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Secular trends in indices of precipitation extremes in Croatia, 1901–2008

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In this study, trends in annual and seasonal precipitation amounts in Croatia are discussed. This discussion is followed by trend analysis in seven indices of precipitation extremes, which indicate intensity and frequency of extreme rainfall events. These indices have been proposed by World Meteorological Organisation and are calculated using daily precipitation amounts. The data sets used in this study cover the period 1901–2008 at five meteorological stations distributed among different climate conditions in Croatia: continental, mountainous and maritime. The trends are estimated by a simple least squares fit of the linear model and tested for statistical significance by a non-parametric Mann-Kendall test. The time series with significant trends are identified, and a Sneyers progressive analysis is then performed to determine the beginning of the trend. The time series analysis of coefficients of variation in consecutive 30-year periods indicates the variability in precipitation. The extreme quantiles for annual one-day and five-day precipitation maxima have been estimated by the Generalised Extreme Value (GEV) distribution and discussed in relation to the original time-series. The results show a downward trend in annual precipitation amounts since the beginning of the 20th century throughout Croatia, which agrees with the drying trend observed across the Mediterranean. Precipitation amounts have large interannual variability, on both annual and seasonal scales. By the end of the 20th century, the precipitation variability decreased in the north-western Croatian mountainous and northern littoral regions and the eastern lowlands. The Dalmatian islands experienced increased variability since the middle of the 20th century. In regions of drying, such as Croatia, there is no evidence of major secular changes in precipitation extremes that are related to the high amounts of precipitation and the frequency of heavy rainfall days over the majority of Croatia.

Keywords: trend analysis, precipitation variability, indices of precipitation extremes, seasonal precipitation, annual precipitation, GEV distribution, Croatia

1. Introduction

The 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) indicated that long-term trends in precipitation amounts have been observed over many large regions from 1900 to 2005. A significant increase in precipitation has been observed in northern Europe due to the increased frequency of heavy precipitation events over the last 50 years. Drying has been observed in southern Europe, which has experienced more intense and longer droughts. As changes in precipitation are highly variable at regional scales, accurate analysis of regional and local precipitation change is necessary to improve the assessment of environmental and social impacts. Many of these impacts will be felt through extreme events. This increases the demand to use the observational record to determine whether there have been significant changes in amount, frequency and intensity of extreme precipitation.

The joint Expert Team on Climate Change Detection and Indices (ETCCDI) of the World Meteorological Organisation, Commission for Climatology (WMO/CCL) and World Climate Research Programme, Climate Variability and Predictability (WCRP/CLIVAR) has designed a system of indices and tools that enable a consistent approach to the monitoring, analysis and detection of changes in extremes of temperature and precipitation by countries and regions across the globe (Folland et al., 1999; Peterson et al., 2001; Klein Tank and Können, 2003; WMO, 2004). The latest developments include the use of the extreme value theory to complement the descriptive indices of extremes in the evaluation of the intensity and frequency of rare events (Klein Tank et al., 2009).

Change in extreme precipitation, based on these indices, has been analysed for individual European countries and stations and, to a lesser extent, for Europe as a whole. Klein Tank and Können (2003) found that all Europe-average wet extremes increased during the second half of the 20th century (1946–1999), although low spatial coherence was found in the trend. There is also evidence of disproportionately large changes in extremes compared to annual totals. At the stations where the annual precipitation amount has increased, the index for the fraction of the annual precipitation that is due to very wet days shows disproportionately large changes in the precipitation extremes. At stations with a decreasing annual precipitation amount, there is no amplified response of the extremes. Centennial (1901–2000) trends in precipitation extremes for Europe show regional differences in seasonality (Zolina, 2005; Moberg et al., 2006). The most outstanding feature of central and western European precipitation (Moberg and Jones, 2005) is the significant increase in winter precipitation, in both the mean precipitation intensity and moderately strong events. There is a little evidence of significant change in the precipitation indices for summer. An analysis undertaken for the United Kingdom that was based on a dense data network during the second half of the 20th century detected a tendency towards wetter conditions in winter and drier conditions in summer (Osborn et al., 2000). During the same period in western Germany, the extreme heavy precipitation in winter and the transition seasons has also become more extreme, both in terms of magnitude and frequency. However, in contrast to winter, the summer trend in extreme heavy precipitation is towards less extreme (Hundecha and Bárdossy, 2005). Central-eastern Germany is dominated in all seasons by positive extreme precipitation trends, whereas the opposite trends prevailed in Poland; the strongest trends occur in summer and winter, mainly in the south (Łupikasza, 2010; Łupikasza et al., 2010). Seasonal and spatial differences in the trends of heavy precipitation extremes are present over the Czech Republic from 1961 to 2005 (Kyselý, 2009). Statistically significant increasing trends have been identified for all indices in the western Czech Republic in winter, but no clear trends have been observed in the east. The increasing summer trend is much less spatially uniform. Decreasing trends of heavy precipitation are observed for the transition seasons. Furthermore, the regional intensity and frequency of extreme precipitation in the Carpathian Basin, specially focusing on Hungary, increased between 1976 and 2001, while the total precipitation decreased and the mean climate in this region became slightly drier throughout the 20th century (Bartholy and Pongrácz, 2007, 2010). Precipitation in Alpine regions fluctuates strongly, depending on the region considered. In the Swiss central lowlands and the northern fringe of the Alps, the number of days with intense precipitation has increased significantly in winter and autumn. No systematic trends are evident for intensive daily precipitation in summer (Frei and Schär 2001; Schmidli and Frei, 2005). South of the Alps, in northern Italy, the negative trend in mean precipitation is associated with a decrease of the frequency of wet days for most seasons, with the greatest decline in winter, and a slight increase of the intensity of wet days is found for all seasons (Brunetti et al., 2000, 2001). There are several papers that primarily deal with the trend analysis for the second half of the 20th century for the entire Iberian Peninsula or particular sub-regions of the peninsula (Ramos, 2001; Gonzáles Hidalgo et al., 2003; Millán et al., 2005; Rodrigo and Trigo, 2007; Martínez et al., 2007; Costa and Soares, 2009; López-Moreno et al., 2010). A prevailing negative trend is present for both annual and seasonal precipitation. Precipitation extremes generally show a decrease in the intensity of daily rainfall, while there is no pronounced change in the number of wet days. This pattern is valid both annually and seasonally. There is a trend toward lower rainfall during the rainy days and an increasing contribution of light and moderate daily episodes to the annual precipitation amounts. The results based on a denser network give a more detailed insight into the spatiotemporal changes observed on the local scale (interior-coast, seasons). These changes can differ from the general pattern, as is observed for the south of Portugal (Costa and Soares, 2009) or north-eastern Spain (Ramos and Martinez-Casanovas, 2006). In the eastern Mediterranean (the Balkan Peninsula, western Turkey and Cyprus), the total annual precipitation and the frequency and intensity of extreme precipitation have significantly decreased over the region, indicating drier conditions in recent times. However, the extreme precipitation percentage has a widespread pattern without a clear trend (Kostopoulou and Jones, 2005; Kioutsioukis et al., 2010).

Spatial differences in the sign, magnitude and seasonality of trends in precipitation extremes over Europe reflect the impacts of changes in circulation patterns, differences in maritime and continental influences and modifications caused by local parameters (relief-elevation, direction of mountain ranges and distance from the sea). The location of Croatia (in the transition region between the continental Panonian lowlands of central Europe and the Adriatic Sea of the northern Mediterranean) and the fact that precipitation change is highly variable both regionally and seasonally increases the need for more accurate analysis of sub-regional and local precipitation change. Earlier papers on the fluctuations and trends of annual precipitation in different climatic regions of Croatia indicate a generally decreasing trend from 1891 to 1990 (Gajić-Čapka, 1993). A reassessment of precipitation trends on annual and seasonal scales was performed within the National Communications of the Republic of Croatia under the United Nations Framework Convention on Climate Change (MZOPUG, 2006, 2009). Some results of the analyses of centennial trends in indices of precipitation extremes in Croatia are presented in the more recent National Communication and the Gajić-Čapka (2006). Recently, predictions of an increase of the intensity of precipitation in Croatia with longer periods between rainfall events have been confirmed in a study that investigated consecutive dry days (Cindrić et al., 2010).

This study contributes to precipitation trend results gathered for different European regions. Furthermore, these results should be used as the initial input to assess the risk of climate change impacts, which is applicable to adaptation and prevention planning in many socio-economic sectors, such as water resource management, agriculture, and transportation. An investigation of the observed change is one of the important steps to validate climate models and towards understanding possible future trends.

2. Data and methods

This study deals with two types of precipitation time series: annual and seasonal amounts and seven indices of precipitation extremes (Table 1) over the period 1901–2008. Due to the availability of secular data series, the study includes five meteorological stations in Croatia that are located in different climate regions: Osijek in the very southern part of the Panonian lowland (H = 89 m asl, φ = 45° 48' N, λ = 18° 58' E); Zagreb-Grič in north-western continental Croatia (H = 157 m asl, φ = 45° 30' N, λ = 15° 33' E); and Gospić on the mountainous Lika plateau in the Dinaric Alps (H = 564 m asl, φ = 44° 33' N, λ = 15° 23' E) (Figure 1). Two locations on the eastern Adriatic coast are also included: Crikvenica in the Kvarner Bay (H = 2 m asl, φ = 45° 10' N, λ = 14° 42' E), characterised by the maritime climate of the northern Adriatic under the strong influence of the mountainous hinterland, and Hvar on the middle Adriatic island of Hvar (H = 20 m asl, φ = 43° 10' N, λ = 16° 27' E).

The five Croatian stations have the longest data series in Croatia. The observations started in the second half of the 19th century and are currently

Figure 1. Locations of the meteorological stations analysed in this study.

maintained by the operational network of the Meteorological and Hydrological Service of Croatia (DHMZ). The data have been checked for quality consistent with the framework of the special program of DHMZ for long-term data series. Special emphasis was given to the comparison of the measured data with the metadata from the station's history. This was important for early data, as there are limited possibilities to use comparative data series for quality assessment (HMZ NRH, 1956; HMZ NRH, 1958; HMZ NRH, 1960; Geofizički zavod PMF, 1970). Later data are subject to the operational quality controls enforced for all stations that are based on basic standards recommended by the WMO (1986) (Zaninović et al., 2008).

Prior to this analysis, the original monthly data series were subjected to a systematic quality control procedure in the framework of the HISTALP project (see Auer et al., 2007), which involved an intensive homogenisation procedure. Then, the outliers were checked, the errors were removed, and finally, the data gaps were filled. The data records from the Osijek, Zagreb-Grič, Gospić and Hvar meteorological stations were included in the list of outstanding sites.

However, when dealing with indices of precipitation extremes, it is the daily data that are of interest. There is an obvious lack of techniques for properly testing and adjusting daily observational records. For example, the procedure mentioned previously was deduced for the Italian stations (Brunetti et al., 2000, 2004). Due to the results of the quality control procedure, the original daily series used for this study took into account the periods without measurements and obeyed these in the selection of data series.

When dealing with daily data analysis for the purpose of identifying the frequency and magnitude of extreme events, it is essential that the data series are entirely or nearly (less than 10% missing daily data) complete for the year. Furthermore, series with more than 20% missing or incomplete years in the analysis period should be excluded from the analyses. Additionally, the years of missing data should not be clustered together during a certain period of the record, as this period may have had an anomalous pattern of precipitation. These rules given in Peterson et al. (2001) and Klein Tank and Können (2003) were used to select the data series to calculate the indices of precipitation extremes for each station. After applying these criteria, the following years were excluded from the analyses at the various stations: (1) Osijek: 1991, 1992, (2) Zagreb-Grič: no missing data, (3) Gospić: 1901–1923, 1943–1945, (4) Crikvenica: 1921, 1987, and (5) Hvar: 1918–1926, 1943–1945.

The indices of precipitation extremes were calculated with the daily precipitation values recommended by ETCCDI. There are two main categories of extreme indices: those based on absolute thresholds and those based on percentiles. The first category refers to the number of days that reach a specified absolute value (e.g., the dry day index counts days with $R_d < 1.0$ mm), whereas the second category of indices are based upon the statistics of a precipitation variable (i.e., percentiles). Percentiles were determined by sampling all the precipitation days ($R_d \geq 1.0$ mm) within the standard reference period 1961–1990.

It can be particularly helpful for some applications to monitor or analyse extreme precipitation events by absolute thresholds (Folland et al., 1999). Values of absolute extremes, such as the highest five-day precipitation in a year (*Rx5d*), can often be related to extreme events that affect human society and the natural environment. The indices of the number of days that reach fixed thresholds can also be related to observed impacts particularly if the thresholds refer to values of hydrological significance. The indices based on the number of days that reach percentile thresholds are less suitable for direct assessment of impacts but may provide useful indirect information that is relevant to studies of impacts and adaptation. For instance, trends in the *R95%* index (the number of days with rainfall greater than the 95th percentile of daily amounts) are relevant for comparing the changes in demands on drainage and sewage systems at different locations. In addition, percentiles are more useful in regional or global spatial comparisons than absolute values (Frich et al., 2002).

The indices of precipitation extremes analysed in this study (Table 1) provide an insight of the frequency and intensity of precipitation extremes. They are defined as the number of days in which the precipitation amount, R_d, exceeds the defined thresholds (dry days, wet days and very wet days), the portion of the annual precipitation amount that occurs during very wet days, and the annual maximum five-day and one-day precipitation amounts.

Table 1. The definitions of the indices of precipitation extremes used in this study.

Nr.	Indices	Unit	Definition
1	*DD*	days	Dry days (absolute extreme) *(Number of days with daily precipitation amount R_d < 1.0 mm)*
2	*SDII*	mm/day	Simple daily intensity index (absolute extreme) *(annual precipitation amount / annual number of precipitation days $R_d \geq$ 1.0 mm)*
3	*R75%*	days	Moderate wet days (percentile threshold) *(Number of days with precipitation $R_d > R_{75\%}$, where $R_{75\%}$ is the 75th percentile of the distribution of daily precipitation amounts at days with 1 mm or more precipitation in the 1961–1990 baseline period)*
4	*R95%*	days	Very wet days (percentile threshold) *(Number of days with precipitation $R_d > R_{95\%}$, where $R_{95\%}$ is the 95th percentile of the distribution of daily precipitation amounts at days with 1 mm or more precipitation in the 1961–1990 baseline period)*
5	*R95%T*	%	Precipitation fraction due to very wet days (percentile threshold) *(Fraction of annual total precipitation $\Sigma R_d / R_t$, where ΣR_d indicates the sum of daily precipitation exceeding the 95th percentile of precipitation at wet days R95% in the 1961–1990 baseline period)*
6	*Rx1d*	mm	Highest 1-day precipitation amount (absolute extreme) *(Maximum precipitation sums for 1-day intervals)*
7	*Rx5d*	mm	Highest 5-day precipitation amount (absolute extreme) *(Maximum precipitation sums for 5-day intervals)*

The long-term trends in precipitation extremes were estimated by a simple least squares fit of the linear model. They were tested for statistical significance at the 95% confidence level using a non-parametric Mann-Kendall rank statistic, t (Mitchell et al., 1966; Sneyers, 1990). In the case of a significant trend, a progressive trend analysis was performed to identify the beginning of detected trend. The test statistic, $u(t)$, was calculated for all values of i from the first to the last term, forming a forward progressive test series. The backward test series, $u'(t)$ was performed in the same manner but was calculated from the last to the first term. The intersection point between the $u(t)$ and $u'(t)$ designates the beginning of the trend, which becomes significant at 0.05 level in the case where the absolute value of $u(t)$ exceedes 1.96.

To eliminate short-term fluctuations and more clearly show the change at a longer time scale, the noise was taken out of the data series. This was performed using the weighted 11-year binomial moving average, which is often used for analyses of climate variability (Böhm et al., 2001). The number of terms in the moving average must be odd to enable the symmetry around the central value that precludes the shift in phase.

To investigate the change in the annual and seasonal variability, the coefficients of variation (c_v) were used. They were calculated for 30-year moving periods using a one-year shift.

To evaluate the intensity and frequency of more rare events, the extreme value theory is applied to the time series of annual one-day and five-day maximum amounts. Estimates of the extreme quantiles or return values that are exceeded with a particular probability were calculated using the Generalised Extreme Value (GEV) distribution (Jenkinson, 1969; Faragó and Katz, 1990; Coles, 2001). The positions of the original data points in relation to the estimated 20-year return values for the observed centennial series are presented. Temporal changes in the 20-year return values obtained from the shifted 50-year periods (1901–1950, 1902–1951, …, 1959–2008) are discussed.

3. Results

3.1. Trends in annual and seasonal precipitation and variability

The trends in annual and seasonal precipitation amounts provide a general indication of the temporal change in precipitation. Throughout the 20th and at the beginning of the 21st century, annual amounts of precipitation showed a downward trend across Croatia, thus joining the drying trend observed across the Mediterranean (Table 2 and Figure 2). This trend is mostly pronounced along the eastern Adriatic coast (Crikvenica) and is observed less inland. Annual trends are due to seasonal precipitation changes, which are consistent across all sites except Crikvenica: negative in autumn, winter and spring and positive in summer. However, these trends have different intensities in different seasons. The decline in annual precipitation over the mainland north of the Sava River is due to a decrease in spring and autumn precipitation amounts. In the mountainous hinterland (Gospić on the Lika plateau) and on the Dalmatian islands, the annual decrease is due mainly to the decline in winter and spring precipitation. In the Kvarner Bay (Crikvenica), the decrease in all seasonal precipitation has been observed with significant value observed in summer.

According to the progressive trend test, the detected decrease in winter precipitation on the Dalmatian islands began in 1981. Spring precipitation in eastern lowlands began to decline in 1920 and was significantly reduced since 1971. Furthermore, the summer precipitation decline in Kvarner Bay began in 1926 and was observed to significantly decline since 2003. A decrease in annual amounts began in 1937 and was observed to decrease significantly since 1985 (Figure 2b).

Precipitation amounts have large interannual variability, both on annual and seasonal scales. Therefore, looking at the positions of the 10 driest years, it can be observed that there was no grouping in any particular period (Table 3). Variability of annual precipitation amounts indicates a decrease in north-western Croatia, the mountainous and northern littoral regions (Figure 3). A similar decrease was also observed in the eastern lowlands by the end of the

20th century, and the changes observed since the beginning of the 21st century contribute to an increase in variability. The Dalmatian islands experienced an increase in variability from the middle of the 20th century.

Table 2. The decadal trends in the seasonal (R_{DJF}, R_{MAM}, R_{JJA}, R_{SON}) and annual (R) precipitation amounts. The trends significant at 5% level are bolded (# since 1924).

	Osijek	Zagreb-Grič	Gospić #	Crikvenica	Hvar
	Precipitation amount trend 1901–2008 (% / 10 years)				
R_{DJF}	–0.0	–0.7	–2.9	–1.6	**–2.9**
R_{MAM}	**–3.2**	–0.9	–1.8	–1.9	–1.3
R_{JJA}	+1.3	+1.1	+0.1	**–2.9**	+2.9
R_{SON}	–2.0	–1.3	–0.2	–1.1	–0.5
R	–0.8	–0.3	–1.0	**–1.7**	–1.0

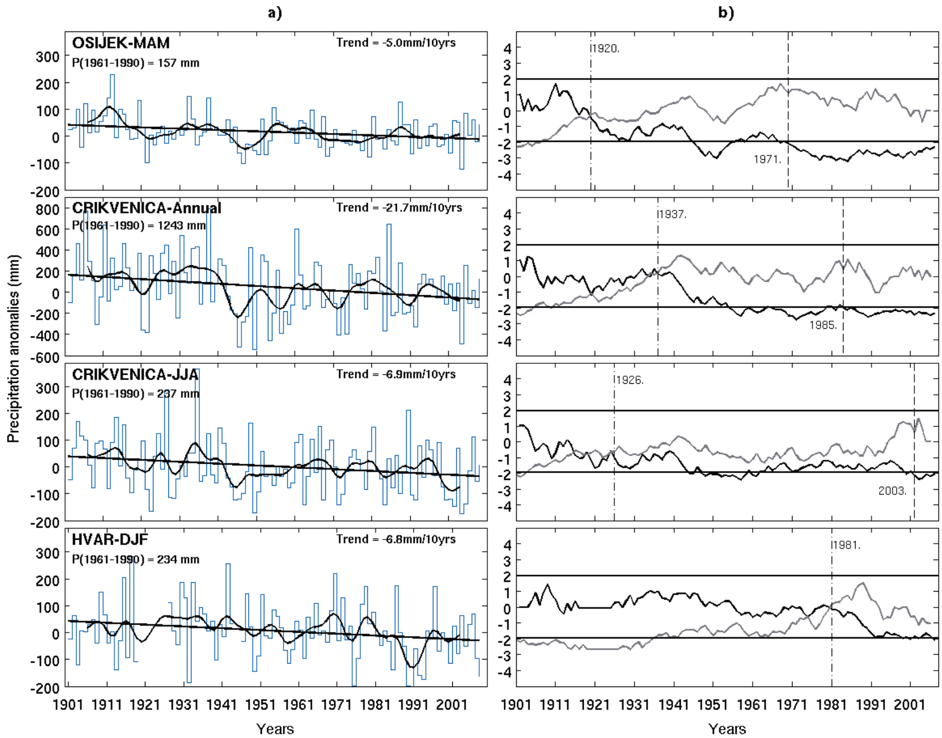

Figure 2. a) The time series for the annual precipitation amounts, related to the 11-year binomial moving averages and trends. The unit is anomalies (mm) with respect to the 1961–1990 average. b) The progressive trend test: forward series, u (black line), and backward series u' (grey line), for the precipitation amounts from 1901–2008. Straight lines indicate a confidence level of 95%.

Table 3. The ten driest years from 1901–2008. Years from 1991–2008 are bolded (# since 1924).

Osijek		Zagreb-Grič		Gospić#		Crikvenica		Hvar	
year	*mm*	year	*mm*	year	*mm*	year	*mm*	year	*mm*
2000	***316***	1949	*581*	1983	*910*	1949	*704*	1983	*384*
1921	*422*	1973	*607*	1953	*973*	1945	*726*	**2003**	***431***
1983	*467*	1971	*616*	1949	*1085*	**2003**	***752***	1989	*444*
1947	*494*	1927	*624*	1971	*1091*	1953	*786*	1913	*461*
1953	*500*	**2003**	***624***	**2003**	***1099***	1971	*835*	1903	*479*
1949	*505*	1921	*651*	**2007**	***1109***	1973	*842*	1977	*496*
2003	***517***	1946	*665*	1989	*1119*	1956	*850*	1938	*505*
1971	*519*	1942	*671*	**1994**	***1121***	1921	*861*	1946	*542*
1928	*522*	1938	*688*	1975	*1135*	1983	*877*	1950	*557*
1924	*523*	1911	*691*	1946	*1136*	1920	*882*	**1992**	***563***

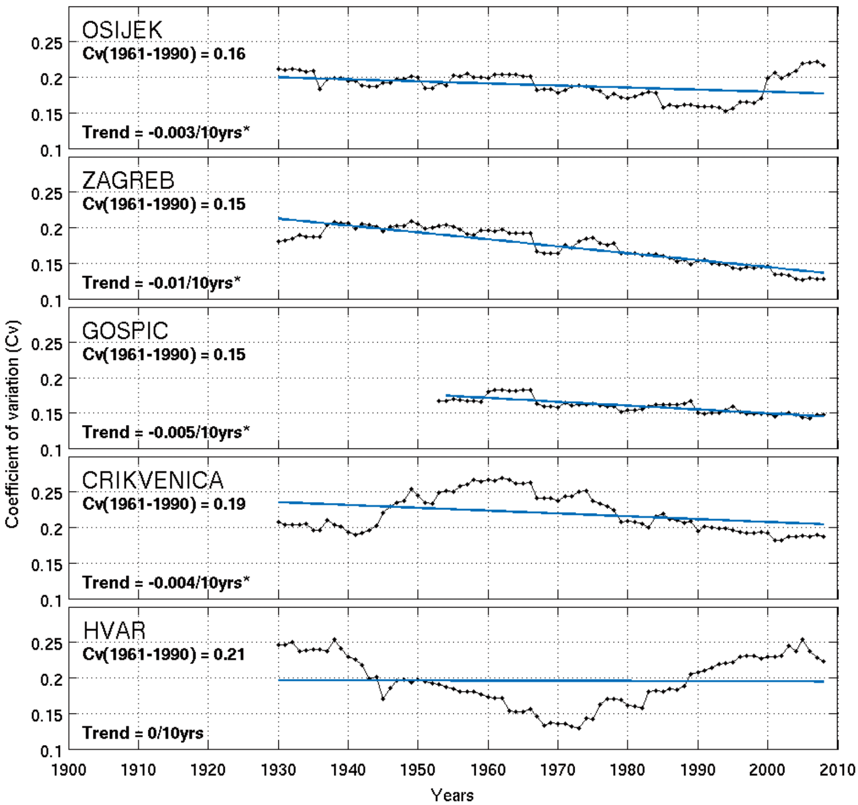

Figure 3. The time series for the coefficients of variation of annual precipitation for the 30-year periods with a one-year shift (dots) and trends (solid line). An asterisk denotes that the trend is significant at the 5% level.

3.2. Trends in indices of precipitation extremes

Precipitation indices enable a consistent approach to the monitoring, analysis and detection of changes in the extremes of precipitation. Changes in precipitation regime patterns, such as the decrease in precipitation observed in Croatia, can also be analysed and identified by trends in the frequency and intensity of dry and wet precipitation extremes. Figure 4 shows the time series of the five indices of precipitation extremes for the Osijek station. Table 4 summarises the results of the trend analysis for all the indices at the five stations.

In the period 1901–2008, there was an increase in the annual number of dry days (R_d < 1.0 mm), which was statistically significant at all stations except Gospić. The forward curves in the Sneyers test (not shown) indicate a rapid increase of dry days at the beginning of 1980s along the coast and in

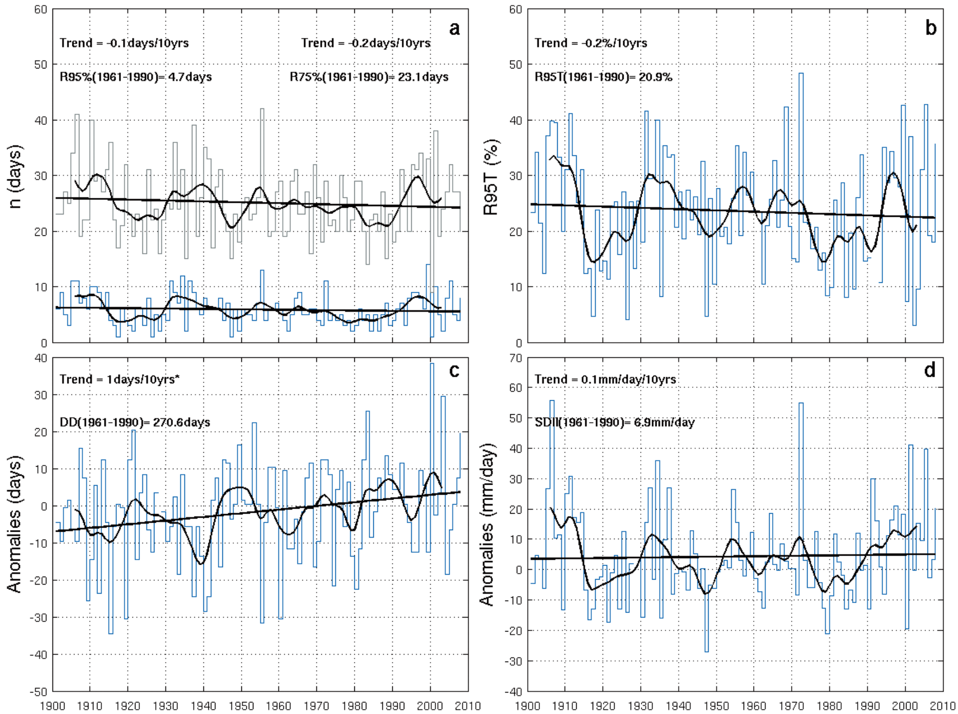

Figure 4. The time series and trends in Osijek for a) the number of wet (top) and very wet days (bottom), b) the percentage of the annual total due to very wet days, c) the anomalies of the number of dry days and d) the anomalies of the simple daily precipitation intensity. The anomalies are calculated with respect to the 1961–1990 average. The bolded curve represents the related 11-year binomial moving averages and the trends. The asterisk denotes a trend that is significant at the 5% level.

1960s on the mainland. The intensity of precipitation for rainy days, as measured by the simple daily intensity index (*SDII*), showed practically no change or only a slight increase. The trend for wet days ($R_d \geq R75\%$) had a statistically significant negative sign in Crikvenica. However, there was no substantial change in the number of very wet days ($R_d \geq R95\%$) (Table 4). The fraction of the annual total precipitation due to very wet days (*R95%T*) was almost unchanged. Finally, the absolute annual one-day and five-day maxima showed large interannual variability. The estimated long-term negative linear trends are statistically significant for the five-day maxima in Osijek. Several outliers in time series of these two parameters are found for all stations. It is generally assumed that the temporal changes are difficult to identify using long-term linear trends, which is why extreme value analysis is introduced in the next section.

Table 4. The trends in the indices of precipitation extremes (DD – dry days, SDII – simple daily intensity index, R75% – wet days, R95% – very wet days, R95%T – the annual precipitation fraction due to very wet days, Rx1d – the annual one-day precipitation maxima, Rx5d – the annual five-day precipitation maxima). The trends that are significant at the 5% level are bolded (# since 1924).

	Osijek	Zagreb-Grič	Gospić #	Crikvenica	Hvar
			Trend 1901–2008 (in 10 years)		
DD (days)	**+1.0**	**+1.4**	+1.4	**+2.3**	**+1.1**
SDII (mm/day)	+0.0	**+0.1**	+0.0	+0.1	+0.0
R75% (days)	–0.2	+0.1	+0.2	**–0.5**	+0.3
R95% (days)	–0.1	+0.1	+0.1	–0.1	+0.1
R95%T (%)	–0.2	+0.3	+0.1	–0.0	+0.3
Rx1d (mm)	+0.2	–0.2	–1.4	+0.8	+0.9
Rx5d (mm)	**–1.0**	–0.6	+0.3	–2.4	+0.6

3.3 Climate change in extreme value analysis

The descriptive indices developed by ETCCDI refer to the moderate extremes that typically occur several times every year. The extreme value theory complements these descriptive indices and evaluates the intensity and frequency of rare events that lie far in the tails of the probability distribution of precipitation variables, such as events that occur once in 20 years.

According to the Kolmogorov-Smirnov test and the quantile-quantile (Q-Q) graph, the GEV distribution was found to be the best adjustment for the data series of the annual daily precipitation maximum in Croatia relative to the fits of several theoretical distributions (Gumbel, Gulton, Frechet, Pearson III, log Pearson III, and the GEV distribution) (Gajić-Čapka and Čapka, 1997). The application of this extreme value theory assumes that the time series are stationary.

The main sources of the uncertainty in the estimates may be related to the statistical techniques. However, uncertainty is particularly dependent on the sample, especially the length of the data series, which does not need to be the same for all regions. Investigations of the normal series length for the daily precipitation maxima at Croatian meteorological stations indicated that rather long data series of 50 years was satisfactory to define a »stable« distribution in eastern Croatia (Osijek, Panonian lowland) and 80 years in north-western Croatia (Zagreb-Grič) and along the Adriatic coast (Crikvenica) (Gajić-Čapka, 2000).

Therefore, the GEV distribution was fitted to the 1901–2008 time series of *Rx1d* and *Rx5d* for the five Croatian stations to evaluate the values of the rare one-day and five-day precipitation events. The maximum likelihood estimates for the three GEV parameters are listed in Table 5. These estimates indicated negative values for the shape parameter k. Due to the length of the data series, it is reasonable to use the estimated return values for the return periods that are not longer than about two times the length of the original data set to obtain confident estimates (Klein Tank et al., 2009). Further discussion considers the values of the observed extremes in relation to the 20-year return value. The design value for the observed locations for both precipitation parameters is indicated by the dashed horizontal line in Figure 5. In the observed 108-year period, it was expected that five to six data points of the one-day and five-day maxima exceed the 20-year return value. For the 82-year period that is analysed in Gospić, it was expected that four data points exceed the 20-year return value. Figure 5a shows that the one-day maximum exceeded the 20-year return value more often at all locations, including seven times at Crikvenica, Hvar and Zagreb-Grič, eight times at Osijek and five times at Gospić. They were evenly distributed across the entire period for inland stations (Osijek and Zagreb-Grič) and the Dalmatian Islands (Hvar). At the mountainous location Gospić, they appeared in the first half of the observed period (1924 to 1969). In Crikvenica (Kvarner bay), the values exceeded the 20-year return value in the very beginning of the 20th century and in the twenty-year period from 1975 to 1993. Five-day maxima that were higher than the estimated 20-year return values were rarer than expected at Hvar (four cases) and Gospić (three cases). At all of the stations, these values mostly appeared in the first half of the 20th century.

The estimates of the 20-year return values that were calculated using the 50-year moving periods created a new data set for each location. A strong influence of the upper outliers was pronounced in each data series of the estimated values. The estimates are mainly within the 95% confidence interval. The estimates of the 20-year return value for the last observed period (1959–2008) were close to the estimates for the whole period (1901–2008). This suggests that the data sets of the last 50 years can be used to calculate the precipitation design parameters of engineering.

Table 5. The GEV distribution parameters for the five Croatian locations, (1901–2008, # 1924–2008).

Parameter	Osijek	Zagreb-Grič	Gospić #	Crikvenica	Hvar
			Rx1d		
Location ($Rx1d_0$)	34.8	40.5	64.5	69.7	50.6
Shape (k)	–0.20	–0.10	–0.05	–0.20	–0.16
Scale (a)	9.68	10.13	16.25	23.40	13.58
			Rx5d		
Location ($Rx5d_0$)	58.3	72.4	124.0	125.8	79.1
Shape (k)	–0.05	–0.09	–0.05	–0.14	–0.15
Scale (a)	16.10	15.86	28.99	33.53	22.04

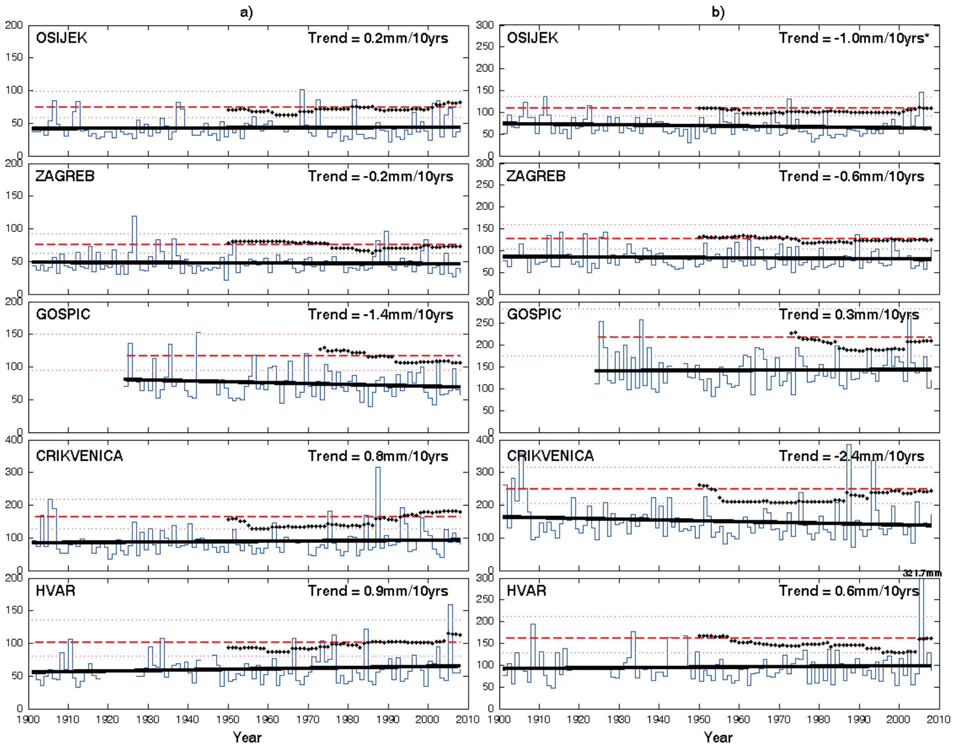

Figure 5. The time series of the annual a) one-day maxima and b) five-day maxima. The line indicates the trend that was observed (per decade) in the right corner. An asterisk indicates that the trend was significant at the 5% level. A bolded dashed line indicates the 20-year return value that was estimated from the fitted GEV distribution with the associated 95% confidence levels (dotted lines). The points denote the 20-year return values for the 50-year moving periods.

4. Discussion and conclusions

Previous studies on the trends in extreme precipitation indices for Europe based on country studies and some European-scale studies have presented information on the trends primarily for the second half of the 20th century and to a lesser extend from the beginning of the 20th century. These studies indicated a low spatial coherence on annual and seasonal scales. They then observed a strong trend in northern and western Europe and a weaker trend in the central Europe towards wetter conditions. These studies also noted an obvious trend towards drier conditions in the Mediterranean region.

This research contributes to the analysis of changes in climate extremes over the last century in Europe, from the Panonian lowlands to the eastern Adriatic coast. It provides general information of the trends in annual and seasonal precipitation and in annual daily precipitation extremes on a centennial scale (1901–2008) for five locations in Croatia.

Since the beginning of the 20th century, negative annual trends in precipitation have dominated across Croatia. This negative trend is strongest at the northern eastern Adriatic coast. In the Carpathian Basin north of Croatia, the total precipitation also decreased and the mean climate became slightly drier during 20th century (Bartholy and Pongrácz, 2010). The decrease in precipitation observed along the eastern Adriatic coast is a common feature across the Mediterranean Europe and is most evident in the eastern Mediterranean (Kostopoulou and Jones, 2005). Observations from the Italian stations also confirm the negative precipitation trend over Italy for the last 100 to 150 years. These trends are more pronounced in the central and southern areas (Buffoni et al., 1999). Auer et al. (2007) detected a precipitation dipole over the Greater Alpine Region (GAR) that shows a remarkable opposite 20th century trend evolution for the north-west (9% increase) versus south-east (9% decrease) subregions.

The decline in annual precipitation in Croatia is mainly due to the decline of the spring and autumn precipitation in the northern mainland (the hilly north-western Croatia and the lowlands of Slavonia), due to winter and spring precipitation decrease along the coast and in the mountainous regions. A significant decrease in summer precipitation only contributed to the annual decline for the northern coast.

Although a decrease of annual and seasonal precipitation amounts has been detected in Croatia, there is no signal of major secular changes in precipitation extremes related to the frequency of wet and very wet days and high amounts of precipitation. The reduction in annual amounts of precipitation can be attributed to a significant increase in the occurrence of dry days across Croatia and to the increase in the frequency of lower-intensity rainy days. The redistribution of the daily rainfall categories (torrential/heavy versus the moderate/light intensities) is of utmost interest, particularly for water management, soil erosion monitoring and flash flood impact management in the semi-arid sub-tropical regions (Alpert et al., 2002). Therefore, it is suggested that further research be conducted to investigate the change in the frequency of rainy days and the fraction of annual precipitation due to rainy days as defined by low and high percentiles. This research is especially needed along the Croatian eastern Adriatic coast based on the denser network that has existed since the mid 20th century.

The GEV distribution was applied for the very rare precipitation extremes, i.e., the highest one-day and five-day precipitation amounts in a year. The location parameters showed clear differences between the locations. The shape parameters were negative for all stations, indicating a strong influence of the outliers and the temporal variability (Klein Tank et al., 2009). This is observed less in mountainous plateau of Croatia for the one-day maxima and inland for the five-day maxima. The highest annual one-day precipitation amounts exceeding the 20-year return values are evenly distributed across the entire observed period for inland stations. The five-day maxima occurred mostly in the first half of the 20th century and there is no evidence of their grouping during the last decades. Finally, a high variability of the short-term precipitation was confirmed. Furthermore, it is necessary to analyse relatively long data series to identify the possible changes in the short-term precipitation maxima through time.

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SAŽETAK

Sekularni trend indeksa oborinskih ekstrema u Hrvatskoj, 1901.–2008.

Marjana Gajić-Čapka i Ksenija Cindrić

U ovom je radu uvodno diskutiran trend godišnjih i sezonskih količina oborine u Hrvatskoj, a potom je analiziran trend sedam indeksa oborinskih ekstrema koji ukazuju na intezitet i učestalost ekstremnih oborinskih događaja. Te je indekse preporučila Svjetska meteorološka organizacija, a računaju se pomoću podataka dnevnih količina oborine. Analiza je provedena za razdoblje 1901.–2008. za pet meteoroloških postaja smještenih u različitim klimatskim uvjetima: kontinentalni, planinski i maritimni.

Trend je procijenjen jednostavnim modelom linearne regresije, a statistička značajnost trenda je testirana pomoću Mann-Kendallovog neparametarskog testa. Za nizove sa statistički značajnim trendom primijenjen je i Sneyersov progresivni test za trend kako bi se odredio početak uočenog trenda. Varijabilnost godišnjih količina oborine je izražena vremenskim nizovima koeficijenta varijabilnosti izračunatih za 30-godišnja razdoblja s pomakom od jedne godine. Nizovi godišnjih jednodnevnih i petodnevnih maksimalnih količina oborine su posebno analizirani usporedbom s ekstremnim kvantilima, koji su određeni primjenom opće razdiobe ekstrema (GEV). Rezultati pokazuju da je od početka 20. stoljeća u Hrvatskoj prisutan negativni trend godišnje količine oborine, čime se ovo područje pridružuje tendenciji osušenja na Mediteranu. Varijabilnost količina oborine se smanjunje u sjeverozapadnoj Hrvatskoj, u gorju, na sjevernom primorju i u istočnom nizinskom području. Na dalmatinskim otocima je u razdoblju od sredine 20. stoljeća prisutno povećanje varijabilnosti. Iako se radi o području osušenja, u većem dijelu Hrvatske nisu utvrđeni znakovi većih promjena u ekstremima, kako količina oborine tako i učestalost vlažnih i vrlo vlažnih dana.

Ključne riječi: analiza trenda, varijabilnost oborine, indeski oborinskih ekstrema, sezonska oborina, godišnja oborina, GEV razdioba, Hrvatska

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