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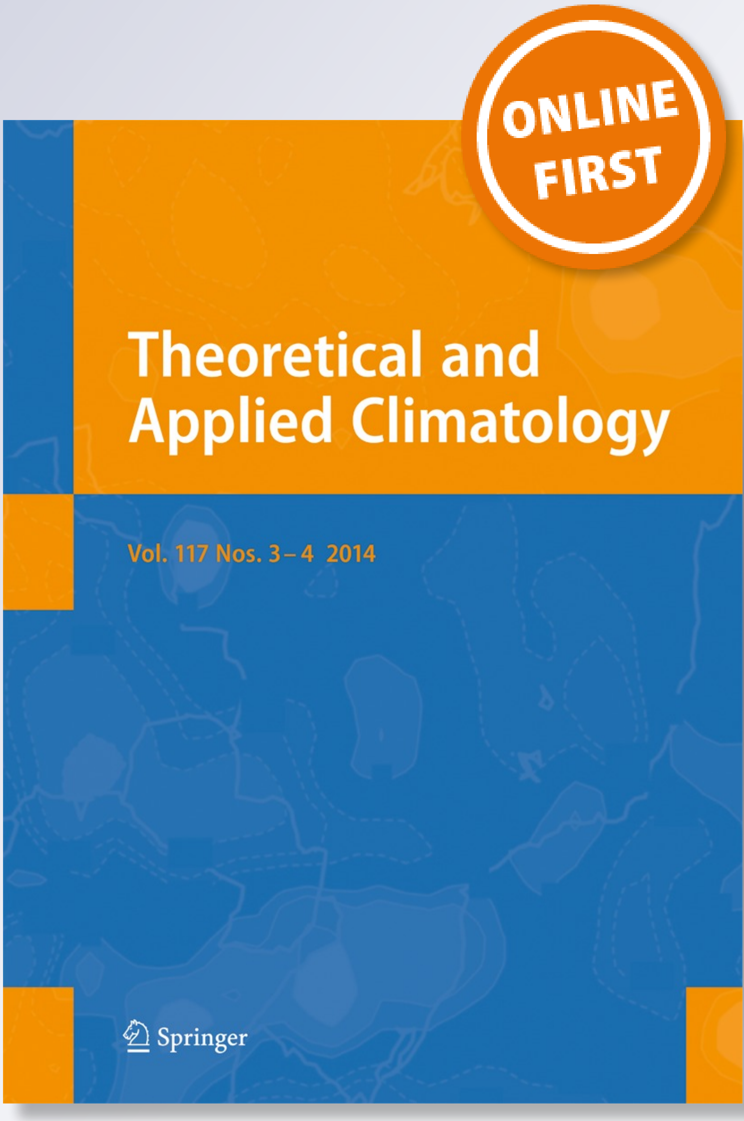

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ORIGINAL PAPER

Trends in precipitation indices in Croatia, 1961–2010

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Abstract Precipitation data from the period 1961–2010 and from a dense rain-gauge network over Croatia is analysed for spatial characteristics of trends in precipitation amounts and precipitation indices. Besides large spatial variability, the area is characterized by large temporal (seasonal) variability. Thus, analysis is performed on annual and seasonal scales over seven predefined subregions. Ten precipitation indices are selected to assess the intensity and frequency of extreme events as well as their contribution to annual and seasonal precipitation changes. The results reveal that the changes in annual and seasonal amounts are predominantly weak. A significant trend is detected only for annual amounts (negative) in the mountainous region and for summer (negative) in the mountainous littoral, mountainous region and central hinterland. A significant positive trend for autumn appears in eastern mainland. Negative trends in summer are associated with a decrease in frequency of moderate wet days, in maximal 1- and 5-day precipitation and in an increase in light precipitation. A negative annual trend is mainly caused by a decrease in frequency of very wet days and their contribution to the total precipitation. A positive autumn trend is associated with more very wet days and an increase of their contribution to the total precipitation as well as an increase in maximal 1- and 5-day precipitation. This study complements the existing analysis of five Croatian secular data series of extreme precipitation indices by involving the whole precipitation dataset since the mid-twentieth century and fills the gap present in the trend assessment of precipitation trends in Mediterranean and Europe.

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1 Introduction

Spatial variability in the sign, magnitude and seasonality of trends in precipitation extremes over Europe has been established in a number of studies focused on individual European countries and stations and on the Mediterranean region and Europe as a whole (e.g. Osborn et al. 2000; Frei and Schär 2001; Alpert et al. 2002; Klein Tank and Können 2003; Hundecha and Bárdossy 2005; Schmidli and Frei 2005; Moberg et al. 2006; Bartholy and Pongrácz 2007; Kyselý 2009; Łupikasza et al. 2010). The regional differences are caused by geographical position and circulation patterns and by modifications due to local factors (e.g. orography and distance from the sea). Croatia is located in the transition region between the continental climate of the Pannonian lowland of central Europe and the marine climate of the Adriatic Sea of the northern Mediterranean. The central part of the country, stretching over the Dinaric Alps, is characterized by the mountain climate (Zaninović et al. 2008). Precipitation in Croatia is generally the consequence of passing cyclones and related atmospheric fronts, within the general circulation of the atmosphere in the northern middle latitudes. Croatian littoral comes only in summer under the influence of the subtropical zone, as a result of the influence of the Azorean anticyclone. However, local factors (such as distance from the sea and extremely developed orography of the Dinarides) strongly modify precipitation amounts at local scale and cause spatially very different precipitation regimes. Annual precipitation totals vary on average from 300 mm over the southern Adriatic islands, 700 to 1,600 mm along the coast, 3,000 to 3,500 mm over the summits of the mountainous region and 1,000 to 1,500 mm in the north-western inland with a decrease

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to the eastern lowland (600 to 700 mm) (Zaninović et al. 2008). Besides large spatial variability, the region is also characterized by large temporal (seasonal) variability. The maritime annual course of precipitation, with monthly maximum in winter and minimum in summer, is a characteristic of the coastal and mountainous region close to the coast. In the inland, there exists continental annual course of precipitation with minimum in winter months and monthly maximum in the early summer and with the secondary one in November as a consequence of maritime influence. The rainiest period on the Adriatic and in the highlands is from November to May, while in inland, it is from April to June. Days with large daily precipitation amounts in inland occur more often during the summer as a result of short-term heavy precipitation, while in the mountainous areas and on the Adriatic, they occur more often during the cold part of the year and they are a result of long-lasting precipitation. Since the changes in precipitation are highly variable at regional scales, accurate analysis of regional and local precipitation temporal changes, with special emphasis on extremes, is necessary to improve the assessment of environmental and social impacts. To that end, one has to use data records from a dense observational network which in Croatia exists since the mid-twentieth century. This should enable the detection of possibly significant changes in the amount, frequency and intensity of extreme precipitation which influence both the flooding and the drought conditions.

A recent study of trends in the annual and seasonal precipitation amounts and in the indices of precipitation extremes in Croatia (Gajić-Čapka and Cindrić 2011) was based on secular precipitation data series from five meteorological stations that represent the main climate regions in Croatia. The results showed a downward trend in annual precipitation amounts since the beginning of the twentieth century throughout Croatia, which is in agreement with the drying trend observed across the Mediterranean (Lionello 2012). Though there is no evidence of major secular changes in precipitation extremes that are related to the high amounts of daily precipitation or to the frequency of moderate wet or very wet days over Croatia, it is argued that the reduction in annual amounts of precipitation can be attributed to a significant increase in the occurrence of dry days across Croatia and to an increase in the frequency of low-intensity rainy days. Therefore, the present study investigates changes in the frequency of precipitation days and the fraction of annual precipitation due to precipitation days as defined by high as well as low percentiles. The possible redistribution of the daily rainfall categories is of major interest for water management practices, particularly for water supply, flood impact and land use management, and soil erosion monitoring.

The results of the present study should be useful as a starting point in assessing the risk of climate change impacts on subregional scale, with consequences on adaptation and prevention planning in many socio-economic sectors, such as water resource management, agriculture, forestry, transportation, construction, civil defence, etc. The observed indices of precipitation extremes and related trends are also useful when validating the results of numerical regional climate models and, consequently, for understanding possible future trends. Recently, trend analysis in seasonal and annual, observed and modelled five indices of precipitation extremes over the Croatian Adriatic was deduced for the reference climate period 1961–1990 (Patarčić et al. 2014). The model results are validated against observations from meteorological stations to reveal possible model deficiencies and to determine the level of model's skill when used in future climate projections.

The paper is organized as follows: in the next section, the data and the applied methods are described; main results are given in the third section, while the final section is devoted to discussion and conclusions.

2 Data series and methods

A total of 137 daily precipitation series across Croatia were retrieved from the Meteorological and Hydrological Service of Croatia (DHMZ). To ensure the highest data availability, the most recent period 1961–2010 was selected for the analysis. The operational quality control has been carried out for all stations based on the standards recommended by WMO (Zaninović et al. 2008). Recently, Zahradníček et al. (2014) subjected the monthly precipitation series of the whole set of 137 stations to additional data quality control including two relative homogeneity tests (standard normal homogeneity test and Maronna and Yohai bivariate test). Possible breaks were detected at 26 stations. The metadata check has revealed that only five stations show the evidence of breaks (due to relocation or changes in observers), so these five stations were excluded from the analysis. The rest of the 132 series is retained and used to divide Croatia into seven regions (Fig. 1). The regions are obtained after considering stations' annual precipitation cycles (Fig. 2) and percentiles of daily precipitation amounts. The mean annual precipitation climate zones (Gajić-Čapka et al. 2003) and clustering of annual maximum daily precipitation amounts (Gajić-Čapka 2001) have also been taken into account. In addition, the selection of regions naturally acknowledges the stations' geographical positions and altitudes. The indication and description of the obtained precipitation regions are given in Table 1. The time series of selected indices (Table 2) were calculated for each station separately and averaged over corresponding regions. According to Klein Tank et al. (2009) averaging over all stations in an area will reduce the effect of natural variability and thus increase detection probability and lead to more robust conclusions. In addition, regional averaging may reduce or eliminate non-systematic inhomogeneities and puts less weight on individual stations resulting in trend estimates which are less affected by outliers.

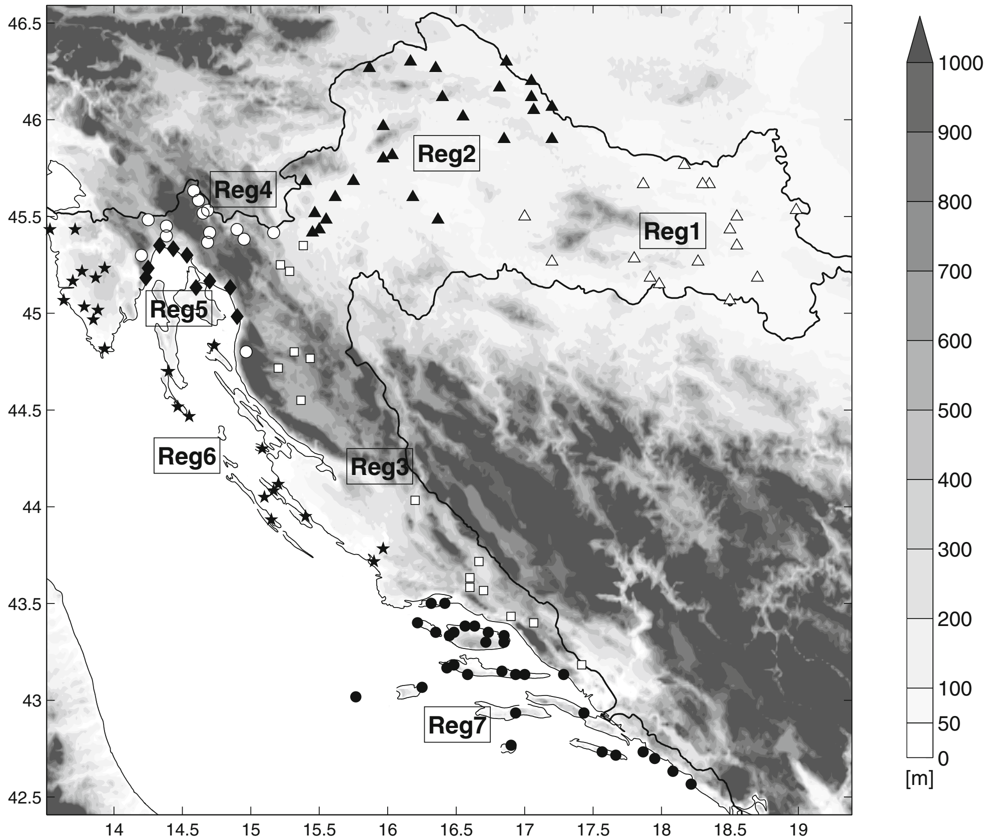

Fig. 1 Locations of the meteorological stations and regions mentioned in the text and Table 1. The orography is depicted in *shades of grey*

The analysis is performed on annual and seasonal precipitation totals as defined by climatological seasons: spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Ten precipitation indices are selected for the investigation of the intensity and frequency of extreme precipitation events and their contribution to the annual precipitation changes. Six of them are calculated following definitions given in Klein Tank and Können (2003) and in WMO (2004), and they are marked by an asterisk in Table 2. There are two main categories of precipitation 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 is based upon the percentile thresholds that were determined by sampling all the precipitation days (R_d≥1.0 mm) within the standard reference period 1961–1990. The selection of indices in this study is obtained following the previous study dealing with secular period for Croatia (Gajić-Čapka and Cindrić 2011). Four extra indices were defined to identify frequency of dry days and the fraction of annual precipitation due to daily amounts from three different percentile categories: less than the 25th percentile, between the 25th and 75th percentiles and above the 75th percentile (Table 2). They should give insight in temporal redistribution of daily precipitation over the whole range of the distribution and their contribution to the change of annual amounts.

When calculating the indices of precipitation extremes, the daily data series should not contain more than 10 % of missing data during a year (or season) and series with more than 20 % of missing or incomplete years in the analysed period should be excluded from the analyses (Klein Tank and Können 2003). A total of 132 stations in our analysis satisfied those criteria.

It is worth to note that the values of absolute extremes, such as the highest 5-day precipitation in a year (Rx5d), can often be related to extreme events that affect human society and the natural environment (Folland et al. 1999). The indices based on the number of days that reach percentile thresholds are less suitable for direct assessment of impacts. However, they 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).

Trends for each region and index are calculated from the associated averaged time series (see Table 1). The long-term annual and seasonal trends in precipitation extremes have been estimated by Kendall's tau method. The non-parametric Mann-Kendall test was applied to assess the statistical significance of trends at the 95 % confidence level (Gilbert 1987).

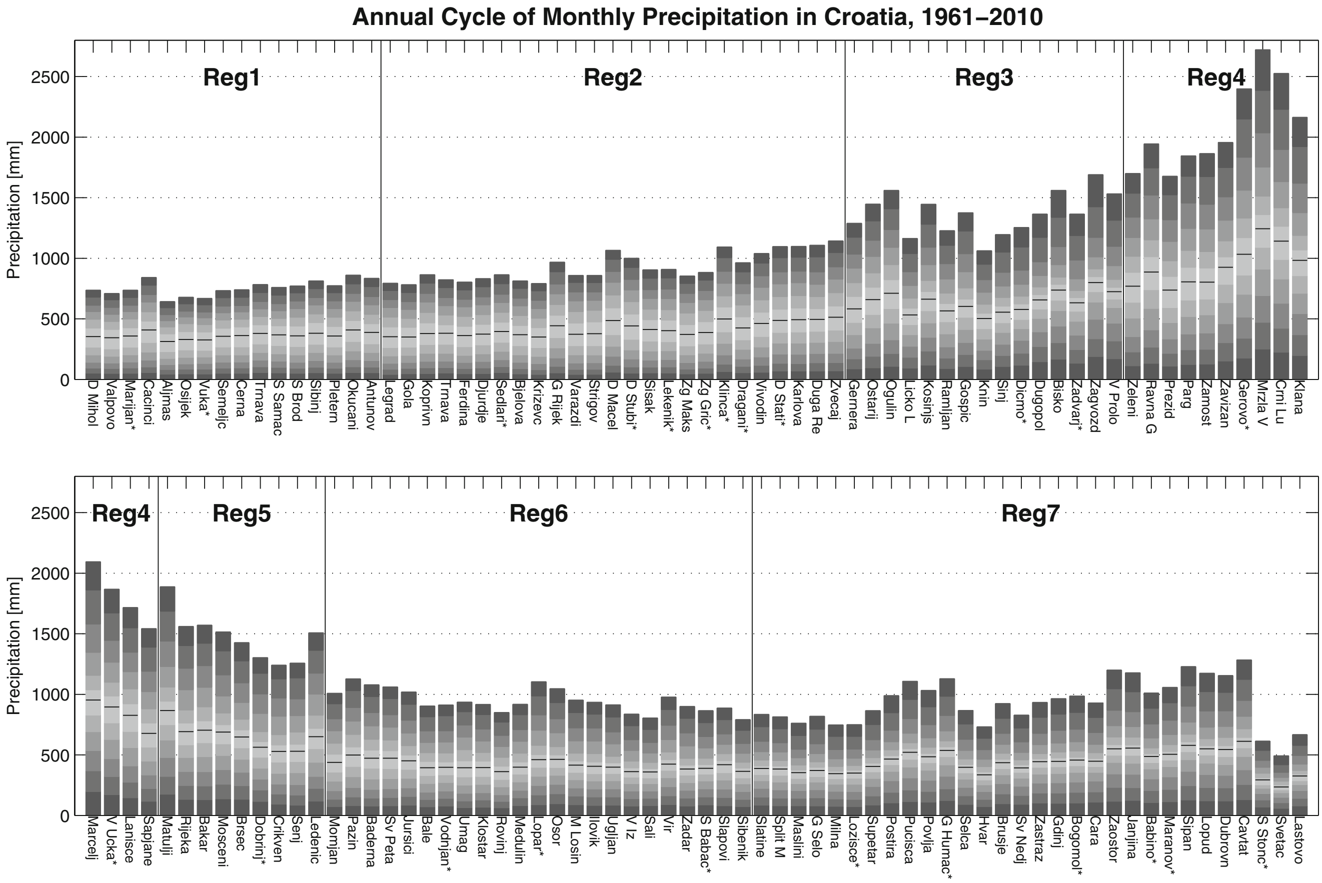

Fig. 2 Annual cycle of monthly precipitation (depicted in *shades of grey*) in Croatia, 1961–2010. *Shortened station names* correspond to names from Table A1 in Zahradníček et al. (2014). Stations with possible inhomogeneities which are not supported by metadata are denoted with an *asterisk*

3 Results

3.1 Precipitation indices in the period 1961–1990

In order to make the present analysis more tractable, Croatia is divided into seven regions according to their precipitation climate. Figure 2 depicts the annual cycles of mean monthly precipitation for the 132 stations used in the analysis. The stations are ordered starting with the most eastern region and ending with the most southern region (see also Table 1). The consistent monthly precipitation distribution within each region suggests that regions are reasonably defined. The continental, maritime and mountainous precipitation regimes are also clearly distinguished.

Table 1 List of precipitation regions in Croatia which are used in the analysis

Region	Description	Number of stations
Reg1	Eastern mainland	16
Reg2	Western mainland	25
Reg3	Central hinterland	15
Reg4	Mountainous region	14
Reg5	Mountainous littoral	9
Reg6	Northern Adriatic coastal region	23
Reg7	Central and Southern Adriatic coastal region	30

An overview of the average annual and seasonal values of regional precipitation amounts and 10 precipitation indices in the reference climate period 1961–1990 is given in Table 3. We note that annual mean values and sums of mean seasonal values of dry days (DD), R75, R95 and R as shown here are not exactly the same as corresponding sums of mean seasonal values. The differences primarily stem from the DJF values which take into account days in December from a year preceding the particular year for which the annual values are calculated.

General spatial and seasonal characteristics of precipitation over Croatia are described in Introduction section. The regional characteristics of dry conditions as defined by average number DD (Table 3) range between 240 (66 %—Reg4) and 286 (78 %—Reg7) days per year. Inter-seasonal differences are low and the largest ones are present in Reg3 and Reg7. For example, in Reg7, there are five dry days more in summer than in winter months. Seasonal maximum over eastern

Table 2 List of the indices and their definitions

No.	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	Standard daily intensity index (absolute extreme) (annual precipitation amount/ annual number of precipitation days, R_d≥1.0 mm)
3	*R75*	Days	Moderate wet days (percentile threshold) (number of days with precipitation $R_d > R_{75\ \%}$)
4	*R95*	Days	Very wet days (percentile threshold) (number of days with precipitation $R_d > R_{95\ \%}$)
5	R25T	%	Precipitation fraction due to days with $R_d < R_{25\ \%}$ (percentile threshold) (fraction of annual total precipitation $\Sigma R_d/R_t$, where the sum is taken over all days with $R_d < R_{25\ \%}$)
6	R25-75 T	%	Precipitation fraction due to days with $R_{25\ \%} \le R_d \le R_{75\ \%}$ (percentile threshold) (fraction of annual total precipitation $\Sigma R_d/R_t$, where the sum is taken over all days with $R_{25\ \%} \le R_d \le R_{75\ \%}$)
7	R75-95 T	%	Precipitation fraction due to days with $R_{75\ \%} < R_d \le R_{95\ \%}$ (percentile threshold) (fraction of annual total precipitation $\Sigma R_d/R_t$, where the sum is taken over all days with $R_{75\ \%} \le R_d \le R_{95\ \%}$)
8	*R95T*	%	Precipitation fraction due to very wet days (percentile threshold) (fraction of annual total precipitation $\Sigma R_d/R_t$, where the sum is taken over all days with $R_{95\ \%} < R_d$)
9	*Rx1d*	mm	Highest 1-day precipitation amount (absolute extreme) (maximum precipitation sums for 1-day intervals)
10	*Rx5d*	mm	Highest 5-day precipitation amount (absolute extreme) (maximum precipitation sums for 5-day intervals)

The symbol R_d (R_t) denotes daily (yearly) precipitation in the analysed period 1961–2010. The symbol $R_{x\%}$ (x=25, 75, 95) denotes the xth percentile of daily precipitation amounts for the 1961–1990 baseline period. Subset of the ETCCDI precipitation indices used in this study is set in italics

mainland Reg1 and western mainland Reg2 appears in SON, while over the other regions under the maritime influence, maxima occurs in JJA. Regarding the wet conditions, the average number of moderate wet days (R75, Table 3) appears in a relatively small range during the year. They are most frequent in the mountainous region Reg4 (31 days) and rarest at the coastal regions Reg6 and Reg7 (21 and 19 days, respectively), while over the other parts, they occur with a similar frequency of 24 and 25 days. Seasonally, the differences between mountainous and southern Adriatic regions are most pronounced during JJA. Such a pattern is influenced by the northerly shifted subtropical high pressure zone in summer, which brings drier and warm weather to the southern coastal region, while the northern coastal and mountainous regions are at its northern edge where more instabilities occur. Generally, moderate wet days are most frequent in MAM and DJF and they are prevalently related to cyclonic and frontal activity. The average annual number of very wet days (R95, Table 3) is similar over the whole country and ranges between 4 (along Adriatic coast, Reg6 and Reg7) and 6 days (in the mountainous region, Reg4). Very wet days occur on average 1 day during each season, with a slightly higher value (up to 1.7) in the mountainous region Reg4 during DJF and MAM. Relative contribution of moderate wet days to the annual precipitation (R75T) varies between 58 and 63 % over the country with the highest values in the mountainous region Reg4 and its littoral Reg5. Similar annual and seasonal pattern is observed for the fraction of the total annual precipitation due to very wet days (R95T), though it varies regionally in some smaller range (20 to 23 %) (Table 3). The annual characteristics of R75T and R95T are mainly due to the JJA and SON season distributions which are mainly the result of local instabilities causing heavy short-term rainfall during summer and early autumn. The contribution of moderate and very wet days to the annual amounts is compensated with the opposite spatial distribution of low-intensity wet days (R25T) and of wet days stemming from the middle part of the distribution of daily precipitation amounts (R25-75 T). Thus, the mountainous regions are characterized with the smallest contributions of those indices (Table 3). Average simple daily intensity index (SDII) has the lowest annual values in the eastern mainland Reg1 (7.5 mm/day) and western mainland Reg2 (9.2 mm/day), having seasonal maxima in JJA and minima in DJF. On the other hand, in the mountainous and coastal regions, maxima appear in SON and minima in MAM.

The 30-year annual mean of the highest 1-day precipitation (Rx1d) has the largest value in the mountainous region Reg4 and the lowest one in the eastern lowland Reg1. Seasonally, the heaviest amounts appear over mainland (Reg1 and Reg2) in JJA and over mountainous and coastal regions in SON, while the lowest mean values are found in DJF for Reg1 and Reg2 and in MAM for other regions.

With the highest 5-day precipitation amounts (Rx5d), annual and seasonal distribution by regions is similar to Rx1d except for the lowest values in mountainous and coastal regions which appear in JJA (Table 3).

3.2 Trends

The results of the seasonal long-term trends in the regional time series of precipitation indices for the period 1961–2010 are summarized in Table 4. They are expressed as absolute changes in the associated indices units per decade.

Table 3 Mean annual and seasonal precipitation indices (see definitions in Table 2) and precipitation amounts (*R*) for seven regions in Croatia from the reference period 1961–1990

Season	Region	DD (days)	SDII (mm/day)	R75 (days)	R95 (days)	R25T (%)	R25-75 T (%)	R75T (%)	R95T (%)	Rx1d (mm)	Rx5d (mm)	*R* (mm)
Year	Reg1	267.7	7.5	24.0	4.8	5.6	34.6	58.0	20.5	44.0	70.4	732.8
	Reg2	265.0	9.2	24.6	4.9	5.0	35.3	58.3	19.8	50.3	88.1	923.1
	Reg3	261.9	13.6	25.4	5.1	4.2	35.0	60.2	20.8	77.8	144.8	1,376.4
	Reg4	240.2	16.3	31.0	6.2	3.7	33.1	62.8	22.7	110.8	202.6	2,032.1
	Reg5	266.4	14.9	24.5	4.9	4.2	33.8	61.6	22.0	96.4	157.5	1,470.6
	Reg6	279.7	11.2	21.1	4.2	4.7	35.0	59.5	21.0	66.7	107.8	955.3
	Reg7	286.2	12.1	19.4	3.9	5.0	34.8	59.7	21.6	72.7	118.1	957.9
DJF	Reg1	65.3	6.0	6.1	1.2	7.3	38.1	51.6	15.5	20.8	39.8	156.2
	Reg2	66.8	7.5	5.8	1.2	6.2	38.2	53.4	16.4	25.5	47.4	178.8
	Reg3	61.0	13.2	7.3	1.4	5.2	38.8	55.3	17.2	52.0	102.1	392.8
	Reg4	58.5	16.5	7.9	1.6	4.2	35.4	59.8	19.7	73.6	144.1	523.8
	Reg5	64.7	14.4	6.3	1.3	5.3	38.7	55.5	17.0	54.8	103.2	377.8
	Reg6	66.6	10.2	5.9	1.2	5.8	38.1	55.1	17.2	37.9	67.8	244.8
	Reg7	64.3	11.6	6.4	1.3	6.6	39.4	53.5	17.2	45.4	84.2	311.6
MAM	Reg1	65.7	6.6	6.5	1.3	6.6	36.8	54.3	17.7	25.7	43.1	178.9
	Reg2	64.8	7.9	6.8	1.4	5.8	36.2	56.2	18.5	32.1	54.7	221.2
	Reg3	63.5	11.5	7.1	1.4	4.9	37.3	57.0	18.5	46.6	83.5	326.7
	Reg4	57.0	13.8	8.7	1.7	4.4	35.4	59.6	20.0	63.2	119.6	486.0
	Reg5	65.1	12.5	6.7	1.3	5.2	35.4	58.8	18.8	50.4	89.7	334.6
	Reg6	69.0	9.2	5.7	1.2	5.6	36.8	56.4	18.3	34.5	57.9	212.2
	Reg7	70.9	10.2	5.2	1.1	6.0	37.0	56.2	18.7	40.4	65.6	218.1
JJA	Reg1	67.8	9.5	6.0	1.2	5.0	35.3	58.4	19.1	39.5	61.4	231.3
	Reg2	65.7	10.5	6.5	1.3	5.1	37.0	56.9	18.2	41.4	70.9	278.1
	Reg3	71.9	12.3	5.0	1.0	4.7	36.0	58.5	20.3	49.7	74.9	247.6
	Reg4	63.6	14.1	7.1	1.4	4.0	34.5	60.9	21.3	64.4	104.3	400.7
	Reg5	71.0	13.2	5.2	1.1	4.5	35.2	59.6	20.5	57.1	87.4	280.2
	Reg6	75.8	11.4	4.0	0.8	5.2	37.1	56.8	18.6	41.9	61.2	187.3
	Reg7	81.2	11.4	2.7	0.5	6.3	37.0	55.6	17.3	39.7	53.1	127.3
SON	Reg1	69.4	7.7	5.3	1.1	6.0	37.3	54.9	17.9	28.0	46.1	168.8
	Reg2	68.2	10.7	5.7	1.1	5.0	37.5	56.4	17.8	38.8	69.5	247.0
	Reg3	66.1	16.6	6.2	1.2	4.3	37.2	58.0	17.9	64.7	119.1	414.8
	Reg4	61.5	21.1	7.3	1.5	3.5	34.8	61.3	20.6	96.9	175.4	621.6
	Reg5	66.1	19.3	6.2	1.2	4.1	35.5	60.1	20.4	84.3	138.4	480.1
	Reg6	69.1	14.0	5.4	1.1	4.9	38.0	56.5	18.5	56.0	92.0	310.9
	Reg7	70.6	14.7	5.1	1.0	5.0	36.9	57.8	18.8	57.2	94.9	301.3

Trends in annual and seasonal precipitation amounts give a general overview of the temporal change in precipitation over the country. During the recent 50-year period (1961–2010), the annual precipitation amounts (*R*) over the regions experienced a positive trend in the eastern mainland Reg1 and negative trends in all other regions, being statistically significant only in the mountainous region Reg4 (−50.6 mm/10 years). In summer, trends are negative in all regions but statistically significant in three of them: central hinterland Reg3 (−16.0 mm/10 years), the mountainous region Reg4 (−21.0 mm/10 years) and mountainous littoral Reg5 (−22.6 mm/10 years). In other seasons, decreasing trends also prevail, and an increase in precipitation amount is found only in autumn in the mainland of Croatia, being statistically significant in the most eastern part Reg1 (12.4 mm/10 years).

Annual and seasonal decadal trends in regional precipitation indices are also presented in Table 4. A tendency of increasing annual frequency of DD is seen all over the country. The most prominent increase (2–3 days/10 years) is found in the northern Adriatic region including the mountainous littoral (Reg6 and Reg5). The annual trend is forced by spring, summer and winter increase of dry days, while in autumn, a

Table 4 Decadal trends in annual and seasonal precipitation indices (see definitions in Table 2) and precipitation amounts (*R*) for seven regions in Croatia from the period 1961–2010

Season	Region	DD (days)	SDII (mm/day)	R75 (days)	R95 (days)	R25T (%)	R25-75 T (%)	R75T (%)	R95T (%)	Rx1d (mm)	Rx5d (mm)	*R* (mm)
Year	Reg1	0.2	0.1	0.5	0.4	−0.1	−0.7	0.9	1.1	−0.5	1.4	4.0
	Reg2	1.1	0.0	−0.2	0.2	0.1	−0.5	0.5	0.6	−0.7	−1.1	−8.2
	Reg3	1.5	−0.1	−0.5	−0.1	0.1	0.2	−0.2	−0.2	0.2	−0.9	−24.6
	Reg4	1.4	*−0.2*	−0.6	*−0.3*	0.1	0.4	−0.4	*−1.0*	*−3.6*	−3.6	*−50.6*
	Reg5	*2.6*	*0.3*	−0.1	0.2	*−0.2*	*−0.9*	*1.0*	1.0	0.6	3.5	−7.7
	Reg6	*2.0*	0.0	−0.6	−0.1	0.1	−0.3	0.2	−0.2	−1.2	−0.9	−24.7
	Reg7	1.9	−0.1	−0.6	−0.1	0.0	−0.1	0.1	0.5	−0.2	−0.1	−28.9
DJF	Reg1	0.8	0.0	−0.2	0.0	−0.2	−0.2	0.4	0.4	0.2	−0.6	−5.9
	Reg2	0.5	0.1	−0.1	0.1	0.0	−0.8	0.8	1.9	0.6	0.9	−1.2
	Reg3	0.6	0.2	−0.1	0.1	0.0	−0.8	1.1	1.5	1.5	1.9	−6.0
	Reg4	0.5	−0.1	0.0	0.0	0.0	−0.4	0.5	0.7	−1.2	−1.2	−7.9
	Reg5	0.8	*0.7*	0.1	0.2	−0.4	−1.9	*2.2*	*2.6*	3.4	3.6	2.9
	Reg6	0.7	0.1	−0.1	0.0	0.0	−0.7	0.7	0.2	−0.1	0.2	−5.9
	Reg7	0.9	−0.1	−0.2	0.0	0.2	−0.6	0.2	0.0	−0.6	−1.8	−15.5
MAM	Reg1	0.3	0.1	0.0	0.1	−0.2	−0.8	0.8	1.2	0.4	0.4	0.3
	Reg2	0.7	0.0	−0.2	0.0	0.1	−0.3	0.0	0.5	−0.4	0.4	−6.9
	Reg3	0.5	0.1	−0.1	0.1	0.0	0.0	−0.1	*1.4*	1.7	1.3	−3.0
	Reg4	1.1	−0.2	−0.5	−0.1	0.1	0.8	−0.8	−0.2	−1.1	−1.4	−17.9
	Reg5	1.3	0.5	−0.2	0.1	−0.2	−1.6	1.7	*2.4*	2.1	3.1	−4.6
	Reg6	1.0	0.1	*−0.3*	0.0	0.0	−0.4	0.4	1.5	0.9	0.1	−7.0
	Reg7	0.2	0.0	0.0	0.0	−0.1	0.0	−0.3	0.7	0.3	−0.2	0.0
JJA	Reg1	0.0	−0.2	0.0	−0.1	0.0	0.2	−0.3	−2.0	*−2.1*	−2.2	−2.9
	Reg2	0.2	−0.1	−0.1	−0.1	0.1	−0.2	0.2	−0.9	−0.9	−1.4	−2.7
	Reg3	0.8	*−0.4*	*−0.4*	−0.1	*0.4*	0.9	−1.6	−0.8	−1.8	−2.7	*−16.0*
	Reg4	0.9	−0.3	*−0.5*	−0.1	0.2	0.9	−1.0	−1.3	*−2.8*	−3.9	*−21.0*
	Reg5	*1.2*	−0.1	*−0.5*	−0.1	0.1	0.9	−1.2	−1.3	−3.3	*−5.2*	*−22.6*
	Reg6	0.5	−0.2	−0.3	−0.1	0.2	0.2	−0.7	−0.9	−1.2	−2.0	−10.8
	Reg7	0.6	−0.2	−0.2	0.0	0.2	0.7	−0.8	0.1	−0.7	−0.7	−7.1
SON	Reg1	−0.7	*0.3*	0.6	*0.2*	−0.3	−1.6	2.0	*2.6*	*1.5*	*3.7*	*12.4*
	Reg2	−0.6	0.0	0.2	0.1	0.1	−0.8	0.7	0.6	0.8	0.5	6.9
	Reg3	−0.7	−0.3	−0.1	−0.1	0.2	0.5	−0.7	−0.9	−1.2	−2.2	−3.6
	Reg4	−0.4	*−0.7*	−0.2	*−0.2*	*0.2*	*1.7*	*−1.8*	*−1.7*	*−5.0*	−5.3	−12.5
	Reg5	−0.1	0.1	0.0	0.0	−0.1	0.0	0.1	0.2	−1.0	1.8	4.0
	Reg6	−0.1	*−0.4*	−0.1	−0.1	*0.2*	0.3	−0.5	−0.6	−1.4	−1.2	−7.9
	Reg7	0.1	0.0	−0.1	0.0	0.1	−0.7	0.6	1.0	1.6	2.6	−1.4

Trends that are statistically significant at 95 % level are in italics

weak negative trend prevails. Positive trends are statistically significant only for spring (1.3 days/10 years) and summer (1.2 days/10 years) in the Reg5 region. Frequency of wet precipitation extremes (R75 and R95) shows a weak annual decrease in all regions along the coast and in the mountainous regions (Reg3–Reg7), while the mainland encounters positive trends. A statistically significant decrease (−0.3 days/10 years) in the number of very wet days (R95) is found only in the mountainous region (Reg4). The annual decrease in moderate wet days (R75) is mainly governed by a summer decrease in the mountainous regions and in the central hinterland (Reg3, Reg4 and Reg5) and by spring decrease in the northern Adriatic coastal region (Reg6). On the other hand, the significant annual decrease in R95 in Reg4 and increase in Reg1 are caused by the associated autumn trend patterns. Regional results for changes in SDII reveal negative trends in summer for all regions (significant in Reg3), while in other seasons, they are mixed in sign and significant only in a number of cases: in SON in Reg1 (positive), in Reg4 and Reg6 (negative); in DJF in Reg5 (positive); and on annual scale in

Reg4 (negative) and in Reg5 (positive). Trends in the intensity of precipitation for wet days, as measured by the SDII, reflect changes of trend magnitudes in annual (seasonal) amounts and also in annual (seasonal) number of wet days. For example, two stations in different regions (e.g. station Cerna in Reg1 and station Svetac in Reg7 depicted in Fig. 2) with the same negative sign of change in the frequency of R_d but with mutually different changes in R resulted in a similar significant increase in SDII (not shown). This shows that SDII is not suitable for explaining the causes of changes in R. Because of this, the trends in SDII should be used with care in applied studies.

Fraction of annual total precipitation was analysed for different classes of daily precipitation in order to find out possible redistribution of precipitation fraction over the full scale of daily precipitation categories. The trend patterns of R25T, R25-75 T, R75T and R95T indices are presented in Table 4. All of them reveal predominant insignificant trends of mixed sign by seasons and regions. Only some regions seem to be affected by significant trends in certain seasons: in MAM, contribution of precipitation from very wet days (R95T) is significant in Reg3 (1.4 %/10 years) and in Reg5 (2.4 %/10 years); in JJA, contribution of light precipitation (R25T) increased significantly in Reg3 (0.4 %/10 years) and in Reg5 (0.2 %/10 years); in SON in Reg4, significant positive trends are detected for R25T and R25-75 T and negative trends in R75T and R95T; increasing SON trends are also detected in Reg6 for R25T and in Reg1 for R95T; and in DJF, significant trends are present in Reg5 for R75T and R95T. On annual scale, significant trends are observed only in two regions: in Reg5 for R25T and R25-75 T (negative) and R75T (positive) as well as in Reg4 for R95T (negative).

The trends in mean highest 1-day (Rx1d) and 5-day (Rx5d) precipitation amounts calculated over regions are weak in magnitude. The exception is the mountainous region Reg4 for which the statistically significant decrease in Rx1d is apparent (−3.6 mm/10 years). Regarding their signs, trends are negative during JJA in all regions and in the mountainous region Reg4 for all seasons; otherwise, they are mixed in sign. In JJA, significant decreasing trends in Rx1d are detected in Reg1 and Reg4 and in Rx5d in Reg5. In SON, a significant negative trend is estimated for Rx1d in Reg4, but positive in Reg1 for indices Rx1d and Rx5d.

Some cases of regional time series with statistically significant trends are presented in Fig. 3: R and R75 for JJA and region Reg4, R95 for SON in Reg1 and Reg4, R95T for year and Reg4 and DD for year and Reg6.

4 Discussion and conclusions

In this study, annual and seasonal features in precipitation amounts and precipitation indices have been analysed for their regional characteristics over the geophysically complex area of Croatia. For the first time, daily precipitation data from a dense rain-gauge network of 132 stations have been used for calculation of average precipitation indices in the reference period 1961–1990 (Table 3) and for their trend analysis in the period 1961–2010 (Table 4). Besides the most commonly used indices of precipitation extremes (R75, R95, R75T, R95T, Rx1d, Rx5d, DD and SDII), additional precipitation indices (R25T, R25-75 T and R75T) have been analysed in order to obtain insight in the redistribution of daily precipitation amounts (see Table 2 for definitions).

First, the average spatial and temporal precipitation characteristics in the reference climate period 1961–1990 are given. The reference values are important in evaluating the intensity of the obtained trends, which are given as absolute values of the associated units.

The annual precipitation trends in Croatia during the recent 50-year period (1961–2010) are mainly negative, thus reflecting the characteristics of the Mediterranean regime. The most expressed seasonal negative trends are found in summer months (JJA), which are statistically significant in the mountainous region (Reg4), its littoral (Reg5) and central hinterland (Reg3) (see Table 1 and Fig. 1 for the definition of regions). A summer precipitation decrease in those regions is accompanied by the significantly less frequent moderate wet days (R75), by smaller maximum 1- and 5-day precipitation amounts (Rx1d, Rx5d), by greater contribution of light precipitation (R25T) and more DD.

However, the eastern mainland (Reg1), belonging to the very southern part of the Pannonian Plain, exhibits a weak positive (not significant) annual precipitation trend, more similar in central Europe. It is strongly influenced by the significant increase found in autumn precipitation amount due to the prominent increase in daily precipitation intensity (SDII) and then due to the increased number of very wet days and their contribution to the autumn totals (R95, R95T), as well as due to an increase in Rx1d and Rx5d.

Over the neighbouring northern area of Hungary, although the total precipitation decreased and the mean climate became slightly drier, strong positive trends in R95T, R75 and R95 were also detected for the last quarter of the twentieth century, indicating the increase of precipitation extremity (Bartholy and Pongrácz 2007).

The overall results of the trend analysis for the climatically complex area of Croatia show that although the detected trends in indices of precipitation extremes are mostly weak, there are regions exposed to more pronounced annual and seasonal changes. Particularly, the mountainous region in Croatia together with the coastal hinterland is mostly affected by drying tendencies in precipitation distribution, especially during summer season while the mainland is subjected to wetter precipitation conditions. These results confirm similar results obtained from the trend analysis of consecutive dry

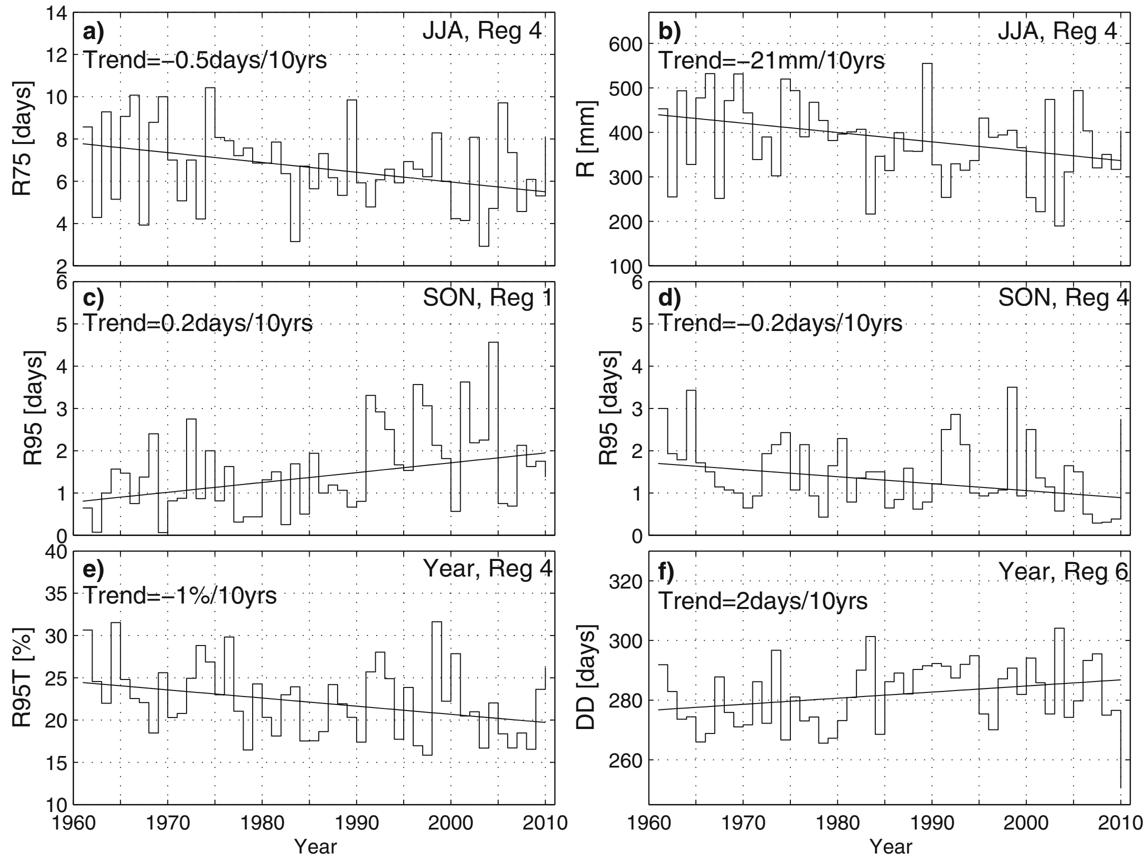

Fig. 3 Examples of regional time series with statistically significant trends. **a** R75 for JJA and region Reg4, **b** *R* for JJA and region Reg4, **c** *R95* for SON and region Reg1, **d** R95 for SON and region Reg4, **e** R95T for the whole year and region Reg4 and **f** DD for the whole year and region Reg6

days (CDD) in the study by Cindrić et al. (2010) though it was performed for a shorter period (1961–2000) and on a smaller number of stations (25). The same results are found further southward along the eastern Adriatic coast in Montenegro (Ducić et al. 2012).

Trends in the intensity of precipitation on wet days (SDII) involve changes in magnitudes both of precipitation itself and the number of wet days, which are tightly connected to each other. But it is hard to specify which one is the cause and which one is the consequence. Because of this, the SDII is in a way an “artificial” index for intensity and the trends in SDII should be used with care in applications.

For the western Mediterranean, different tendencies in precipitation extremes exist on regional and seasonal scales, both in sign and magnitude. The recent study for mainland Portugal (1941–2007) by de Lima et al. (2013) has shown that trends in annual precipitation indices are generally weak, but a decreasing trend is revealed by regional indices of total wet-day precipitation and extreme precipitation (above the 99th percentile). At the seasonal scale, statistically significant drying trends are found in spring together with a reduction in extremes (Santo et al. 2013), whereas in autumn, wetting trends are detected for all indices, although overall they are not significant at the 5 % level. Study for NE Spain (1951–2003) showed no general trends at a regional scale considering the annual or the seasonal regionally averaged series of precipitation indices; only a locally significant trend pattern was found, positive for CDD index and negative for Rx5d (Turco and Llasat 2011). In eastern Mediterranean (the Balkan Peninsula, western Turkey and Cyprus), the drying tendencies in total annual precipitation and the frequency and intensity of extreme precipitation are found during the second half of twentieth century (Kostopoulou and Jones 2005). However, Kioutsioukis et al. (2010) found for Greece that annual precipitation fraction due to very wet days exhibited increased variability and no clear trend.

Regarding the Mediterranean, which is considered to be the climate change “hot spot” because of projected intense summer drying and increased precipitation variability (Giorgi 2006), the obtained results should complete the lack of trend analysis in precipitation totals and precipitation extremes for the eastern Adriatic coast. In the northern part of the Mediterranean, there are a number of papers for the Iberian Peninsula, Italy and Greece (e.g. Ramos 2001; Alpert et al. 2002; Kostopoulou and Jones 2005; Millán et al. 2005; Brunetti et al. 2006; Rodrigo and Trigo 2007; Costa and Soares 2009; Kioutsioukis et al. 2010; López-Moreno et al. 2010; Gallego et al. 2011). Contrary to many middle to upper latitude regions of Europe in which positive trends in recent precipitation were identified, over the northern Mediterranean, a prevailing decreasing trend is present. However, because of high spatial variability of precipitation and results obtained from different datasets of varying densities and covering different periods, it is difficult to define clear regional and seasonal patterns in precipitation (Klein-Tank et al. 2002; Xoplaki et al. 2004; Brunetti et al. 2006; Norrant and Douguédroit 2006; De Luis et al. 2009; González-Hidalgo et al. 2010).

The present study complements the study of Gajić-Čapka and Cindrić (2011) on Croatian secular trends in precipitation extreme indices by calculating the trends in extreme precipitation from extended number of stations since the mid-twentieth century. The outcomes of this study supplement the knowledge about the temporal change in precipitation indices over the wider area of the northern Mediterranean. It fills the gap that is present in the assessment of precipitation trends in Mediterranean and Europe (see Fig. 1 in van den Besselar et al. 2012). Results obtained in our study are consistent with other studies and with the position of Croatia between the central Europe and Mediterranean regions where interaction between the atmosphere and complex local geophysical features may cause large spatial and temporal variations in the distribution of precipitation.

Due to regional differences, it is worth having fairly dense network of rain-gauge stations. Attention should be paid when analysing the global data networks for such areas. Using absolute trend values is favourable to assess their significance in applications, such as in the assessment of environmental and social impacts of climate change and also in the preparation of mitigation and adaptation strategies. In addition, absolute trend results are complemented with the average values of indices, thus providing the insight in relative changes, too. Finally, the results should also be important for validation of precipitation simulated by climate models (Branković et al. 2013).

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