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CHANGES IN AIR TEMPERATURE AND PRECIPITATION IN BANJALUKA IN 1961–2022

Abstract: Study analyses climate change in Banjaluka. It provides understanding of long-term trends (1961–2022) and shifts between last two standard thirty-year climatological periods: 1961–1990 and 1991–2020. Results showed significant warming; mean, maximum and minimum air temperatures displayed significant upward trends, at the annual level (0.51°C/10yr, 0.63°C/10yr, and 0.50°C/10yr, respectively) and in all seasons (strongest in summer; 0.68°C/10yr, 0.80°C/10yr, and 0.64°C/10yr, respectively). Emergence of heat extremes was apparent in last decades. Highest magnitude of trends was obtained for TXx (0.73°C/10yr), TN90p (14.8 days/10yr), TX90 (12.4 days/10yr), SU25 (7.6 days/10yr), TX30 (7.1 days/10yr), WSDI (4.8 days/10yr). Changes in precipitation were mainly insignificant, however suggest redistribution of precipitation within the year (decrease in summer season and increase in autumn), increasing precipitation intensity and drying tendency (particularly in summer).

Key words: climate change, air temperature, precipitation, extreme climate indices, Banjaluka (Bosnia and Herzegovina)

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Introduction

Global air temperature had been increasing since the end of 19th century (IPCC, 2021). Sixth Assessment Report on Climate Change of IPCC states that average global air temperature in 2001–2020 was for almost a 1°C higher compared to the 1850–1900 (IPCC, 2021). Larger increases in temperature were found over land area than over the ocean. Researchers found that numerous climate tipping points could be triggered if 1.5°C warming (in relation to the levels before industrialization started) exceed and that this could cause abrupt, irreversible, and dangerous impacts on environment and humanity in general (Armstrong McKay et al., 2022).

Globally, the magnitude of heat/cold extremes significantly increased/decreased (Zhang et al., 2022). Changes in indices representing extreme air temperature were almost universal over the globe and all consistent with warming (Dunn et al., 2020). All indices which express absolute lowest and highest minimum and maximum air temperatures displayed positive trends (with almost 4°C change for TNn globally) (Dunn et al., 2022). Global trends of air temperature percentile indices were also consistent with a warming condition (Zhang et al., 2019; Dunn & Morice, 2022) – cold nights and cold days frequency substantially declined, whereas warm nights and warm days frequency substantially increased all over the world (Alexander, 2016). Trend slopes of indices derived from Tmin (TN90p, TN10p) were stronger than those derived from Tmax (TX90p, TX10p); the growing frequency of warm days was much substantial than the drop in occurrence of cool days (globally on average about 30 days vs. about 15 days, for the period since the 1970s) (Dunn et al., 2022). Lo & Hsu (2010) state that extensive and abrupt warming trend over mid-latitudes happened during the late 1980s.

The fact that a warming tendency is present globally was confirmed by numerous researches around the world, at different latitudes, continents, climate zones etc. – Europe (Peña-Angulo et al., 2020; Twardosz et al., 2021); Africa (Gebrechorkos et al., 2019); Asia (Salameh et al., 2019; Moon et al., 2022); North America (Shenoy et al., 2022); Central America (Ruiz-Alvarez et al., 2022); South America (Regoto et al., 2021; Collazo et al., 2022) etc.

The investigation of modifications of air temperature in Europe in the last seventy-year period (from 1951 to 2020) showed that air temperature has grown since 1985 (Twardosz et al., 2021). Study on temperature extremes over the European continent given in Atlas of Climate Indices over Europe revealed same trends observed globally (Domínguez-Castro et al., 2020). The upward warming tendency was found in all parts of Europe: Western Europe (Dong et al., 2017); Central Europe – Switzerland (Scherrer et al., 2016); Czech Republic (Zahradníček et al., 2021); South-Eastern Europe (Charalampopoulos & Droulia, 2022); Mediterranean Region (Kelebek et al., 2021) etc.

Spatial patterns of changes in precipitation in 1951–2018 were less coherent (for both mean and extreme precipitation) than those globally observed for extreme air temperature indices consistent with the warming (Dunn et al., 2020). Similar was found worldwide (Gebrechorkos et al., 2019; Hänsel et al., 2022; Kelebek et al., 2021; Regoto et al., 2021; Zeder & Fischer, 2020; Zheng et al., 2022 etc.). However, it had been reported that there were, globally, more heavy precipitation events (Alexander, 2016; Sun et al., 2021) which were also more severe and contributed in a higher fraction to the total sums of precipitation (Dunn et al., 2020). Europe was one of the regions with clear significant trends (Alexander, 2016) and higher percentage of meteorological stations with significantly increasing trends (Sun et al., 2021).

Contribution of very wet days precipitation (R95p) is reported to increase globally (additional 1–2 % of precipitation occurred during such days) (Dunn et al., 2020). Annual maximum daily precipitation increased over almost two-third of the global land areas (Sarkar & Maity, 2021). Rx1day showed growing trends, but smaller increase was found over Europe (Dunn et al., 2020). In most land regions (among which in Europe) the occurrence of extreme precipitation on consecutive days has been increasing (Du et al., 2022). The upward tendencies in indices representing heavy precipitation events (for example, Rx1day, R95p, R99p), averaged for Europe, was observed during the latest period from 1991 to 2018 in comparison to the three previous thirty-year periods covering the beginning (1901–1930), the middle (1931–1960) and the end (1961–1990) of the 20th century (Hänsel et al., 2022).

This research represents a continued analysis of climate change in Banjaluka, Bosnia and Herzegovina (Trbić et al., 2017; Popov et al., 2017b, 2018a, 2018b, 2019; Popov, 2020), that covers extended period compared to previous researches, i.e. covered last seven years (2016–2022) which were globally the hottest years since 1880 (NOAA National Centres for Environmental Information, 2023). The key aim of research was to analyse trends in both the mean as well as the extreme air temperatures and precipitation amounts in Banjaluka in 1961–2022 and to investigate changes that occurred between last two standard thirty-year climatological periods – 1961–1990 and 1991–2020.

Material and methods

Banjaluka is situated in the north-western Bosnia and Herzegovina, at 44.490–44.988 N and 16.793–17.303 E. Banjaluka is located where the Dinaric Alps mountains (with mountainous peaks such as: Manjača, Čemernica, Tisovac, Osmača etc.) from the south descend into the Pannonian Basin. The urban area of Banjaluka itself is located at the banks of Vrbas River, where it enters the Banja Luka Basin from the canyon (at the average altitude of 163 m).

Moderate continental climate characterizes the studied area of Banjaluka. Average air temperature at the annual level, in coldest month (January) and in the warmest month (July) is 11.2°C, 0.2°C, and 21.4°C, respectively (Popov, 2020). The highest air temperature in Banja Luka was measured in August 2017 (41.8°C). Absolute minimum air temperature reached -26.4°C during an extremely cold wave in January 1963. Precipitation regime is also in accordance with a continental climate; highest precipitation amounts come in late spring and beginning of the summer season, whereas a minimum precipitation amounts occur during the winter months. At the annual level, on average, there is 1040 mm of precipitation.

Climate change in Banjaluka in 1961–2022 was analysed using daily climatological data on air temperatures – mean, maximum, and minimum ones (Ta, Tmax, Tmin) and precipitation (R) from Banjaluka meteorological station located at 44.80806 N and 17.21278 E and altitude of 153 meters. Republic Hydrometeorological Institute of the Republic of Srpska provided data required for analysis. Statistical parameters of input temperature and precipitation variables time series are displayed in Tab. 1. Average values of input variables (at the annual and seasonal levels) in 1961–2022 are shown in Tab. 2.

The average annual values of Ta, Tmax, and Tmin in Banjaluka are 11.3°C, 17.5°C, and 6.0°C, respectively. Summer is the warmest season (20.8°C, 27.7°C, and 14.2°C, respectively), and winter the coldest (1.6°C, 6.3°C, and -2.4°C, respectively). Autumn and spring seasons are almost equally warm. The average annual sum of precipitation in 1961–2022 is 1040.3 mm. All seasons contribute relatively even fraction to the total sum of precipitation within a year.

Tab. 1. Characteristics of the input variables in Banjaluka in 1961–2022

Variable	Ta (°C)	Tmax (°C)	Tmin (°C)	R (mm)
Average	11.3	17.5	6.0	1040.3
Maximum	13.5	20.2	8.5	1686.2
Minimum	9.7	15.1	4.3	588.2
Standard deviation	1.1	1.4	1.1	175.6
Skewness	0.3	0.1	0.4	0.5
Kurtosis	-1.1	-1.1	-0.8	2.4

Tab. 2. Average values of the input variables in Banjaluka in 1961–2022

Variable	Year	Winter	Spring	Summer	Autumn
Ta (°C)	11.3	1.6	11.5	20.8	11.4
Tmax (°C)	17.5	6.3	17.9	27.7	17.8
Tmin (°C)	6.0	-2.4	5.4	14.2	6.5
R (mm)	1040.3	228.0	263.2	273.7	276.3

Based on input data, 15 extreme air temperature indices as well as 10 extreme precipitation indices of the ETCCDI which are widespread used for climate change investigations were calculated. The selected indices used for analysis covered those representing the absolute, percentile, fixed threshold, and duration indices. Selected indices are defined, marked and calculated as recommended by the ETCCDI (2009). Additionally, four more temperature indices and one precipitation index based on fixed thresholds were calculated:

- tropical days (TX30): annual count of days with maximum air temperature >= 30°C;
- very hot days (TX35): annual count of days with maximum air temperature >= 35°C;
- extreme hot days (TX37): annual count of days with maximum air temperature >= 37°C;
- very extreme hot days (TX39): annual count of days with maximum air temperature >= 39°C; and
- wet days (R01mm): annual count of days with sum of precipitation >=1 mm.

Indices were calculated in RClimDex (Zhang & Yang, 2004). Indices' average values in 1961–2022 are given in Tab. 3.

Tab. 3. Averaged values of indices used for analysis in 1961–2022

Index	Value	Index	Value	Index	Value
TXx	37.0°C	TR20	1.8 days	RX1day	55.4 mm
TXn	-5.2°C	SU25	95.8 days	RX5day	97.7 mm
TNx	20.2°C	TX30	35.3 days	SDII	9.2 mm/days
TNn	-15.7°C	TX35	6.6 days	R01mm	110.4 days
TX10p	29.7 days	TX37	2.7 days	R10mm	35.3 days
TX90p	57.9 days	TX39	0.9 days	R20mm	13.4 days
TN10p	28.7 days	WSDI	13.2 days	R95p	233.5 mm
TN90p	63.3 days	CSDI	2.9 days	R99p	75.3 mm
ID0	15.0 days	GSL	281.0 days	CDD	22.8 days
FD0	85.7 days	PRCPTOT	1016.9 mm	CWD	6.8 days

The nonparametric Man-Kendal test was applied to estimate trend slopes and their statistical significance in 1961–2022 (at the annual and seasonal levels). Changes between last two thirty-year climatological periods 1961–1990 and 1991–2020 were further analysed – analysis covered determination of differences in averaged values between two periods and changes in distributions which were investigated using the nonparametric Kolmogorov-Smirnov test.

Results

Changes in mean, maximum, and minimum air temperature

In 1961–2022 Ta displayed statistically significant growing trends; at the annual level (0.51°C/10yr) and throughout the year, i.e. in all seasons (Tab. 4, Fig. 1 and Fig. 2). Summer was the season with the highest warming rates (0.68°C/10yr); then come winter (0.57°C/10yr) and spring (0.35°C/10yr). The temperature increased the least in autumn season (0.35°C/10yr). Extreme temperatures Tmax and Tmin also increased significantly and were followed the same patterns of change. Annual Tmax increased 0.63°C/10yr, whereas Tmin increased 0.50°C/10yr. Increase in seasonal Tmax and Tmin ranged between 0.80°C/10yr and 0.64°C/10yr in summer to 0.36°C/10yr and 0.43°C/10yr in autumn.

Tab. 4. Trends in Ta, Tmax, and Tmin in Banjaluka in 1961–2022 (in °C/10yr)

Index		Year	Winter	Spring	Summer	Autumn
Ta	Slope	0.51	0.57	0.35	0.68	0.35
	p-value	<0.0001	<0.0001	<0.0001	<0.0001	0.0001
Tmax	Slope	0.63	0.72	0.54	0.80	0.36
	p-value	<0.0001	<0.0001	<0.0001	<0.0001	0.0004
Tmin	Slope	0.50	0.56	0.33	0.64	0.43
	p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

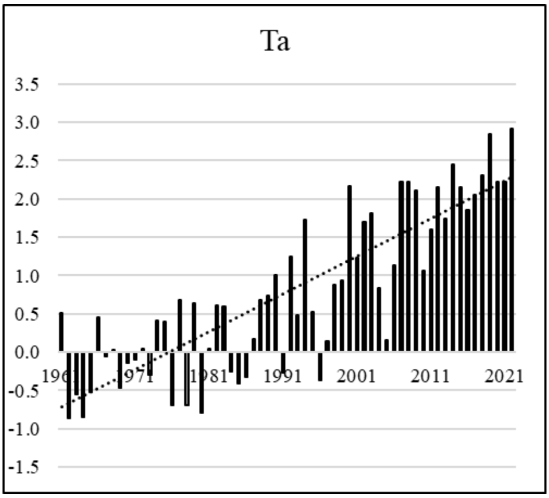
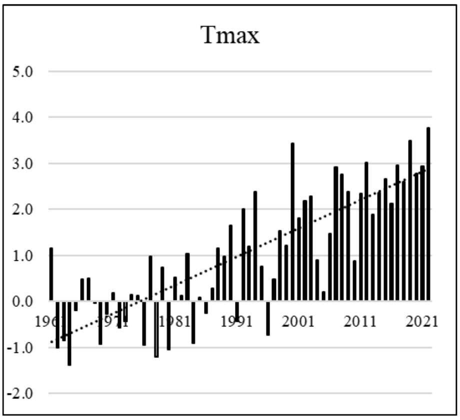


Fig. 1. Deviations (in °C) of Ta from 1961–1990 averages (the dashed line represents the trendline)



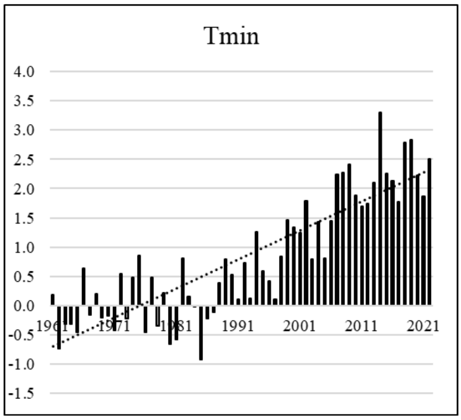


Fig. 2. Deviations (in °C) of Tmax, and Tmin from 1961–1990 averages (the dashed line represents the trendline)

Comparative analysis of the average Ta in 1991–2020, in reference to 1961–1990, also proves the increasing warming tendency, given that average increased by 1.4°C (Tab. 5). Average values of Tmax (1.9°C) as well as Tmin (1.5°C) also increased, between two stated periods. Moreover, distribution of Ta, Tmax and Tmin changed significantly between the two analysed periods (a shift towards higher temperature values was found). Seasonal Ta, Tmax, and Tmin also showed higher averages in latter period – most prominently in summer when increase was above 2°C. Increase of average values in all other seasons was higher than 1°C (even 2.2°C for Tmax in winter). Changes in distribution were statistically significant for all parameters and in all seasons (shift towards higher values), except in winter for Ta and Tmin (borderline statistical significance).

Tab. 5. Difference in average values of Ta, Tmax, and Tmin in Banjaluka in 1991–2020 in reference to 1961–1990

Index	Year	Winter	Spring	Summer	Autumn
Ta					
1961–1990	10.6	0.8	10.9	19.7	10.9
1991–2020	12.0	2.3	12.1	21.8	12.0
Difference (°C)	1.4	1.5	1.2	2.1	1.1
Difference (%)	13.7	202.3	10.7	10.7	10.3
D [KS test]	0.767	0.333	0.533	0.767	0.433
p-value [KS test]	<0.0001	0.055	0.0002	<0.0001	0.005
Tmax					
1961–1990	16.5	5.1	17.0	26.4	17.2
1991–2020	18.3	7.3	18.8	28.9	18.3
Difference (°C)	1.9	2.2	1.7	2.5	1.2
Difference (%)	11.3	42.2	10.3	9.5	6.8
D [KS test]	0.733	0.433	0.500	0.667	0.433
p-value [KS test]	<0.0001	0.005	0.001	<0.0001	0.005
Tmin					
1961–1990	5.2	-3.2	4.8	13.1	5.8
1991–2020	6.7	-1.6	6.0	15.2	7.2
Difference (°C)	1.5	1.6	1.2	2.1	1.4
Difference (%)	29.7	49.2	25.0	15.9	24.4
D [KS test]	0.733	0.333	0.533	0.867	0.500
p-value [KS test]	<0.0001	0.055	0.0002	<0.0001	0.001

Changes in extreme temperature indices

All absolute air temperature indices in Banjaluka displayed significant positive trends in 1961–2022 (Tab. 6 and Fig. 3) – at the annual level and throughout the year, except of maximum and minimum values of Tmax in autumn and minimum values of Tmax and Tmin in spring. Trend slopes were highest for annual TNn (0.88°C/10yr) and TXx (0.73°C/10yr) suggesting an upward warming tendency given that both minimum and maximum temperatures within a year are rapidly increasing. Annual maximum value of Tmax and Tmin in 1991–2020 increased by more than 2°C, in relation to 1961–1990 (with statistically significant shifts towards higher values in 1991–2020) (Tab. 7). TXx and TNx displayed significant distributional shift in all seasons, except in autumn for TXx and in winter for TNx.

Tab. 6. Trends in absolute air temperature indices in Banjaluka in 1961–2022 (in °C/10yr)

Index		Year	Winter	Spring	Summer	Autumn
TXx	Slope	0.73	0.67	0.61	0.74	0.17
	p-value	0.0001	<0.0001	0.0002	0.0001	0.3400
TXn	Slope	0.45	0.53	0.44	0.48	0.36
	p-value	0.0372	0.0303	0.0889	0.0183	0.0781
TNx	Slope	0.60	0.63	0.29	0.58	0.57
	p-value	<0.0001	0.0036	0.0076	<0.0001	<0.0001
TNn	Slope	0.88	0.88	0.38	0.55	0.61
	p-value	0.0047	0.0064	0.1319	<0.0001	0.0042

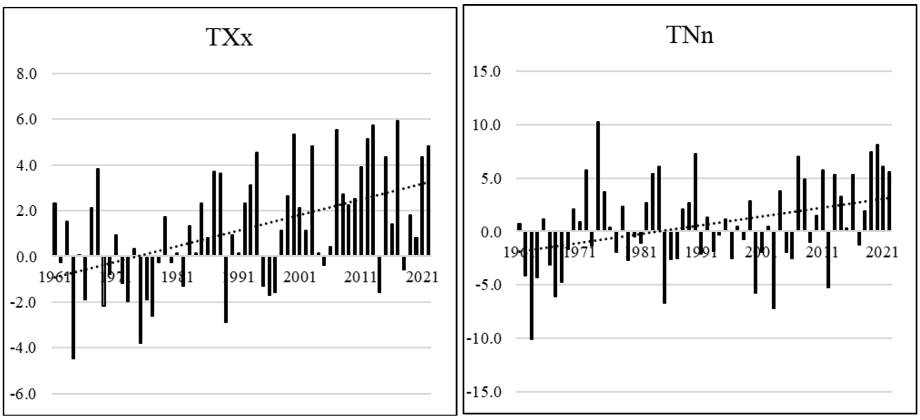


Fig. 3. Deviations (in °C) of the selected absolute air temperature indices from 1961–1990 averages (the dashed line represents the trendline)

All indices calculated based on percentile thresholds displayed trends also consistent with warming (Tab. 8 and Fig. 4) – annual occurrence of TX10p and TN10p decreased significantly, whereas warm days and warm nights displayed even stronger upward trends (-5.0 days/10yr and -6.1 days/10yr vs. 12.4 days/10yr and 14.8 days/10yr). TX90p and TN90p doubled their annual frequency between 1961–1990 and 1991–2020 and significantly shifted distribution towards higher index values in second period (Tab. 9). In contrast, TX10p and TN10p significantly moved their distribution towards lower index values and almost halved their frequency of occurrence in 1991–2020 in reference to 1961–1990. The stated trends were found in every season of the year, but most intense were in summer.

Tab. 7. Difference in average values of absolute values air temperature indices in Banjaluka in 1991–2020 in reference to 1961–1990

Index	Year	Winter	Spring	Summer	Autumn
TXx					
1961–1990	35.9	18.8	29.3	35.8	31.7
1991–2020	38.0	21.2	31.5	37.9	31.9
Difference (°C)	2.1	2.4	2.2	2.1	0.2
Difference (%)	5.8	12.5	7.4	5.8	0.7
D [KS test]	0.367	0.533	0.600	0.367	0.133
p-value [KS test]	0.026	0.000	<0.0001	0.026	0.936
TXn					
1961–1990	-5.7	-5.8	1.6	15.2	1.6
1991–2020	-5.1	-4.5	2.9	16.7	2.5
Difference (°C)	0.7	1.3	1.2	1.6	1.0
Difference (%)	11.3	22.6	74.8	10.3	62.0
D [KS test]	0.200	0.233	0.267	0.267	0.233
p-value [KS test]	0.537	0.342	0.200	0.200	0.342
TNx					
1961–1990	19.1	8.0	15.0	19.1	15.5
1991–2020	21.2	9.8	16.1	21.0	18.0
Difference (°C)	2.1	1.7	1.1	1.9	2.5
Difference (%)	11.1	21.5	7.4	9.8	16.2
D [KS test]	0.633	0.333	0.400	0.567	0.700
p-value [KS test]	<0.0001	0.055	0.011	<0.0001	<0.0001
TNn					
1961–1990	-16.3	-16.3	-7.2	5.8	-6.5
1991–2020	-15.4	-14.6	-5.6	7.6	-4.5
Difference (°C)	0.9	1.6	1.6	1.8	2.0
Difference (%)	5.5	10.1	22.4	30.4	31.2
D [KS test]	0.200	0.233	0.333	0.533	0.267
p-value [KS test]	0.537	0.342	0.055	0.000	0.200

Tab. 8. Trends in percentile-based air temperature indices in Banjaluka in 1961–2022 (in days/10yr)

Index		Year	Winter	Spring	Summer	Autumn
TN10p	Slope	-6.1	-1.5	-1.0	-1.6	-1.2
	p-value	<0.0001	0.000393	0.004908	<0.0001	0.001283
TX10p	Slope	-5.0	-1.2	-0.9	-1.5	-1.2
	p-value	<0.0001	0.00383	0.001985	<0.0001	0.001082
TN90p	Slope	14.8	2.3	2.4	7.2	2.5
	p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
TX90p	Slope	12.4	2.0	2.6	5.4	1.5
	p-value	<0.0001	0.00013	<0.0001	<0.0001	0.000613

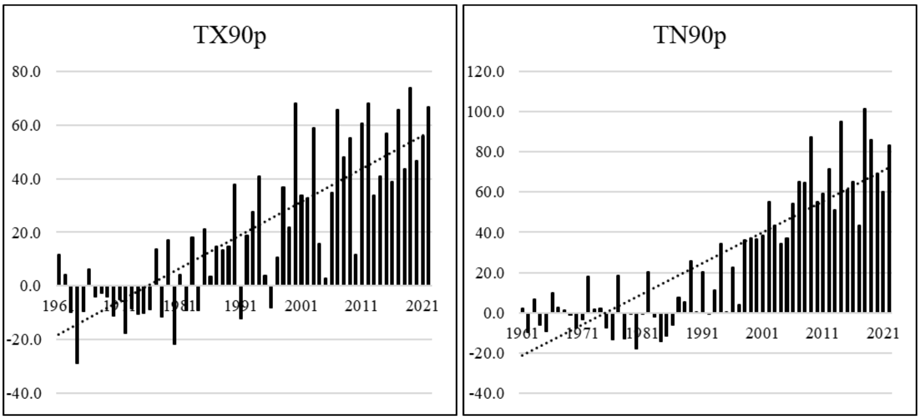


Fig. 4. Deviations (in days) of the selected percentile-based air temperature indices from 1961–1990 averages (the dashed line represents the trendline)

Changes of fixed threshold air temperature indices were as well as expected in a warming climate – all of the observed warm indices (TR20, SU25, TX30, TX35, TX37, and TX39) displayed significant upward trends, whereas cold ones (ID0 and FD0) displayed significant downward trends (Tab. 10 and Fig. 5). Average annual values of ID0 and FD0 decreased in 1991–2020 by -38.0 % and -17.5 %, respectively, in reference to 1961–1990 (with statistically significant distributional shifts towards lower values in second period), whereas average annual values of SU25 and TX30 increased by 30.3 % and 96.8 %, respectively (with significant shifts in distribution towards higher values in stated period) (Tab. 11).

Tab. 9. Difference in average values of percentile-based air temperature indices in Banjaluka in 1991–2020 in reference to 1961–1990

Index	Year	Winter	Spring	Summer	Autumn
TX10p					
1961–1990	38.5	9.9	9.6	9.7	9.4
1991–2020	22.3	4.9	6.0	4.9	6.2
Difference (days)	-16.2	-5.0	-3.6	-4.8	-3.2
Difference (%)	-42.1	-50.7	-37.4	-49.1	-33.9
D [KS test]	0.700	0.300	0.400	0.633	0.333
p-value [KS test]	<0.0001	0.109	0.011	<0.0001	0.055
TX90p					
1961–1990	38.3	9.7	9.4	9.7	9.5
1991–2020	74.8	15.6	18.1	27.0	14.4
Difference (days)	36.5	5.9	8.6	17.3	4.9
Difference (%)	95.5	60.1	91.8	177.9	52.4
D [KS test]	0.700	0.367	0.600	0.633	0.500
p-value [KS test]	<0.0001	0.026	<0.0001	<0.0001	0.001
TN10p					
1961–1990	38.3	10.0	9.7	9.4	9.6
1991–2020	19.8	5.5	5.6	3.0	5.3
Difference (days)	-18.4	-4.6	-4.0	-6.3	-4.2
Difference (%)	-48.1	-45.5	-41.6	-67.6	-44.3
D [KS test]	0.600	0.233	0.367	0.700	0.367
p-value [KS test]	<0.0001	0.342	0.026	<0.0001	0.026
TN90p					
1961–1990	37.8	9.4	9.9	9.4	9.4
1991–2020	85.8	16.8	18.3	32.2	18.7
Difference (days)	48.0	7.5	8.4	22.8	9.4
Difference (%)	126.8	79.7	85.3	242.2	100.3
D [KS test]	0.833	0.400	0.667	0.800	0.500
p-value [KS test]	<0.0001	0.011	<0.0001	<0.0001	0.001

The even more prominent changes occurred with indices which displayed relatively rare occurrence during 1961–2022 (and particularly in 1961–1990). Although rare in occurrence, significant positive trends displayed indices TR20, TX35, and TX37 (0.7 days/10yr, 1.5 days/10yr, and 0.3 days/10yr, respectively) and increased their average annual occurrence in 1991–2020 17-fold, 3-fold and 6-fold, respectively, in reference to 1961–1990 (with statistically significant shifts in their distribution towards higher values in 1991–2020). That warm extremes are becoming more pronounced and more frequent indicates that in 1961–1990 there was total 5 TR20, 17 TX37 and 3 TX39, whereas since than even 105, 152 and 52 such day, respectively, have occurred.

Tab. 10. Trends in annual fixed threshold air temperature indices in Banjaluka in 1961–2022 (in days/10yr)

Index	ID0	FD0	TR20	SU25
Slope	-2.8	-6.1	0.7	7.6
p-value	<0.0001	<0.0001	<0.0001	<0.0001
Index	TX30	TX35	TX37	TX39
Slope	7.1	1.5	0.3	0.0
p-value	<0.0001	<0.0001	<0.0001	0.001

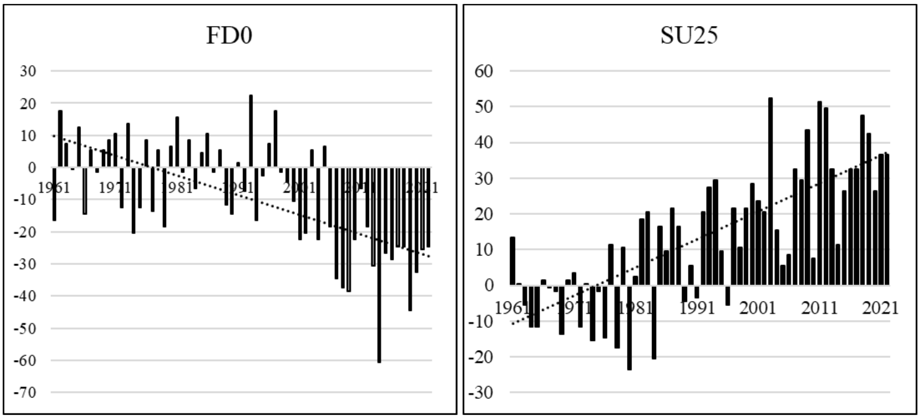


Fig. 5. Deviations (in days) of the selected fixed threshold air temperature indices from 1961–1990 averages (the dashed line represents the trendline)

Tab. 11. Difference in average values of annual absolute-based (fixed) threshold temperature indices in Banjaluka in 1991–2020 in reference to 1961–1990

Index	ID0	FD0	TR20	SU25
1961–1990	19.1	94.5	0.2	82.5
1991–2020	11.8	78.0	3.1	107.6
Difference (days)	-7.3	-16.5	3.0	25.0
Difference (%)	-38.0	-17.5	1780.0	30.3
D [KS test]	0.367	0.500	0.633	0.633
p-value [KS test]	0.026	0.001	<0.0001	<0.0001
Index	TX30	TX35	TX37	TX39
1961–1990	23.0	2.5	0.6	0.1
1991–2020	45.3	9.6	4.1	1.4
Difference (days)	22.3	7.1	3.5	1.3
Difference (%)	96.8	287.8	617.6	1333.3
D [KS test]	0.667	0.500	0.400	0.267
p-value [KS test]	<0.0001	0.001	0.011	0.200

Trend estimate of duration-based air temperature indices showed that in 1961–2022 there was a significant positive trend in WSDI (4.8 days/10yr), whereas as CSDI significantly decreased (due to rare occurrence trend slope was negligible) (Tab. 12 and Fig. 6). Average annual warm spell duration increased 5-fold in 1991–2020 in reference to 1961–1990 (Tab. 13). The highest annual values of WSDI were recorded in 2007, 2015, 2011, 2012, 2003, 2000, 2006, 2017, 2021 (all in 21st century); and of CSDI in 1963, 1962, 1987, 1991, 1964, 1985, 2012, 1996 (majority before 1990).

As a result of the significant growing trends in Ta, Tmax, Tmin growing season extended in 1961–2022 in the range of 9.5 days/10yr; between last two thirty-year periods extended for more than a month (Tab. 12 and Tab. 13).

Tab. 12. Trends in annual duration-based air temperature indices in Banjaluka in 1961–2022 (in days/10yr)

Index	WSDI	CSDI	GSL
Slope	4.8	0.0	9.5
p-value	<0.0001	0.0048	<0.0001

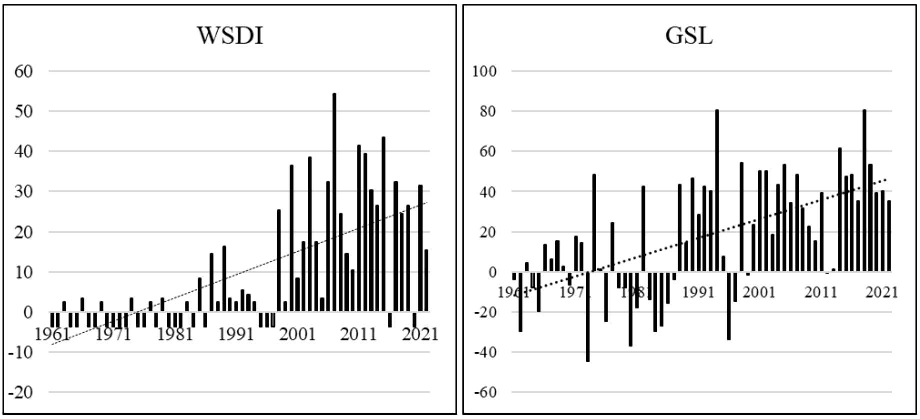


Fig. 6. Deviations (in days) of the selected duration-based air temperature indices from 1961–1990 averages (the dashed line represents the trendline)

Tab. 13. Difference in average values of annual duration-based air temperature indices in Banjaluka in 1991–2020 in reference to 1961–1990

Index	WSDI	CSDI	GSL
1961–1990	3.6	4.0	263.6
1991–2020	21.8	1.9	297.0
Difference (days)	18.2	-2.2	33.4
Difference (%)	505.6	-53.7	12.7
D [KS test]	0.600	0.233	0.600
p-value [KS test]	<0.0001	0.342	<0.0001

Changes in mean precipitation

Unlike to a consistent warming trend observed for air temperature in Banjaluka, annual, as well as and seasonal, precipitation in observed 1961–2022 displayed trends mixed in sign (Tab. 14 and Fig. 7) – precipitation decreased in warmer half of a year, particularly in summer (-17.7 mm/10yr) and slightly in spring (-0.8 mm/10yr), and increased in winter

(0.6 mm/10yr) and to a much higher extent in autumn season (8.3 mm/10yr) (Tab. 14). However, significant trends were present only in summer. In summer average precipitation decreased -14.0 % in 1991–2020 compared to the reference period. In autumn season average precipitation increased 21.7 % with significant distributional shift towards higher values in more recent period. Average values of spring precipitation were somewhat higher in latter period (1991–2020), however trend in 1961–2022 was negative, given that in the latest few years some of driest spring seasons were recorded. Annual precipitation showed an insignificant trend (-10.6 mm/10yr or -1.0 %/10yr).

Tab. 14. Trends in precipitation in Banjaluka in 1961–2022 (in mm/10yr and %/10yr)

Season	Year	Winter	Spring	Summer	Autumn
Slope (mm)	-10.6	0.6	-0.8	-17.7	8.3
Slope (%)	-1.0	0.3	-0.3	-6.5	3.0
p-value	0.388	0.955	0.875	0.028	0.239

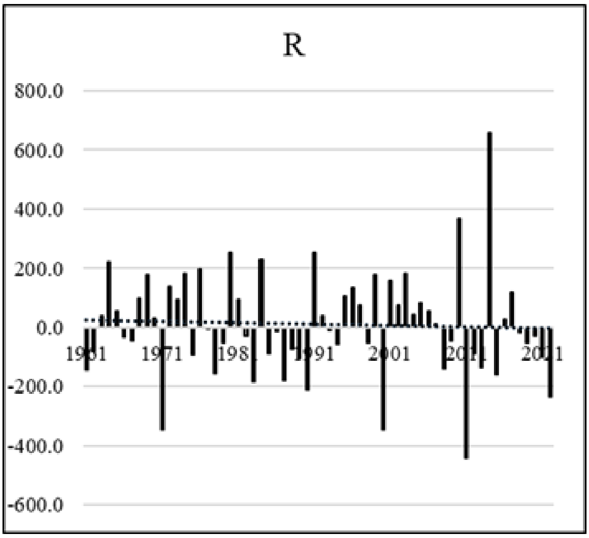


Fig. 7. Deviations (in mm) of mean precipitation from 1961–1990 averages (the dashed line represents the trendline)

Tab. 15. Difference in average values of precipitation in Banjaluka in 1991–2020 in reference to 1961–1990

Season	Year	Winter	Spring	Summer	Autumn
1961–1990	1029.5	222.0	261.8	298.8	247.7
1991–2020	1063.0	234.6	270.9	257.0	301.4
Difference (mm)	33.5	12.6	9.1	-41.8	53.6
Difference (%)	3.3	5.7	3.5	-14.0	21.7
D [KS test]	0.167	0.133	0.200	0.200	0.433
p-value [KS test]	0.760	0.936	0.537	0.537	0.005

Changes in extreme precipitation indices

Trends in extreme precipitation indices in Banjaluka in 1961–2022 (Tab. 16, Tab. 18 and Fig. 8) suggest increase in magnitude (RX1day, RX5day, R95p, R99p) and frequency (R20mm) of intense precipitation events (however, still insignificant) and drying tendency – significant for R01mm (-1.9 days/10yr) and CDD (0.8 days/10yr), and insignificant for PRCPTOT (-13.0 mm/10yr). Comparative analysis of these indices average annual values in Banjaluka between last two thirty-year periods (1961–1990 and 1991–2020) also has confirmed that no significant changes in averaged values nor in distribution of extreme precipitation indices were present (Tab. 17 and Tab. 19). Significant changes in distribution were determined only for R99p (shift towards higher index values in latter period).

Tab. 16. Trends in annual absolute and percentile precipitation indices in Banjaluka in 1961–2022 (mm/10yr, except for SDII mm/day/10yr)

Index	PRCPTOT	SDII	RX1day	RX5day	R99p	R95p
Slope	-13.0	0.0	0.5	2.5	1.2	2.1
p-value	0.288	0.507	0.653	0.145	0.786	0.766

Tab. 17. Difference in average values of annual absolute and percentile precipitation indices in Banjaluka in 1991–2020 in reference to 1961–1990

Index	PRCPTOT	SDII	RX1day	RX5day	R99p	R95p
1961–1990	1012.2	9.0	54.4	95.1	65.5	212.1
1991–2020	1033.1	9.4	57.5	100.5	90.0	260.4
Difference*	20.9	0.5	3.1	5.3	24.5	48.2
Difference (%)	2.1	5.3	5.7	5.6	37.4	22.7
D [KS test]	0.133	0.233	0.300	0.333	0.200	0.233
p-value [KS test]	0.936	0.342	0.109	0.055	0.050	0.342

*mm, except for SDII mm/day

Tab. 18. Trends in annual fixed-thresholds and duration precipitation indices in Banjaluka in 1961–2022 (in days/10yr)

Index	R01mm	R10mm	R20mm	CDD	CWD
Slope	-1.9	-0.3	0.2	0.8	0.2
p-value	0.0329	0.4911	0.5701	0.0459	0.1561

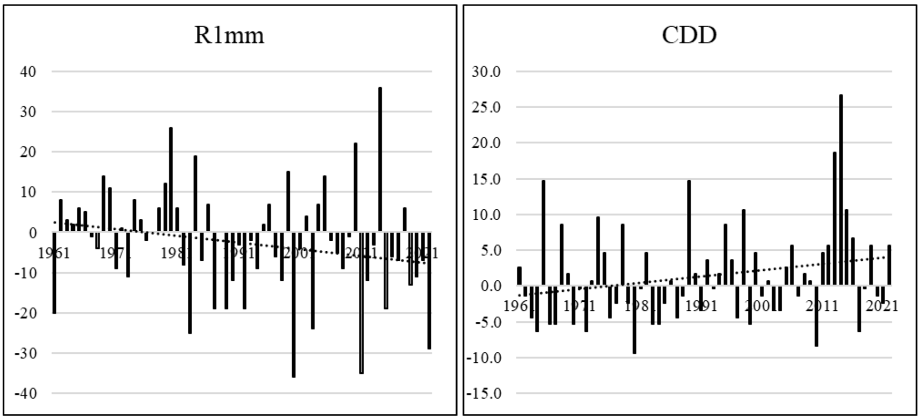


Fig. 8. Deviations (in days) of the selected extreme precipitation indices from 1961–1990 averages (the dashed line represents the trendline)

Tab. 19. Difference in average values of fixed-thresholds and duration precipitation indices in Banjaluka in 1991–2020 in reference to 1961–1990

Index	R01mm	R10mm	R20mm	CDD	CWD
1961–1990	113.0	35.2	12.6	21.4	6.4
1991–2020	108.8	35.8	14.2	24.1	7.3
Difference (days)	-4.2	0.6	1.5	2.8	0.9
Difference (%)	-3.7	1.7	12.1	12.9	13.5
D [KS test]	0.300	0.100	0.233	0.233	0.200
p-value [KS test]	0.109	0.997	0.342	0.342	0.537

Discussion and conclusion

Results obtained in this research show intensification of all temperature and precipitation trends in Banjaluka in comparison to previous research which covered period until 2015/2016 (Trbić et al., 2017; Popov et al., 2017b, 2018a, 2018b, 2019; Popov, 2020).

Trends determined in this study for mean temperatures (positive), warm extremes (positive), cold extremes (negative), mean and extreme precipitation (mixed in sign) were in line with those obtained previously by other researches for Banjaluka, Bosnia and Herzegovina and Southeast Europe. Over the Sava lowlands in Serbia, Croatia, and Slovenia, increasing trends in temperatures, particularly in the warmer half of the year (spring and summer seasons) were found by Ogrin et al. (2022). The upward temperature tendency was reported in researches in Serbia (Bajat et al., 2015; Vuković et al., 2018; Tošić et al., 2022), Croatia (Bonacci et al., 2021), Slovenia (Tošić et al., 2016), Montenegro (Burić et al., 2014; Doderović et al., 2020; Burić & Doderović, 2021). In Serbia the positive trends in TXx, TX90p, SU25, TNn, TN90p, TR20 etc. and downward trends in FD0, TN10p, TX10p were determined (statistically significant at the annual and summer levels) (Tošić et al., 2021, 2022). In Montenegro, in 1951–2010 the most significant trends were found for warm condition (TN90p, Tx90p and SU25) (Burić et al., 2014). Local scale researches confirmed same patterns of change – for instance, for

Zagreb (Nimac et al., 2021), Podgorica (Burić & Doderović, 2021), Kolašin (Doderović et al., 2020), Sarajevo (Gnjato et al., 2021), Mostar (Popov et al., 2017a), Bijeljina (Popov & Delić, 2019) etc.

Although global and continental researches in Europe (Zhang et al., 2019; Domínguez-Castro et al., 2020; Dunn et al., 2022) found stronger warming for minimum than for maximum air temperatures, in Banjaluka, as over the other regions (Popov et al., 2018a, 2019; Popov, 2020) and cities (Popov et al., 2017a; Popov & Delić, 2019; Gnjato et al., 2021) of Bosnia and Herzegovina and the Southeast Europe region in general (Bonacci et al., 2021; Tošić et al. 2022), changes in maximum air temperatures were more pronounced. Tošić et al. (2022) found slightly more prominent trends in mean maximum air temperatures than for minimum ones in Serbia in 1951–2020. At Croatian stations of Zagreb and Lastovo, significant increasing trends in both Tmax and TXx were determined, whereas the increase in minimum air temperatures was not significant (Bonacci et al., 2021).

Emergence in heat extremes occurred particularly prominent during the last two decades. The heatwaves rapidly increased in intensity, frequency and/or duration, particularly in 21st century; and is projected that these trends will be even more prominent under enhanced global warming in future (Perkins-Kirkpatrick & Lewis, 2020). Mega-heat waves were observed over Europe in summer of 2003, 2006, 2015, 2018; in summer of 1994 and 2013 in Central Europe, in 2007 over the Balkans, in 2010 in Russia etc. (Unkašević & Tošić, 2011; Hoy et al., 2016; Tomczyk & Bednorz, 2016; Bastos et al., 2020; Tošić et al., 2021). Malcheva et al. (2022) state that over the Southeastern Europe extreme heat events displayed statistically significant upward trends in 1961–2020. In some regions the probabilities of extreme temperatures occurrence increased at least fivefold (Estrada et al., 2023).

Mainly non-significant trends, that were of both signs, in precipitation (at both annual and seasonal levels) were found over many areas in the regions of Serbia, Croatia, Slovenia, Montenegro (Luković et al., 2014; Tošić et al., 2016; Milovanović et al., 2017; Doderović et al., 2020; Burić & Doderović, 2021; Milošević et al., 2021; Ogrin et al., 2022;) as well as in Bosnia and Herzegovina (Popov et al., 2017b; Popov et al., 2018b; Popov, 2020; Gnjato et al., 2021). One of the most prominent changes was decrease in summer precipitaton. In just two recent decades, over the Europe or its different parts (including where Banjaluka is located) numerous severe droughts were recorded – in 2003, 2007, 2011–2012, 2015, 2017–2020 (Blauhut et al., 2022). Although summer precipitation is decreasing, Lakatos et al. (2021) found that over the Pannonian Basin in 1998–2019 hourly precipitation intensity increased.

Numerous climate change attribution studies found that observed emergence of hot temperature extremes, increasing extreme precipitation and increase in the drought frequency/duration would be impossible without anthropogenic global warming, mostly attributed to anthropogenic greenhouse gas increases (Hu et al., 2020; Paik et al., 2020; Chiang et al., 2021; Dong et al., 2021; Madakumbura et al., 2021; Robinson et al., 2021; Sun et al., 2022; Estrada et al., 2023).

Given the intensification of climate change in recent two decades in Banjaluka, as well as projections of change until the end of century, serious and immediate mitigation and adaptation measures are necessary. Future researches should also address the climate change impact of natural resources (food production, biodiversity, soil and water resources), human health, major economic sectors etc.

Conflicts of Interest: The authors declare no conflict of interest.

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