2. In all cases the results of the t-test show extreme statistically significant differences between the average values of air temperatures in the analysed sub-periods. The variances of subseries are statistically significant in two following cases: (1) yearly absolute minimum ${}_{Y.a.m}T$; and (2) yearly mean daily minimum ${}_{Y.md.m}T$. It can be concluded that in all five analysed yearly ATI there is a strong shift (jump) in the second (recent time) sub-period in comparison with the first sub-period.

3. Month as a time unit

Of crucial importance is to understand how the air temperature increases or jump, established in the previous chapter, are reflected during the year, i.e. in different months. Table 3 gives the results of the F-test and t-test between values of the monthly ATI time subseries. It can be seen that the F-test shows a statistical significant difference between variances of two subseries (for January ${}_{MO.a.m}T$) only in one case. The situation with the t-test is very different. Statistically significant differences between the average ATI subseries values were established in most of the ATIs and months.

Results of t-tests show statistically significant differences between practically all five pairs (except in two cases for ${}_{MO.a.m}T$) of the analysed monthly ATI subseries for the period from January to August. From September to December for most pairs (except in six cases) of the analysed monthly ATI subseries the differences are not statistically significant. All analysed ATIs in September are under the smallest influence of the GW and UHI processes.

Figure 8 depicts four time series of monthly absolute minimum air temperatures ${}_{MO.a.m}T$ in January and October for two sub-periods: (1) 1881-1969; (2) 1970-2017. January is the month with the higher statistically significant differences between two subseries (p<0.01), while in October the difference is not statistically significant (p=0.591). The absolute minimum air temperatures values during the whole 12 months were significantly lower in the first (1881-1969) than in the second (1970-2017) sub-period, especially in March when the difference was 8.3 °C.

Figure 9 depicts four time series of monthly mean monthly minimum air temperatures ${}_{MO.mm.m}T$ in August and September for two sub-periods: (1) 1881-1969; (2) 1970-2017. August is the month with the higher statistically significant differences between the two subseries (p<0.01), while in September the difference is not statistically significant (p=0.033).

Figure 10 shows four time series of monthly mean monthly average air temperatures ${}_{MO.mm.av}T$ in August and September for two sub-periods: (1) 1881-1987; (2) 1988-2017. August is the month with the higher statistically significant differences between the two subseries (p<0.01), while in September the difference is not statistically significant (p=0.422).

Figure 11 shows four time series of monthly mean monthly maximum air temperatures ${}_{MO.mm.M}T$ in July and September for two sub-periods: (1) 1881-1997; (2) 1998-2017. July is the month with the higher statistically significant differences between the two subseries (p<0.01), while in September the difference is not statistically significant (p=0.257).

Figure 12 depicts four time series of monthly absolute maximum air temperatures, ${}_{MO.a.M}T$, in June and September for the two sub-periods: (1) 1881-1997; (2) 1998-2017. June is the month with the higher statistically significant differences between the two subseries (p<0.01), while in September the difference is not statistically significant (t=0.496). The data in Table 3 show that the absolute maximum air temperatures values in seven months (March, June, July, September, October, November, and December) were higher in the first (1881-1997) than in the second (1998-2017) sub-period.

Table 3: *Results of F-test and t-test between values of monthly CATs time subseries.*

Preglednica 3: *Rezultati F-testa in t-testa med vrednostmi mesečnih CAT pod-serij.*

	January	February	March	April	May	June	July	August	September	October	November	December
						MO.a.mT (°C)						
1881-1969	-22.20	-21.70	-17.00	-1.90	0.50	4.60	7.30	7.30	2.30	-6.00	-9.70	-18.70
1970-2017	-17.20	-15.80	-9.70	-0.50	1.60	6.70	9.40	7.80	3.00	-2.00	-7.50	-15.60
F-test	<0.01	0.012	0.119	0.960	0.786	0.428	0.760	0.196	0.300	0.051	0.036	0.010
t-test	<0.01	<0.01	<0.01	0.013	<0.01	0.246	<0.01	<0.01	<0.01	0.591	0.033	0.248
						MO.mm.mTav (°C)						
1881-1969	-2.80	-1.21	2.98	7.33	11.55	14.71	16.55	15.86	12.78	8.16	3.70	-0.37
1970-2017	-0.54	0.74	4.28	8.15	12.49	15.69	17.57	17.28	13.31	8.84	4.35	0.44
F-test	0.012	0.072	0.890	0.785	0.505	0.269	0.025	0.026	0.221	0.455	0.845	0.016
t-test	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.033	0.014	0.075	0.029
						MO.mm.avTav (°C)						
1881-1987	0.12	2.23	6.93	11.64	16.21	19.44	21.55	20.76	17.11	11.74	6.31	2.09
1988-2017	2.35	4.47	8.77	12.98	17.49	20.88	23.00	22.51	17.37	12.49	7.47	2.88
F-test	0.163	0.500	0.617	0.659	0.642	0.354	0.889	0.022	0.572	0.692	0.354	0.206
t-test	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.422	0.018	<0.01	0.085
						MO.mm.MTav (°C)						
1881-1980	2.72	5.49	11.04	16.27	21.18	24.51	26.83	25.93	21.58	15.36	8.91	4.28
1981-2017	5.38	7.91	13.28	18.55	23.09	26.98	28.84	27.94	22.10	16.88	11.19	5.91
F-test	0.575	0.686	0.361	0.212	0.197	0.985	0.454	0.043	0.798	0.819	0.626	0.507
t-test	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.257	<0.01	<0.01	<0.01
						MO.a.MT (°C)						
1881-1997	17.6	20.9	26.1	28.7	32.3	37.0	40.3	37.3	34.2	27.6	25.0	21.5
1998-2017	19.0	21.6	24.6	29.8	33.4	36.2	38.2	38.8	33.0	25.9	23.6	19.1
F-test	0.069	0.363	0.329	0.476	0.175	0.677	0.459	0.065	0.657	0.077	0.287	0.825
t-test	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.496	0.033	<0.01	0.031

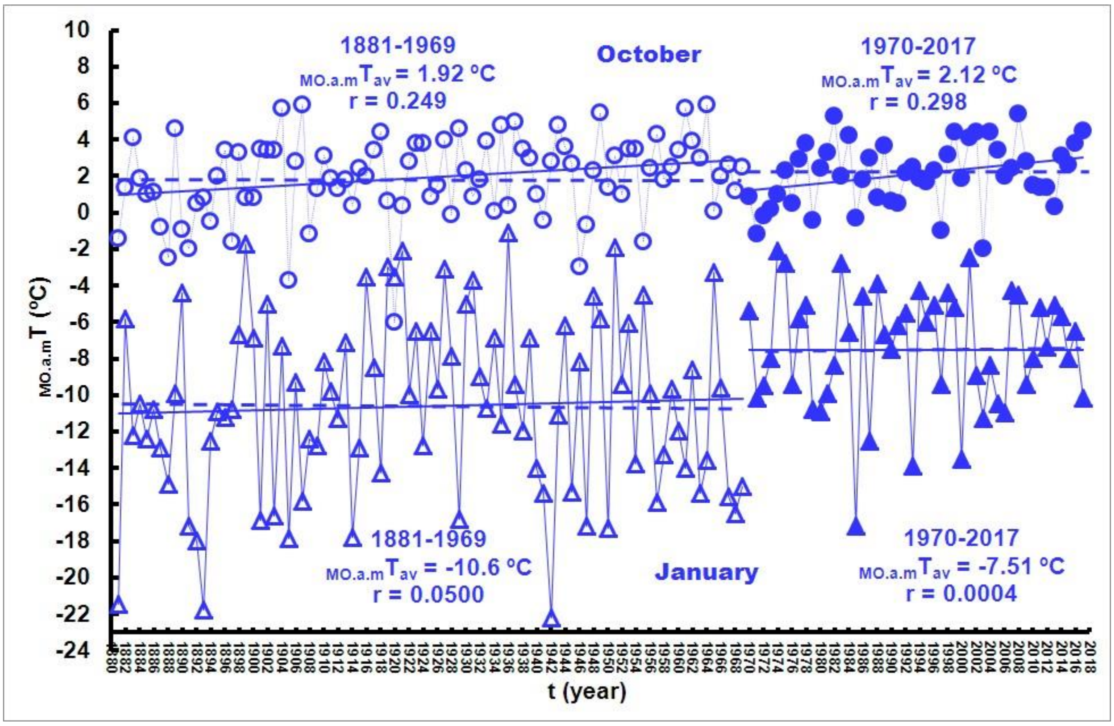

Figure 8: *Four time series of monthly absolute minimum air temperature $_{MO.a.m}T$ in January and October for two sub-periods: (1) 1881–1969; (2) 1970–2017.*

Slika 8: *Štiri časovne vrste mesečne absolutne minimalne temperature zraka $_{MO.a.m}T$ v januarju in oktobru za dve podobdobji: (1) 1881–1969; (2) 1970–2017.*

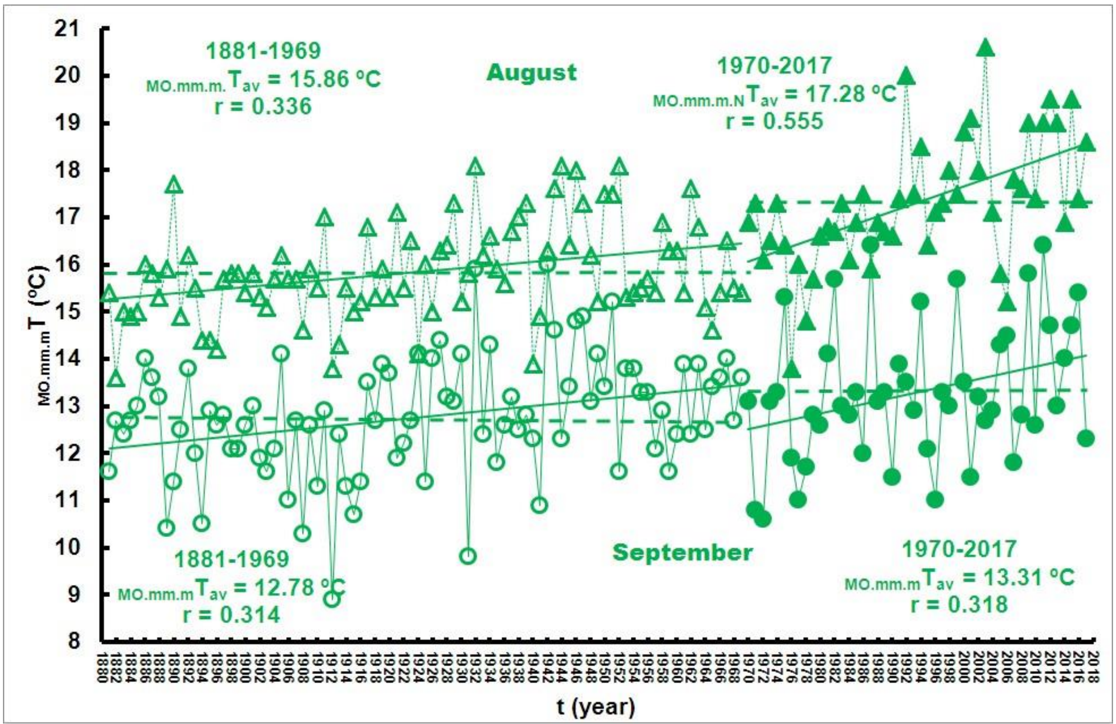

Figure 9: *Four time series of monthly mean monthly minimum air temperature $_{MO.mm.m}T$ in August and September for two sub-periods: (1) 1881–1969; (2) 1970–2017.*

Slika 9: *Štiri časovne vrste mesečnih srednjih vrednosti mesečne minimalne temperature zraka $_{MO.mm.m}T$ v avgustu in septembru za dve podobdobji: (1) 1881–1969; (2) 1970–2017.*

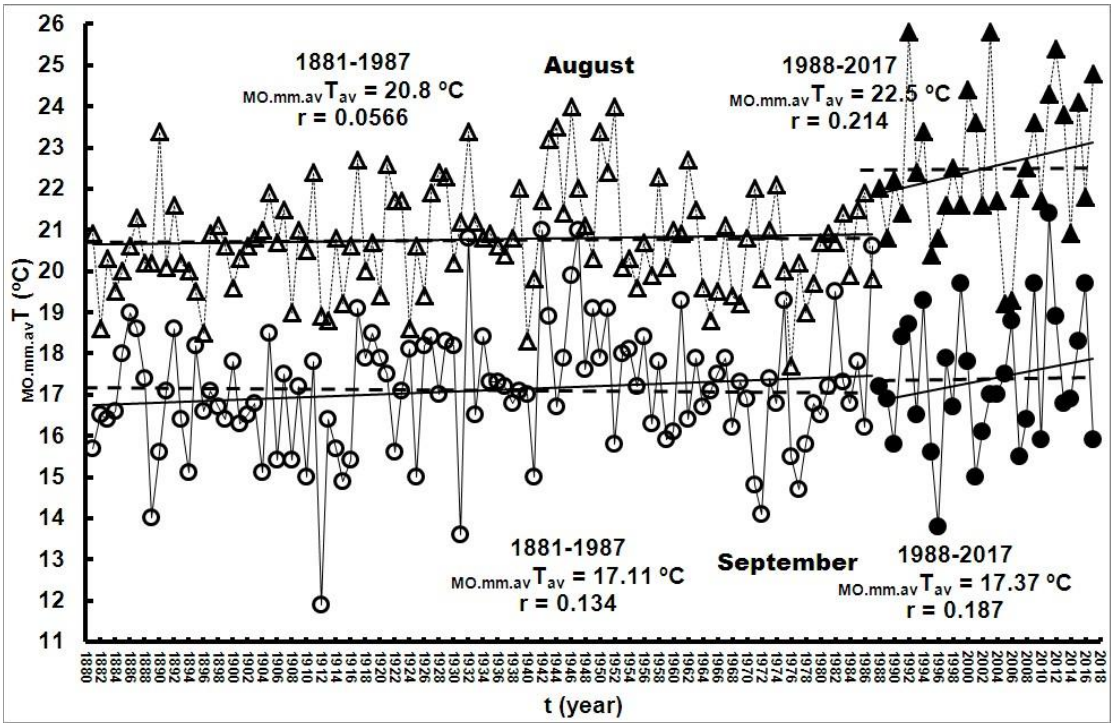

***Figure 10:** Four time series of monthly mean monthly average air temperature $_{MO.mm.av}T$ in August and September for two sub-periods: (1) 1881–1987; (2) 1988–2017.*

***Slika 10:** Štiri časovne vrste mesečnih srednjih vrednosti mesečne povprečne temperature zraka $_{MO.mm.av}T$ v avgustu in septembru za dve podobdobji: (1) 1881–1987; (2) 1988–2017.*

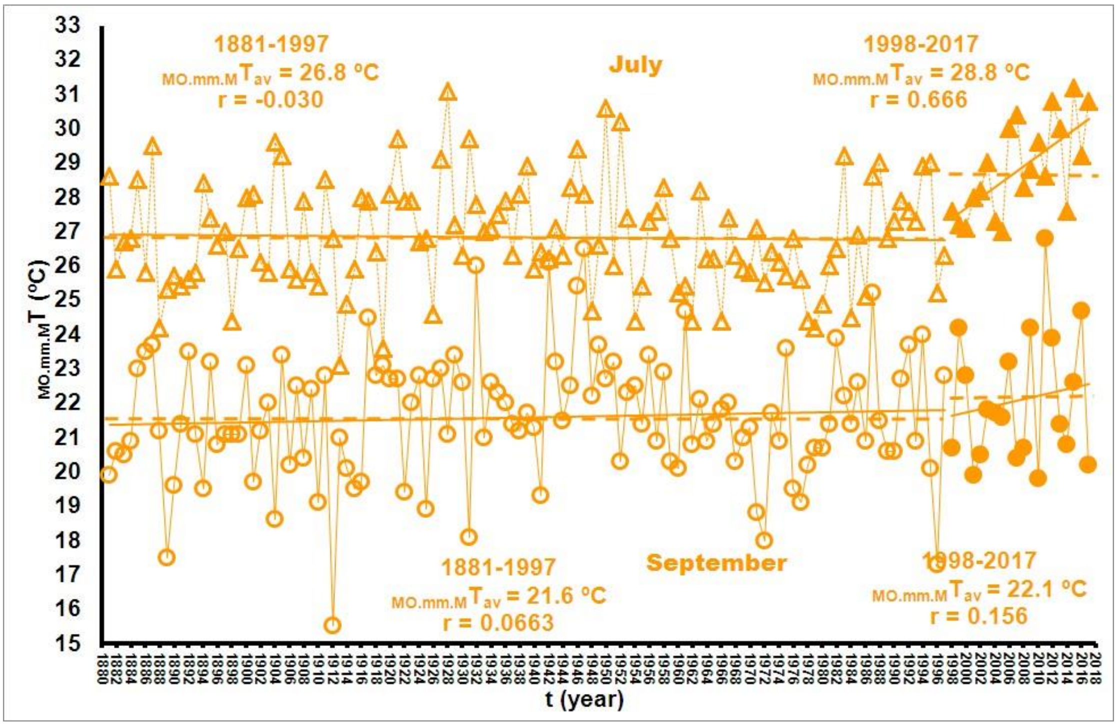

***Figure 11:** Four time series of monthly mean monthly maximum air temperature $_{MO.mm.M}T$ in July and September for two sub-periods: (1) 1881-1997; (2) 1998-2017.*

***Slika 11:** Štiri časovne vrste mesečnih srednjih vrednosti mesečne maksimalne temperature zraka $_{MO.mm.M}T$ v juliju in septembru za dve podobdobji: (1) 1881–1997; (2) 1998–2017.*

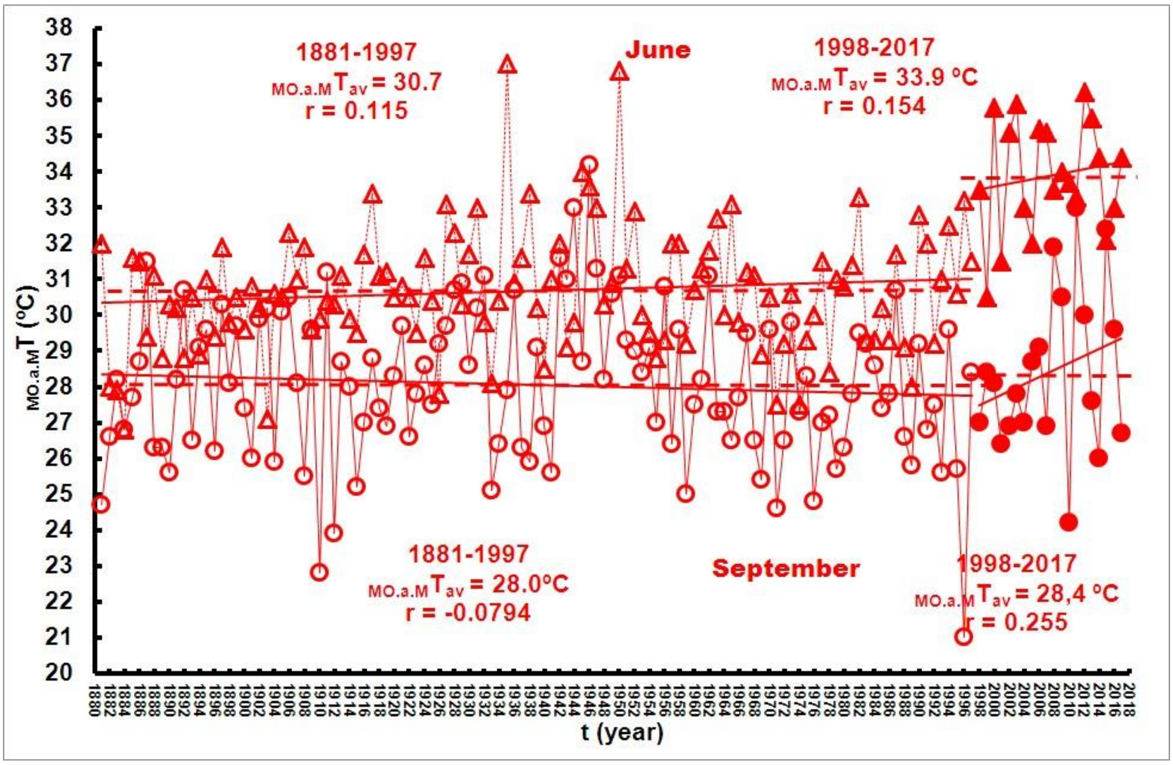

Figure 12: *Four time series of monthly absolute maximum air temperature $_{MO.a.M}T$ in June and September for two sub-periods: (1) 1881–1997; (2) 1998–2017.*

Slika 12: *Štiri časovne vrste mesečne absolutne maksimalne temperature zraka $_{MO.a.M}T$ v juniju in septembru za dve podobdobji: (1) 1881–1997; (2) 1998–2017.*

4. Day as a time unit

The graphical presentation of daily absolute maximum $_{D.a.M}T$ and minimum $_{D.a.m}T$ air temperatures measured during the period from 1 Jan. 1881 to 31 Dec. 2017 gives the impression of very large variations between temperatures that occurred on one particular day (Figure 13). The values of air temperature range ΔT on a particular day during the 137 analysed years is designated in green (Figure 13). The maximum value $\Delta T_{MAX}=32.7$ °C occurs in 11 February, while the minimum value $\Delta T_{MIN}=14.6$ °C occurs on 28 September. The average annual value is $\Delta T_{av}=21.6$ °C. During the hotter part of the year (especially from the end of May to the middle October) the ranges between absolute minimum and maximum daily temperatures are significantly lower than in the colder part of the year (from November to February).

Figure 14 presents the following four time series of characteristic daily air temperatures for the period from 1 Jan. 1881 to 31 Dec. 2017: (1) mean daily minimum $_{D.md.m}T$; (2) average mean daily $_{D.md.av}T$; (3) mean daily maximum $_{D.md.M}T$; (4) $\Delta T={}_{D.md.M}T-{}_{D.md.m}T$. As it is expected values calculated with mean daily air temperatures are lower than with absolute daily temperatures, but results and conclusions are practically the same. The maximum value $\Delta T_{MAX}=29.9$ °C occurs in 11 February, while the minimum value $\Delta T_{MIN}=11.6$ °C occurs on 3 September. The average annual value is $\Delta T_{av}=18.8$ °C.

Table 4 gives the results of F-test and t-test of differences ΔT between daily mean daily ATI time subseries. In the second column the average values of ΔT for each analysed subseries are given. The last column notes the number of days N when the average daily ATI in the second (recent) subseries is lower or the same as the temperature in the first sub-periods.

Graphical presentation of three time series of differences between characteristic daily mean daily minimum air temperatures $_{D.md.m}\Delta T$ in two sub-periods (1881-1969 and 1970-2017) is given in

Figure 15. Figure 16 presents a graphical presentation of three time series of the differences between the characteristic daily mean of the daily average air temperatures $_{D.md.av}\Delta T$ in two sub-periods (1881-1987 and 1988-2017), while Figure 17 is a graphical presentation of three time series of the differences between the characteristic daily mean of the daily maximum air temperatures $_{D.md.M}\Delta T$ in two sub-periods (1881-1997 and 1998-2017).

Table 4 : *Results of F-test and t-test of differences ΔT between daily CAT time subseries.*

Preglenica 4: *Rezultati F-testa in t-testa za razlike ΔT med vrednostmi dnevnih CAT pod-serij.*

sub-period	$_{D.md.m.m}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1969	-1.8	0.0011	7.8E-05	56
1970-2017	0.8			
sub-period	$_{D.md.m.av}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1969	7.5	0.525	0.0227	21
1970-2017	8.6			
sub-period	$_{D.md.m.M}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1969	15.2	0.132	0.297	144
1970-2017	15.6			
sub-period	$_{D.md.av.m}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1987	2.0	0.0166	7.8E-07	25
1988-2017	5.2			
sub-period	$_{D.md.av.av}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1987	11.4	0.718	0.01213	19
1988-2017	12.8			
sub-period	$_{D.md.av.M}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1987	20.0	0.422	0.964	181
1988-2017	20.0			
sub-period	$_{D.md.M.m}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1997	4.5	0.196	1.7E-12	14
1998-2017	9.3			
sub-period	$_{D.md.M.av}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1997	15.4	0.771	0.0014	10
1998-2017	17.4			
sub-period	$_{D.md.M.M.}\Delta T_{av}$ (ºC)	F-test	t-test	$N \leq 0$ (day/year)
1881-1997	25.4	0.565	0.492	214
1998-2017	25.0			

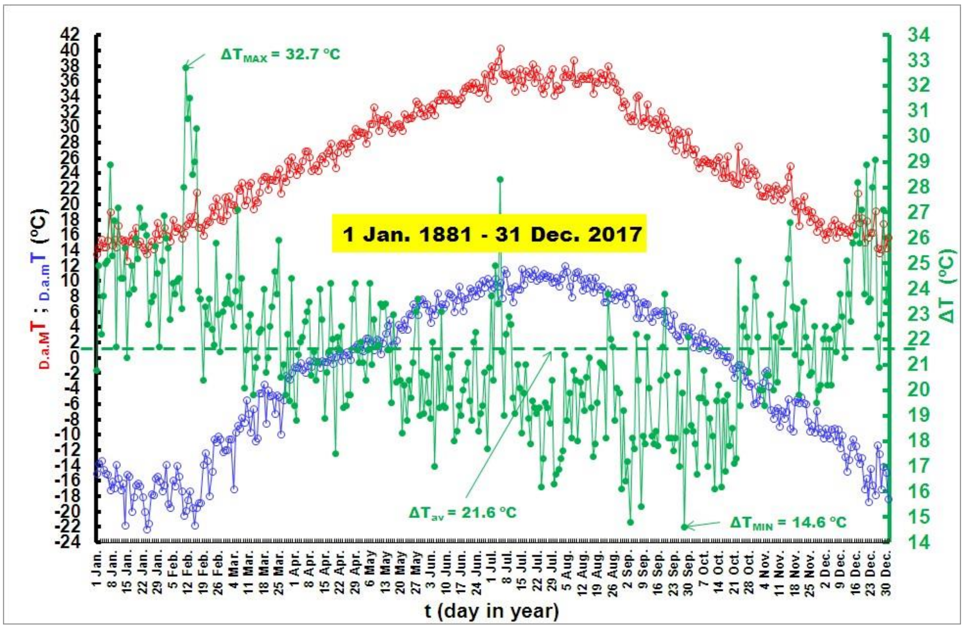

***Figure 13:** Three time series of characteristic daily air temperature for the period from 1 Jan. 1881 to 31 Dec. 2017: (1) absolute minimum $_{D.a.m}T$ (dark blue); (2) daily maximum $_{D.a.M}T$ (red); (4) $\Delta T = {}_{D.a.M}T - {}_{D.a.m}T$ (green).*

***Slika 13:** Tri časovne vrste za značilno dnevno temperaturo zraka za obdobje od 1. 1. 1881 do 31. 12. 2017: (1) absolutna minimalna $_{D.a.m}T$ (temnomodra); (2) dnevna maksimalna $_{D.a.M}T$ (rdeča); (4) $\Delta T = {}_{D.a.M}T - {}_{D.a.m}T$ (zelena).*

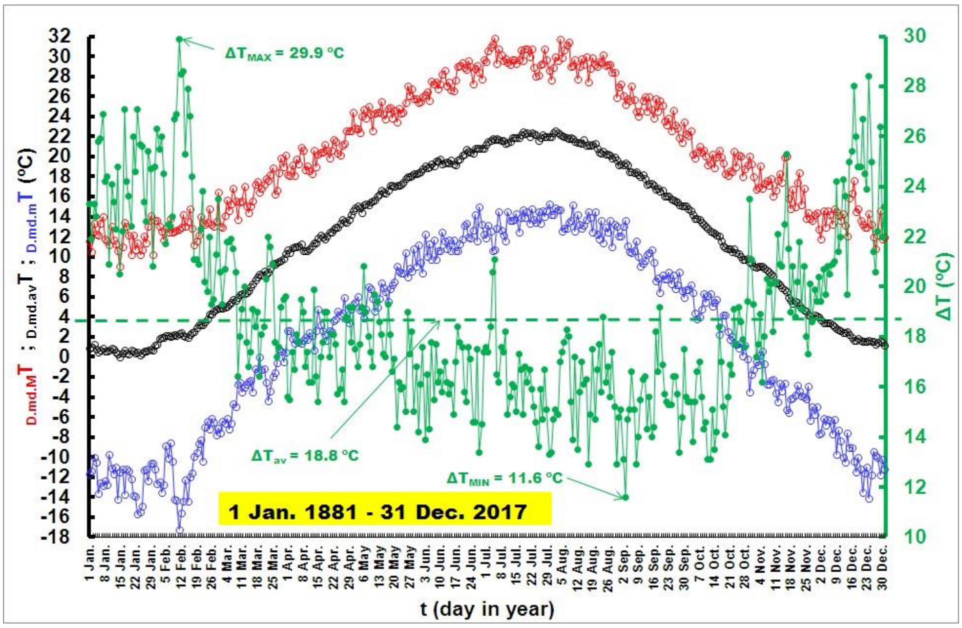

***Figure 14:** Four time series of characteristic daily air temperature for the period from 1 Jan. 1881 to 31 Dec. 2017**:** (1) mean daily minimum $_{D.md.m}T$ (dark blue); (2) average mean daily $_{D.md.av}T$ (black); (3) mean daily maximum $_{D.md.M}T$ (red); (4) $\Delta T = {}_{D.md.M}T - {}_{D.md.m}T$ (green).*

***Slika 14:** Štiri časovne vrste za značilno dnevno temperaturo zraka za obdobje od 1. 1. 1881 do 31. 12. 2017: (1) srednja dnevna minimalna $_{D.md.m}T$ (temnomodra); (2) povprečna srednja dnevna $_{D.md.av}T$ (črna); (3) srednja dnevna maksimalna $_{D.md.M}T$ (rdeča); (4) $\Delta T = {}_{D.md.M}T - {}_{D.md.m}T$ (zelena).*

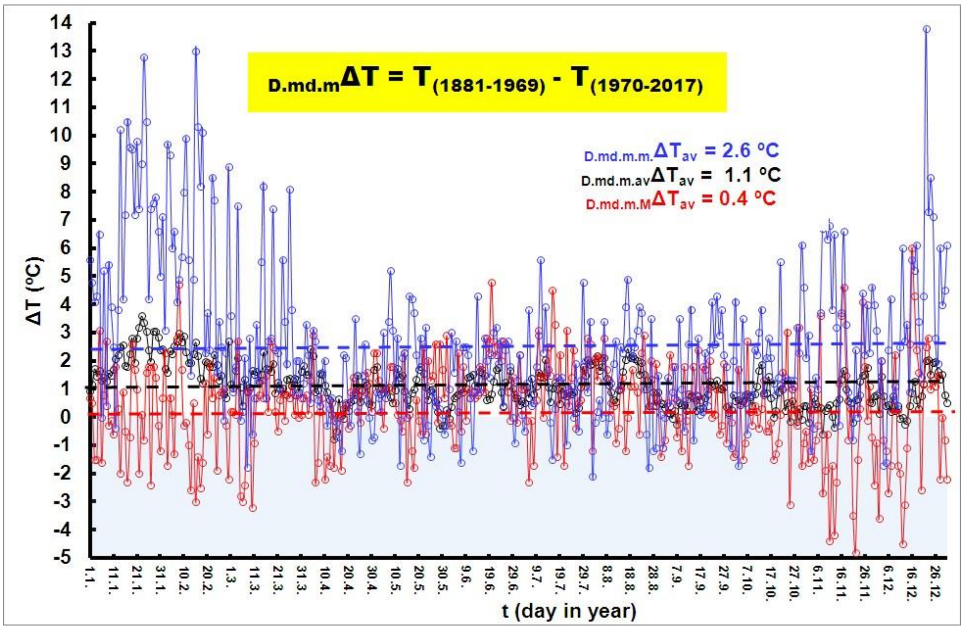

***Figure 15:** Three time series of differences between characteristic daily mean daily minimum air temperature in two sub-periods $_{D.md.m}\Delta T = T_{(1881\text{-}1969)} - T_{(1970\text{-}2017)}$: (1) $_{D.md.m.m}\Delta T$; (2) $_{D.md.av}\Delta T$; (3) $_{D.md.M}\Delta T$.*

***Slika 15:** Tri časovne vrste razlik med značilnimi dnevnimi srednjimi vrednostmi dnevnih minimalnih temperatur zraka v dveh podobdobjih $_{D.md.m}\Delta T = T_{(1881\text{-}1969)} - T_{(1970\text{-}2017)}$: (1) $_{D.md.m.m}\Delta T$; (2) $_{D.md.av}\Delta T$; (3) $_{D.md.M}\Delta T$.*

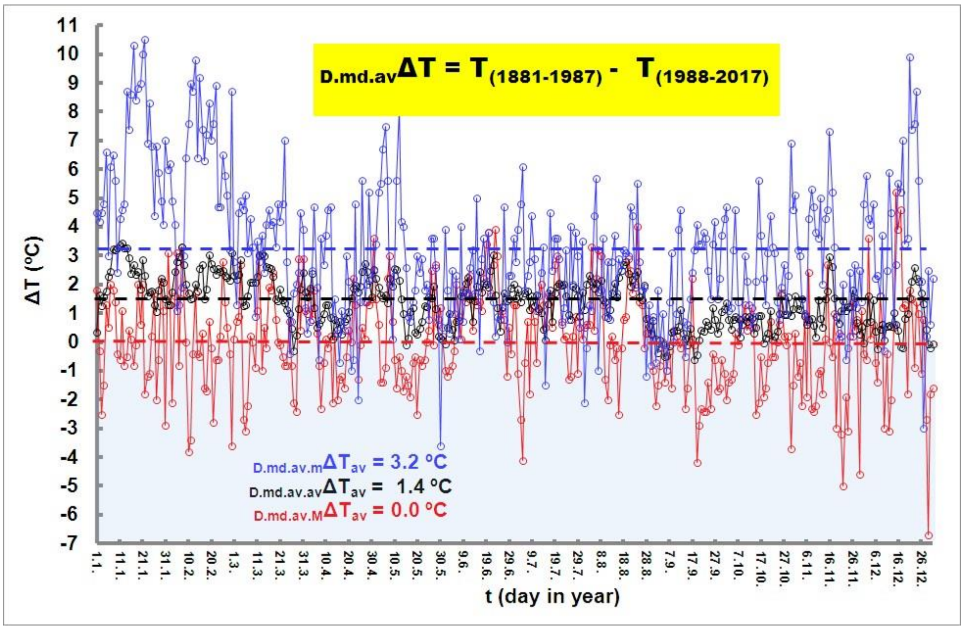

***Figure 16:** Three time series of differences between characteristic daily mean daily average air temperature in two sub-periods $_{D.md.av}\Delta T = T_{(1881\text{-}1987)} - T_{(1988\text{-}2017)}$: (1) $_{D.md.av.m}\Delta T$; (2) $_{D.md.av.av}\Delta T$; (3) $_{D.md.av.M}\Delta T$.*

***Slika 16:** Tri časovne vrste razlik med značilnimi dnevnimi srednjimi vrednostmi dnevnih povprečnih temperatur zraka v dveh podobdobjih $_{D.md.av}\Delta T = T_{(1881\text{-}1987)} - T_{(1988\text{-}2017)}$: (1) $_{D.md.av.m}\Delta T$; (2) $_{D.md.av.av}\Delta T$; (3) $_{D.md.av.M}\Delta T$.*

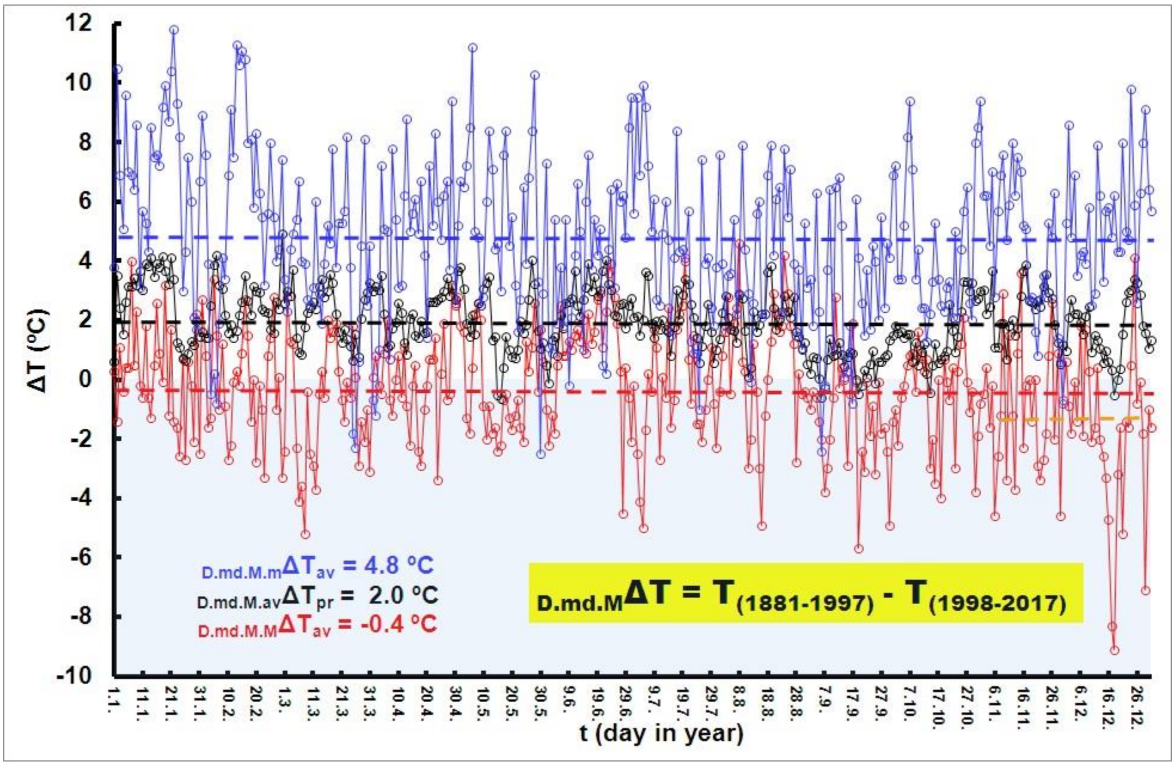

Figure 17: *Three time series of differences between characteristic daily mean daily maximum air temperature in two sub-periods* $_{D.md.M}\Delta T = T_{(1881\text{-}1997)} - T_{(1998\text{-}2017)}$ *: (1)* $_{D.md.M.m}\Delta T$*; (2)* $_{D.md.M.av}\Delta T$*; (3)* $_{D.md.M.M}\Delta T$.

Slika 17: *Tri časovne vrste razlik med značilnimi dnevnimi srednjimi vrednostmi dnevnih maksimalnih temperatur zraka v dveh podobdobjih* $_{D.md.M}\Delta T = T_{(1881\text{-}1997)} - T_{(1998\text{-}2017)}$ *: (1)* $_{D.md.M.m}\Delta T$*; (2)* $_{D.md.M.av}\Delta T$*; (3)* $_{D.md.M.M}\Delta T$.

5. Conclusions

The analyses in this paper showed that the warming trend in minimum air temperatures started in 1970, of the mean air temperatures in 1988, and of the maximum air temperatures in 1998. Before these landmark years there were no statistically significant increasing trends in all characteristic air temperatures to be observed. It seems that the GW effect on Zagreb-Grič air temperatures during the 20th Century, till the 1970s, was not very strong. The statistically significant increasing trend of minimum temperatures, which started in 1970, can be explained mainly by the effect of an UHI. One of the main reasons could be the rapid development of individual heating.

The differences between the two analysed sub-periods are statistically significant for all five ATI from January to August. It seems that in second part of the year, from September to December, air temperature is under less influence from GW or UHI than in the period from January to August. The reasons behind this behaviour should be investigated and explained by more detailed investigations and analysis. Annual air temperature variations, along with those at the level of decade, should be considered together with UHI and GW.

It seems that Zagreb's urbanisation had its primary and most significant influence on minimum rather than on maximum temperatures. The increasing trend in the time series of maximum temperatures started 20 years later.

In all analysed yearly and many monthly ATI time subseries there is a strong shift (jump) of air temperatures in the second (recent time) sub-period in comparison with the first sub-period.

Many scientists studying the time series of different climate-related variables had been noticing a sudden change around the mid 1980s (Levi, 2008). For example the time series of mean annual air temperatures in the Yelow River basin (China) during the 1956-2000 period shows a strong jump in mean annual temperatures which started in 1987 (Li, 2010; Bonacci, 2010). Kothawale and Kumar (2005) consider that the pan-Indian mean annual air temperature has shown significant accelerated warming starting from 1970s. Kim et al. (2015) reported that, based on several lines of evidence, many studies have argued that an abrupt winter climate change occurred in the Northern Hemisphere in the late 1980s and several hypotheses have been proposed to explain this shift.

Intense interdisciplinary cooperation based on detailed and careful long-lasting monitoring of many climatological and other affects will lead to a better understanding of UHI and how to separate it from GW effect.

References

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmna, R., Schöner, W., Umgersböck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, l., Mestre, O., Moisselin, J.-M., Bergertt, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., Nieplova, E. (2007). HISTALP– Historical Instrumental Climatological Time Series of The Greater Alpine Region. *International Journal of Climatology* **27(1)**, 17–46. https://doi.org/10.1002/joc.1377.

Bonacci, O. (2012). Increase of Mean Annual Surface Air Temperature in the Western Balkans during Last 30 Years. *Vodoprivreda* **44(255–257)**, 75–89.

Bonacci, O., Trninić, D., Roje-Bonacci, T. (2008). Analysis of the Water Temperature Regime of the Danube and its Tributaries in Croatia. *Hydrological Processes* 22**(7).** 1014–1021. https://doi.org/10.1002/hyp.6975.

Bonacci, O., Željković, I., Šakić Trogrlić, R., Milković, J. (2013). Differences between True Mean Daily, Monthly, Annual Air Temperatures and Air Temperatures Calculated with Three Equations: A Case Study from Three Croatian Stations. *Theoretical and Applied Climatology* **114(1–2)**, 271–279. https://doi.org/10.1007/s00704-012-0830-8.

Bonacci, O., Željković, I. (2018). Differences Between True Mean Temperatures And Means Calculated With Four Different Approaches: A Case Study From Three Croatian Stations. *Theoretical and Applied Climatology* **131(1–2)**, 733–743. https://doi.org/10.1007/s00704-016-1993-5.

Garbrecht, J., Fernandez, G. P. (1994). Visualization of Trends and Fluctuations in Climatic Records. *Water Resources Bulletin* **30(2)**, 297–306. https://doi.org/10.1111/j.1752-1688.1994.tb03292.x.

Hamed, K. H., R. Ramachandra, R. (1998). A Modified Mann-Kendal Trend Test for Autocolerrated Data. *Journal of Hydrology* **204(1–4)**, 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X.

Heino, R. (1994). *Climate in Finland during the Period of Meteorological Observations*. Finnish Meteorological Institute Contributions 12, Helsinki.

Juras, J. (1985). Neke karakteristike promjene klime Zagreba u posljednjem tri desetljeću. *Geofizika* **2**, 93–102.

Kim, Y.-H., Kim, M.-K., Lau, W.K.M., Kim, K.-M., Cho, C.-H. (2015). Possible Mechanism of Abrupt Jump in Winter Surface Air Temperature In The Late 1980s Over The Northern Hemisphere. *Journal of Geophysical Research: Atmospheres* **120**, 12, 474–12, 485. https://doi.org/10.1002/2015JD023864.

Klaic, Z. B., Nitis, T., Kos, I., Moussiopoulos, N. (2002). Modification of the Local Winds due to Hypothetical Urbanization of the Zagreb Surroundings. *Meteorology and Atmospheric Physics* **79**, 1–12. https://doi.org/10.1007/s703-002-8225-z.

Kothawale, D. R., Kumar, K. R. (2005). On the Recent Changes in Surface Temperature Trends over India. *Geophysical Research Letters* **32(18)**, L18714. https://doi.org/10.1029/2005GL023528.

Levi, B. G. (2008). Trends in the Hydrology of the Western US Bear the Imprint of Manmade Change. *Physics Today* **61(4)**, 16–18. https://doi.org/10.1063/1.2911164.

Li, G. (2010). Changes of the Yellow River Water Resources and Countermeasures. Climate Change and Adaptation for Water Resources in Yellow River Basin, China, *IHP VII Technical Documents in Hydrology, UNESCO Office in Beijing*, 11–23.

Likso, T. (2003). Inhomogeneities in Temperature Time Series in Croatia. *Hrvatski Meteorološki Časopis* **38**, 3–9.

Likso, T., Pandžić, K. (2014). Frequency Analysis of Extreme Temperature Events. 20th International Congress of Biometeorology 28 September–1 October 2014 Cleveland, Ohio.

Mann, H.B. (1945). Non-Parametric Test of Randomness Against Trend. *Econometrica* **13(3)**, 245–259. Htpps://doi.org/10.2307/1907187.

Kendall M.G. (1975). *Rank Correlation Methods, 4th edition*. Charles Griffin, London, Great Britain.

Nitis T., Bencetić Klaić, Z., Moussiopoulos, N. (2005). Effects of Topography on the Urban Heat Island. In: *Proceedings of the 10th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, 1–5, Sissi, Crete, Greece.

Ogrin, D., Krevs, M. (2015). Assessing Urban Heat Island Impact on Long-Term Trends of Air Temperatures in Ljubljana. *Dela* **43**, 41–59.

Pandžić, K., Likso, T. (2010). Homogeneity of Average Annual Air Temperature Time Series for Croatia. *International Journal of Climatology* **30(8)**, 1215–1225. https://doi.org/10.1002/joc.1922.

Pandžić, K., Trninić, D., Likso, T., Bošnjak, T. (2009). Long-Term Variations in Water Balance Components for Croatia. *Theoretical and Applied Climatology* **95(1–2)**, 39–51. https://doi.org/10.1007/s00704-007-0366-5.

Penzar, B., Penzar, I., Juras, J., Marki, A. (1992). Brief Review of Climatic Fluctuations Recorded in Zagreb between 1862 and 1990. *Geofizika* **9(1),** 57–67.

Piani, C., Weedon, G., Best, M., Gomes, S., Viterbo, P., Hagemann, S., Haerter, J. (2010). Statistical Bias Correction of Global Simulated Daily Precipitation and Temperature for the Application of Hydrological Models. *Journal of Hydroogy* **395**, 199–215. https://doi.org/10.1016/j.jhydrol.2010.10.024.

Radić, V., Pasarić, N., Šinik, N. (2004). Analiza zagrebačkih klimatoloških nizova pomoću empirijski određenih prirodnih sastavnih funkcija. *Geofizika* **21(1)**, 15–36.

Schneider, A., Breitner, S. (2016). Temperature Effects on Health – Current Findings and Future Implications. *EBioMedicine* **6**, 29–30.

Šegota, T. (1981). More about the Secular Fluctuations of Air Temperature in Zagreb, Croatia. *Quaestiones Geographicae* **7**, 147–154.

Tadić, L., Dadić, T., Leko-Kos, M. (2016). Variability of Hydrological Parameters and Water Balance Components in Small Catchment in Croatia. *Advances in Meteorology* **4**, 1–9. http://dx.doi.org/10.1155/2016/1393241.

Wang, J., Yan, Z.-W. (2016). Urbanization-Related Warming in Local Temperature Records: a Review. *Atmospheric and Oceanic Science Letters* **9(2)**, 129–138. https://doi.org/10.1080/16742834.2016.1141658.