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Changes in precipitation extremes in Romania

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ABSTRACT

Changes in daily extreme precipitation have been identified in many studies conducted at local, regional, or global scales. In Romania, little research on this issue has been done. The present study focuses on the analysis of the trends in daily extreme precipitation indices over a period of 53 years (1961–2013). Data sets of daily precipitation recorded in 34 weather stations were analyzed. Among them, three are located in the Carpathians and four on the Black Sea Coast. The main goal was to find out changes in extreme daily precipitation using a set of 13 indices adopted from the core indices developed by ETCCDMI adapted to suit to the studied area. The series of indices and their trends were generated using RClimDex software. The trends have been calculated by employing modified Mann–Kendall test and Sen's slope. Generally, the climate of Romania has become wetter over the 53-yr period considered, especially in the northern regions, although the spatial distribution of the significant trend slopes in the area is extremely irregular. Based on fixed threshold indices analysis, extreme precipitation events are characterized by a decreasing in the total number of precipitation days (R0.1), and a dominant increasing trend for the number of isolated days with moderate and heavy precipitation (R5, R10).

1. Introduction

During the last decades, recent and future climate change has attracted international attention and has become one of the most important topics in climatic research. Changes in temperature and precipitation and their impact have been studied worldwide. Regarding precipitation, scientists recorded an increase both in the magnitude, frequency and probability of extreme precipitation events (Sen Roy and Balling, 2004; Bengtsson and Rana, 2013; Wang et al., 2013; Du et al., 2014). Those events usually trigger, at local or regional scale, extreme hydrological events like floods, flash-floods or drought, with strong social and economic impact, especially in developing countries, implying serious damages on settlements and agriculture, the main source for income and subsistence in many cases (Alexandrov et al., 2006; Nandintsetseg et al., 2007; Toreti and Desiato, 2008; Choi et al., 2009; Dos Santos et al., 2011; Wang et al., 2012). Moreover, changes in precipitation have been considered as one of the most important topics in global climate change, due to concerns related to the negative impacts on natural vegetation and ecosystems, water supply and management, river discharges, as well as human welfare and regional political stability (Radinović and Ćurić, 2009; Estrela and Vargas, 2012; Capra et al., 2013; Wan et al., 2013).

Most of the existing studies investigated the changes in annual and seasonal precipitation rates, but recently, changes in extreme precipitation events expressed by different indices based on historical data or on simulations of the regional climate models (RCMs) outputs have become attractive in research. Some previous papers on extreme temperature and precipitation events have been at large scale, such as global or hemispheric (Frich et al., 2002; Alexander et al., 2006; Fang et al., 2008), mid-scale, as the European continent (Klein Tank and Können, 2003; Moberg et al., 2006) or at small/regional scale. In Europe, significant positive trends in annual precipitation extremes were detected in different regions (Brunetti et al., 2004; Ramos and Martínez-Casasnovas, 2006; Bartholy and Pongracz, 2007; Łupikasza et al., 2011). Some other papers focused on this topic over Eastern Europe, as it is a region that could be significantly impacted by possible future changes in rainfall, temperature and evaporation (Ivanova and Alexandrov,

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2012; Villarini, 2012). Some other studies conducted in Southeastern Europe considered the areal-accumulated convective precipitation. Ćurić and Janc (2011a,b) focused on this topic for a 15-year period over mountainous and flat land areas. They also performed comparisons between observations and three model samples. The statistical analysis shows that the model version most closely matches observations better for the flat land area (with a correlation coefficient of 0.94) than for the mountainous area (correlation coefficient is 0.89).

Generally, statistical tests have shown changes in precipitation indices that were consistent with a wetter climate. The results indicate that the widespread global warming and wetting detected in the last 50 years or so, is likely to be part of a much longer-term trend. Moreover, the evidence suggests complex changes in precipitation extremes that support a generally wetter world. Numerous studies reported increasing heavy precipitation trends in many regions of the world (Frich et al., 2002; Alexander et al., 2006; Fang et al., 2008).

Although in different areas of the world extreme precipitation were investigated in detail at larger or smaller scales, in Romania only a few studies have been conducted. Some previous studies focused on precipitation extremes, but they covered small areas (Croitoru, 2006; Bartholy and Pongracz, 2007) or considered very few indices (one to four) (Dragotă, 2006; Busuioc et al., 2010; Villarini, 2012).

Accepting the fact that extreme precipitation trends strongly depend both on the study period and on other climatic and non-climatic factors (global warming, changes in circulation patterns, changes in land cover, urbanization), an approach that considers the large spatial and temporal variability of precipitation in Romania is needed. The objective of this article is to provide an analysis of detected changes in precipitation extremes over the whole territory of Romania. The study aims at identifying if the weather is getting more extreme in terms of precipitation by determining the spatial and temporal variability of annual series trends in extreme precipitation indices over a period of 53 years by using 13 extreme precipitation indices.

2. Data and methods

2.1. Study area

Romania is located in Eastern Europe in a temperate climate in transition from western maritime climate to arid continental climate. The Carpathian Mountains divide the Romanian territory into two groups: intra-Carpathian regions and extra-Carpathian regions. The first group includes the areas located inside the mountain chain as well as those located westward from the mountains (the Transylvanian Depression and the Western Plain and Hills). The extra-Carpathians regions are located southward and eastward from the Carpathians (the Romanian Plain, the Moldavian and Dobrudja tablelands) (Fig. 1). From the climatic perspective, such a division mirrors the spatial variability in the climatic features of the two groups of regions: the first group is dominated by western moist air masses, while the second group is more influenced by the southern tropical or eastern continental air masses.

The studied area extends over more than 4° of latitude (between 43°40′ and 48°11′N) and 8° on longitude (between 22°39′ and 29°41′E). The topography of the area is very complex, including plains, hills, highlands, and mountains. The altitude ranges between 0 and 2544 m. Thus, dominant continental (eastern) conditions are more specific to Eastern Romania, while the southeastern region is particularly affected by the Black Sea maritime influences; the western regions are open to the air masses originated over the Atlantic Ocean. At the same time, southwestern Romania seems to receive the influence of the Mediterranean Sea weather conditions against those of the Black Sea (Sandu et al., 2008). Under these circumstances, in the intra-Carpathian regions, floods generated by heavy precipitation are quite common, whereas in extra-Carpathian areas, droughts are more frequent and stronger, but floods are not excluded.

In the present study, we investigated the specific regional behavior of the extreme precipitation in Romania and identified changes in different extreme precipitation indices. The annual amounts of precipitation generally decrease eastward, from more than 550 mm/yr in the Western Plain to less than 300 mm/yr along the northern half of the Black Sea coast. The amounts increase considerably with altitude, reaching up to 986 mm/yr at 2500 m in the Carpathians.

2.2. Data

2.2.1. Data description

Changes in precipitation extremes indices were identified by using daily precipitation time series recorded in 34 weather stations, which belong to the Romanian National Meteorological Administration network. Among them, one is located on a summit (34), two in the intra-Carpathian depressions (20, 21) and four on the Black Sea Coast (11, 19, 25, 28). All the other locations cover plain and hilly areas. The datasets cover a period of 53-years (1961–2013). The data sets recorded in eight locations (13, 16, 19, 24, 25, 27, 30, 33) were provided by the Romanian National Meteorology Administration (RNMA), while the rest of the series were freely downloaded from ECA&D project database (Klein Tank et al., 2002).

The weather stations used in the study benefit from a reasonable spatial coverage, including all types of topography and all climatic regions in Romania (Fig. 1, Table 1). Thus, the regional features in the variability of the precipitation extremes in Romania could be detected.

Table 1
Geographical coordinates of the weather stations considered.

Code	Weather station[a]	Latitude (N)	Longitude (E)	Elevation (m)	Region
1.	Arad	46°08′ 15″	21°21′13″	117	Intra-Carpathians West
2.	Bacau	46°31′ 54″	26°54′45″	184	Extra-Carpathians East
3.	Bistrita	47°08′ 56″	24°30′49″	367	Intra-Carpathians Center
4.	Botosani	47°44′ 08″	26°38′40″	161	Extra-Carpathians East
5.	Bucuresti Baneasa	44°31′00″	26°05′00″	90	Extra-Carpathians South
6.	Bucuresti Filaret	44°25′00″	26°06′00″	82	Extra-Carpathians South
7.	Buzau	45°07′ 57″	26°51′05″	97	Extra-Carpathians South
8.	Calarasi	44°12′ 22″	27°20′18″	19	Extra-Carpathians South
9.	Caransebes	45°25′ 01″	22°13′30″	21	Intra-Carpathians West

Table 1 (*continued*)

Code	Weather station[a]	Latitude (N)	Longitude (E)	Elevation (m)	Region
10.	Cluj-Napoca	46°46′ 39″	23°34′17″	410	Intra-Carpathians Center
11.	Constanta	44°12′ 49″	28°38′ 41″	13	Extra-Carpathians East
12.	Craiova	44°18′ 36″	23°52′ 00″	192	Extra-Carpathians South
13.	Dej	47°07′ 40″	23°53′ 56″	232	Intra-Carpathians Center
14.	Deva	45°51′ 52″	22°53′ 55″	230	Intra-Carpathians Center
15.	Drobeta Turnu Severin	44°37′ 43″	22°37′ 33″	77	Extra-Carpathians South
16.	Dumbraveni	46°13′ 40″	24°35′ 29″	318	Intra-Carpathians Center
17.	Galati	45°28′ 23″	28°01′ 56″	71	Extra-Carpathians East
18.	Iasi	47°10′ 15″	27°37′ 42″	102	Extra-Carpathians East
19.	Mangalia	43°48′ 58″	28°35′ 14″	7	Extra-Carpathians East
20.	Miercurea Ciuc	46°22′ 16″	25°46′ 21″	661	Carpathians-depression
21.	Ocna Sugatag	47°46′ 37″	23°56′ 25″	504	Carpathians-depression
22.	Ramnicu Valcea	45°05′ 19″	24°22′ 45″	239	Extra-Carpathians South
23.	Rosiori de Vede	44°06′ 26″	24°58′ 42″	102	Extra-Carpathians South
24.	Sebes	45°57′ 51″	23°32′ 29″	253	Intra-Carpathians Center
25.	Sfantu Gheorghe-delta	44°53′ 47″	29°35′ 56″	2	Extra-Carpathians East
26.	Sibiu	45°47′ 21″	24°05′ 28″	444	Intra-Carpathians Center
27.	Suceava	47°37′ 58″	26°14′ 25″	352	Extra-Carpathians East
28.	Sulina	45°02′ 26″	23°16′ 35″	3	Extra-Carpathians East
29.	Targu Jiu	45°02′ 26″	23°16′ 35″	203	Extra-Carpathians South
30.	Targu Mures	46°32′ 00″	24°32′ 01″	308	Intra-Carpathians Center
31.	Turnu Magurele	43°45′ 36″	24°52′ 41″	31	Extra-Carpathians South
32.	Tulcea	45°11′ 26″	28°49′ 26″	4	Extra-Carpathians East
33.	Turda	46°34′ 59″	23°47′ 28″	424	Intra-Carpathians Center
34.	Varful Omu	45°26′ 45″	25°27′ 24″	2504	Carpathians-summit

[a] Stations are ranged in alphabetical order.

The 53-year period (1961–2013) was chosen in order to avoid as much as possible inhomogeneities and gaps in the datasets that could be determined by some non-climatic factors, such as relocation of the weather stations, changing in the observation practice and timetable, interruptions during wars, changing the measurement devices etc. Since 1961, January 1st, the timetable has not been changed and only a few missing data were identified. Only weather stations with less than 5% missing data in the considered period have been selected in this study.

2.2.2. *Quality control*

Data quality control (QC) is a very necessary step prior to calculate the possible trends in any climatic data series. An exhaustive data quality control (QC) has been conducted as indices

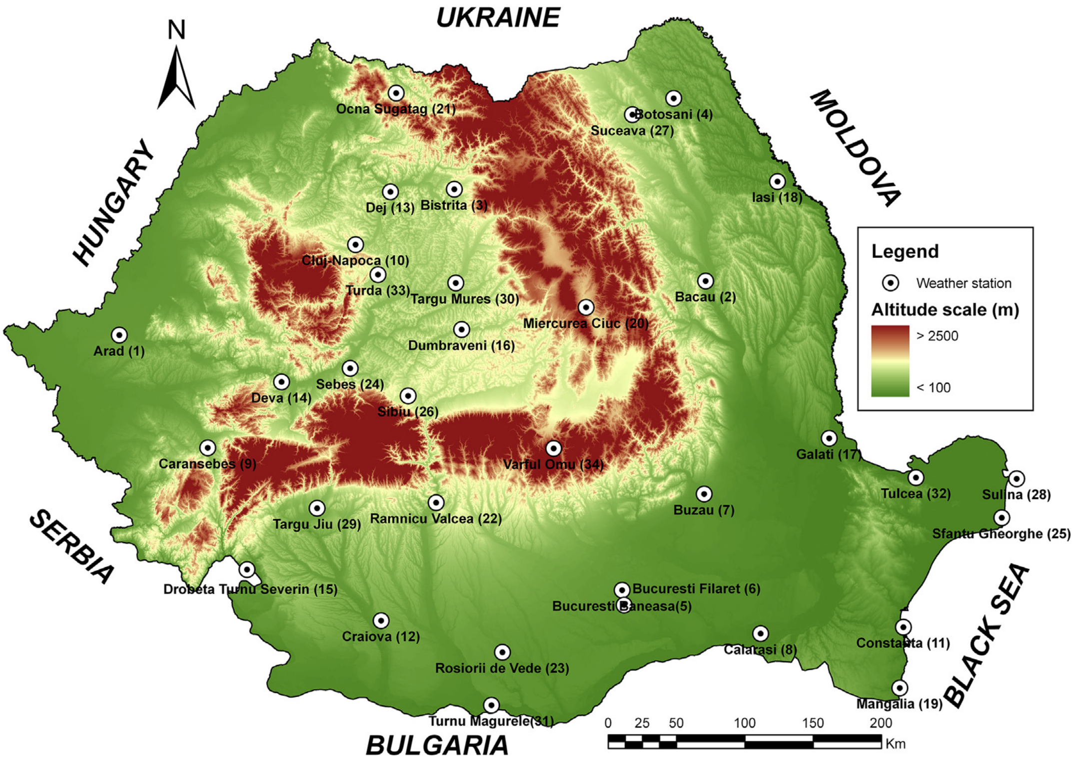

Fig. 1. Topography and the weather stations considered.

of extremes are sensitive to station relocation, exposure, equipment, and observation practice (Haylock et al., 2006; Dos Santos et al., 2011; Croitoru et al., 2013). We used the RHtests_dlyPrcp package (Wang and Feng, 2013) in order to test the datasets provided by the RNMA for QC and homogeneity. The application is developed in two steps: first, all missing values are replaced into an internal format that the software recognizes (i.e. NA, not available) and then all unreasonable values are replaced into NA (Dos Santos et al., 2011; Wang and Feng, 2013). Because of the large spatial and temporal variability of precipitation in the area under study, especially related to the extreme values, only one condition was retained for QC: all negative values of daily amounts of precipitation were rejected. The same method was used for QC of the data sets in ECA&D Project (Wang and Feng, 2013). The routine observation practices and timetable of the weather stations have not been changed since 1961, but some of the stations have been relocated during this period and almost all of them shifted from classical instruments to electronic measuring (i.e. automatic weather stations) in the early 2000s. Under these conditions, all primary data series were subject to the homogeneity control. They were checked by using RHtests_dlyPrcp package software (Wang and Feng, 2013) in order to detect possible changes potentially generated by the relocation or by the adoption of new measurement devices. Running the software, the series are evaluated by using the penalized maximal F (PMF) test (Wang, 2008). All the data series passed the QC test and the homogeneity test.

2.3. Methods

2.3.1. Precipitation extremes indices

It has long been accepted as part of a weather forecaster's task to predict the occurrence and severity of the extreme values of meteorological parameters (extreme weather events), but without any general agreement of the scale (Radinović and Ćurić, 2012). Because of the difficulty of this issue, in recent decades researchers defined extreme temperature and precipitation events in many ways. Relative definitions are a logical consequence of the need to define extremes within a local or regional context. What may be the norm in a tropical environment would possibly be very extreme in a moderate climate environment (Alexander et al., 2006). Although the scientific community in the field of climatology emphasizes using indices, the common opinion is that the more indices are used, the better and more reliable image of the changes in the extreme precipitation in a specified area (Croitoru et al., 2013).

In this paper, 13 indices on extreme precipitation were used (Table 2). Most of them (11) were selected from the list established by the climatic community (core ETCCDMI indices). The other two indices (R0.1 and R5) were added by the authors in order to complete the list. The lower precipitation indices are necessary because the drought phenomenon increasingly affects the lower regions of the country, which are also the most important for agriculture. The standard indices established by ETCCDMI have been used to assess changes in extreme precipitation in many different regions of the world (Hundecha and Bárdossy, 2005; Alexander et al., 2006; Moberg et al., 2006; Ramos and Martínez-Casasnovas, 2006; Bartholy and Pongracz, 2007; Choi et al., 2009; Costa and Soares, 2009; Kioutsioukis et al., 2010; López-Moreno et al., 2010; Fan et al., 2012).

Table 2
ETCCDMI precipitation-related extreme indices used for this study (after Zhang and Feng, 2004, completed).

No	Acronym	Name of the index	Description	Unit
1.	R0.1	Number of precipitation days	Annual number of days with more than 0.1 mm/day	days
2.	R5	Moderate precipitation days	Annual number of days with more than 5 mm/day	days
3.	R10	Heavy precipitation days	Annual number of days with more than 10 mm/day	days
4.	R20	Very heavy precipitation days	Annual number of days with more than 20 mm/day	days
5.	R30	Extremely heavy precipitation days	Annual number of days when precipitation ≥ 30 mm[a]	days
6.	CDD	Consecutive dry[b] days	Annual maximum number of consecutive days with RR <1 mm	days
7.	CWD	Consecutive wet[c] days	Annual maximum number of consecutive days with RR ≥1 mm	days
8.	R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
9.	R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
10.	Rx1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
11.	Rx5days	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
12.	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days in the year	mm
13.	PRCPTOT	Annual total wet-day precipitation	Annual total amount of precipitation cumulated in wet days	mm

[a] 30 mm was the threshold defined by the authors.
[b] Dry days are those days when the amount recorded was <1 mm.
[c] Wet days are those days when the amount recorded was ≥1 mm.

The indices have been used primarily for the assessment of several aspects in relation to the changing regional climate, including changes in the intensity and frequency of precipitation events. Thus, they can represent events that occur several times per season or year, giving them more robust statistical properties than simply measuring the extremes, which are far enough into the tails of the distribution so as not to be observed during some years (Alexander et al., 2006).

Some of the authors previously studying extreme precipitation based on indices classified them in different ways (Manton et al., 2001; Hundecha and Bárdossy, 2005; El Kenawy et al., 2011; Łupikasza et al., 2011). In this paper, the indices were grouped in three classes, based on their computation algorithm. Their definitions are presented in Table 2.

a. Indices based on fixed thresholds are those defined on a certain fixed threshold of recorded precipitation amounts and may vary according to the analyzed region (Hundecha and Bárdossy, 2005). This is a frequency-defining category of indices, as they express changes in the annual number of days. They are appropriate especially for detailed spatial scales and are very sensitive when changing the region. Seven fixed threshold defined indicators were employed: precipitation days (R0.1), moderate precipitation days (R5), heavy precipitation days (R10), very heavy precipitation days (R20), extremely heavy precipitation days (R30), consecutive dry days (CDD) and consecutive wet days (CWD). The user-defined threshold of the extremely heavy precipitation days is 30 mm.
b. Indices based on station-related thresholds are those indices defined on a percentile-based threshold. Generally, they are

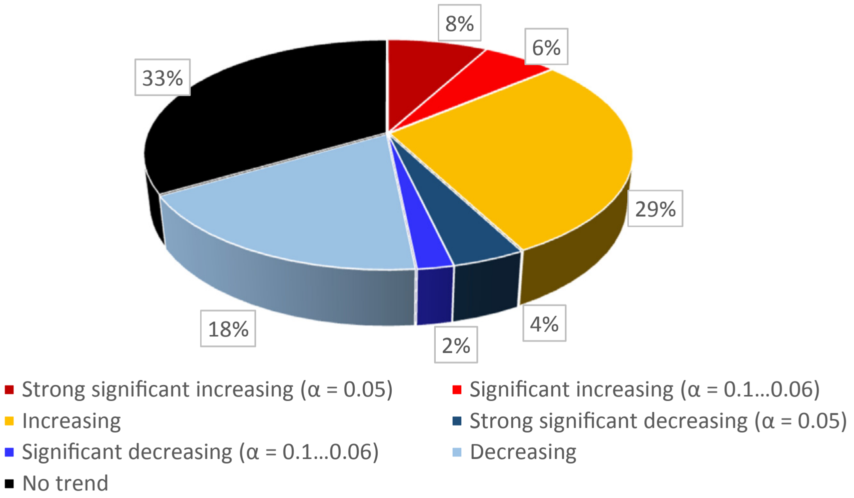

Fig. 2. Frequency of extreme precipitation indices trends.

defined as days surpassing the long-term percentiles (El Kenawy et al., 2011) and may be also considered an intensity-defining category. This is a commonly used method to determine the extreme values in climatology (Alexander et al., 2006; Solomon et al., 2007). They can be used for a wide variety of climates, their definitions are objective, site independent and facilitate direct comparison between different regions (Haylock, 2004; Choi et al., 2009). It is the smallest category in term of number of indices considered. Only two indices were analysed: very wet days (R95p) and extremely wet days (R99p), but the indices were calculated both for annual and monthly data series.

c. Non-threshold indices class includes indices computed by considering the absolute amounts of precipitation in a specific area. No threshold is considered. They are computed based on the monthly and annual absolute values of the precipitation recordings. They are intensity indices. This category of indices is very sensitive to the general climate of the area under study. At the same time, the use of these indices in comparing regions with different climates is restrictive. In this category, we included four indices: maximum 1-day precipitation amount (Rx1day), maximum five consecutive days precipitation amount (Rx5days), simple daily intensity index (SDII), and annual total wet-day precipitation (PRCPTOT).

The chosen indices provide a good combination of intensity (R95p, R99p, Rx1day, Rx5days, SDII, PRCPTOT) and frequency (R0.1, R5, R10, R20, R25, CDD, CWD) indices.

All the indices were calculated by employing RClimDex software (Zhang and Feng, 2004; Wang and Feng, 2010; R version, 2011) following the methodologies of Zhang and Feng (2004) and Haylock et al. (2006). The resulting series were analysed through their trends.

2.3.2. *Trends calculation*

To calculate the trends, 34 series for each index were considered. Although the Mann–Kendall is widely used to detect and estimate trends, in this paper we employed the modified Mann–Kendall test. Based on the nonparametric Mann–Kendall test for trends (Mann, 1945) and on the test statistic distribution (Kendall, 1975) this procedure allows testing non-linear trends and turning points. The null hypothesis in the Mann–Kendall test is that the data are independent and randomly ordered. Because the existence of positive autocorrelation in the data series constructed could increase the probability of detecting trends when actually, none exists, and vice versa, we decided to use the modified Mann–Kendall test (Hamed and Rao, 1998) in this study. Thus, we avoided autocorrelation, which could have affected the results. The scientific community accepted that its performance is better than that of the original Mann–Kendall trend test, and thus it is recommended for application to different climatic parameters such as temperature and rainfall (Hamed and Rao, 1998). Presently the method is used in studies conducted worldwide (Zhang et al., 2012, 2013, 2014; Furl et al., 2014; Huang et al., 2014; Ouarda et al., 2014; Croitoru and Minea, 2015; Tabari et al., 2015).

We used two statistical significance levels in this paper, because the statistical significance of precipitation trends is usually lower as compared to other climate elements due to its large spatial and temporal variability (Rapp, 2000; Łupikasza et al., 2011). In order to compare our results to those obtained for other regions in Europe, we considered both for $\alpha = 0.05$ as ‘strong significant changes’ and for $\alpha = 0.1 \ldots 0.06$ as ‘significant changes’.

3. Results

Changes in the indicators series in this chapter are presented first as a general issue and then in sub-sections according to their type: fixed threshold indices, station-related threshold indices and non-threshold indices.

3.1. *General changes in extreme precipitation based on all indices used*

Trends were calculated for each of the 13 indices datasets. The number of significant or strong significant slopes was expressed as a percentage of all examined series. As a general overview, increasing trends are the most frequent, with about 43% of the series, whereas series with negative slopes are about 25% of the total number of the analyzed series (Fig. 2), and 14% of all series were significant or strongly significant. In 8% of the series, we have detected strong significant increases, and only 6% of the slopes are significant. The same difference of about 2% was found between significant (2%) and strongly significant (4%) negative slopes. No change was detected in almost one third of the datasets (33%).

These results are in agreement with other studies that have previously asserted that increase in extreme precipitation indices is the most frequent class when averaged across the globe or regional scale (Frich et al., 2002; Kiktev et al., 2003; Alexander et al., 2006). Although most of the studies conducted in different regions concluded that precipitation indices have a less spatially coherent pattern of change (Alexander et al., 2006; Fan et al., 2012), in Romania, the great majority of both strong significant and significant decreasing trends have been recorded in the southern half of the country. The most significant and strong significant increasing changes have been detected in the northern half, as well as in southeastern Romania (Figs. 3–5).

Compared with changes in extreme temperature indices in Romania or in other mid-latitude regions (Alexander et al., 2006; Łupikasza et al., 2011; Croitoru and Piticar, 2013), the extreme precipitation indices have a lower level of statistical significance. The results are similar to those revealed for other regions in Central and Eastern Europe, where usually less than 20% of the trends were found significant ($\alpha = 0.1$) (Łupikasza et al., 2011).

In Table 3, a synthesis of the slopes calculation is presented. From the total number of the data series computed (442), we calculated the frequency of the positive, negative and stationary trends for each index. Then, we computed the percentage of those values from the total number of the series, because it is more relevant than the absolute values. The same statistics have been conducted for significant and strong significant positive and negative slopes. The ratio was calculated by taking into account the total number of data sets considered.

Table 3
Frequency of different trend types of extreme precipitation indices (%).

Indicator	Increasing			Decreasing			Stationary
	Total	Significant*	Strong significant**	Total	Significant	Strong significant	Total
Indices based on fixed thresholds							
R0.1	26.5	0.0	2.9	67.6	11.8	14.7	5.9
R5	47.1	0.0	8.8	26.5	0.0	5.9	26.5
R10	55.9	8.8	11.8	20.6	0.0	5.9	23.5
R20	35.3	17.6	8.8	2.9	0.0	2.9	61.8
R30	5.9	0.0	5.9	2.9	0.0	2.9	91.2
CDD	32.4	5.9	0.0	41.2	5.9	0.0	26.5
CWD	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Indices based on station-related thresholds							
R95p	64.7	8.8	14.7	35.3	0.0	5.9	0.0
R99p	17.6	2.9	8.8	0.0	0.0	0.0	82.4
Non-threshold indices							
Rx1day	64.7	0.0	8.8	35.3	5.9	0.0	0.0
Rx5day	70.6	8.8	11.8	29.4	2.9	2.9	0.0
SDII	67.6	11.8	17.6	14.7	0.0	5.9	17.6
PRCPTOT	61.8	11.8	2.9	38.2	0.0	5.9	0.0

$^{*}\alpha = 0.1 \ldots 0.06$; $^{**}\alpha = 0.05$.

3.2. Changes in the indices based on fixed thresholds

The analysis of the intensity indices in this category revealed that very low precipitation days (R0.1) are decreasing for more than half of the considered locations, and more than 26% are significant or even strongly significant (Table 3, Fig. 3a). The frequency of increasing trends in the moderate precipitation days (R5) covers almost 50% of the stations (Table 3, Fig. 3b), while in the case of indices based on higher thresholds, positive slopes are dominant only for R10 (almost 56%) (Fig. 3c). For R20, more than 60% of the locations experienced no change and almost 36% had positive slopes. 26% of the series had significant or strongly significant positive slopes (Table 3, Fig. 3d). For the R30 index, more than 90% of the series had no change and only about 6% of the series had strongly significant increasing trends (Table 3, Fig. 3e).

Most of the significant positive changes were recorded in the northern half of the country, while the great majority of the negative slopes, including the significant and strongly significant ones, were identified in the southern regions. Thus, according to those indices, the climate of Romania became wetter over the last decades, especially in the northern regions.

Comparing the significant and the strongly significant series, the strongly significant slopes are more frequent that those significant. Frich et al. (2002) and Kiktev et al. (2003) found significant increases in R10 for large areas in the second half of the 20th century. In Romania, the situation is quite similar to those identified in the large-scale studies. The highest slopes were recorded for R10, with more than one day/decade for significant values.

The two frequency indices in this category differ in behaviour: consecutive dry days (CDD) became less frequent in the 53-yr period in more than 40% of the locations and only a small number had statistical significance. Consecutive wet days (CWD) experienced no change in all locations. These results lead to the conclusion that extreme precipitation events are characterized by an increase in isolated days with higher precipitation (R10, R20, R30), rather than concentration in a longer period.

In terms of spatial variation of the slope magnitude in fixed threshold indices, at country level, we found out that the magnitude increases with reduced threshold. Thus, the highest values, both in positive and negative slopes, were calculated for the lower threshold indices (slopes ranged from −8.45 to 3.57 days/decade in case of R0.1), while for the higher fixed threshold indices (as R30), the slopes drop to −0.67 … 0.29 days/decade.

3.3. Changes in indices based on station-related thresholds

This category includes those indices defined on a percentile-based threshold. They are considered as days surpassing the long-term percentiles: 95 percentile (R95p) and 99 percentile (R99p). The two indices do not have similar behavior. Most of the R95p series are characterized by increasing slopes (64.7% of the locations). Among them, about 15% are strongly significant, while almost 9% have been found significant (Table 3, Fig. 4a). The spatial distribution of the trends is similar to that identified in case of fixed threshold indices: dominant increasing in the northern half of the country, and decreasing trends with higher frequency in the southern areas.

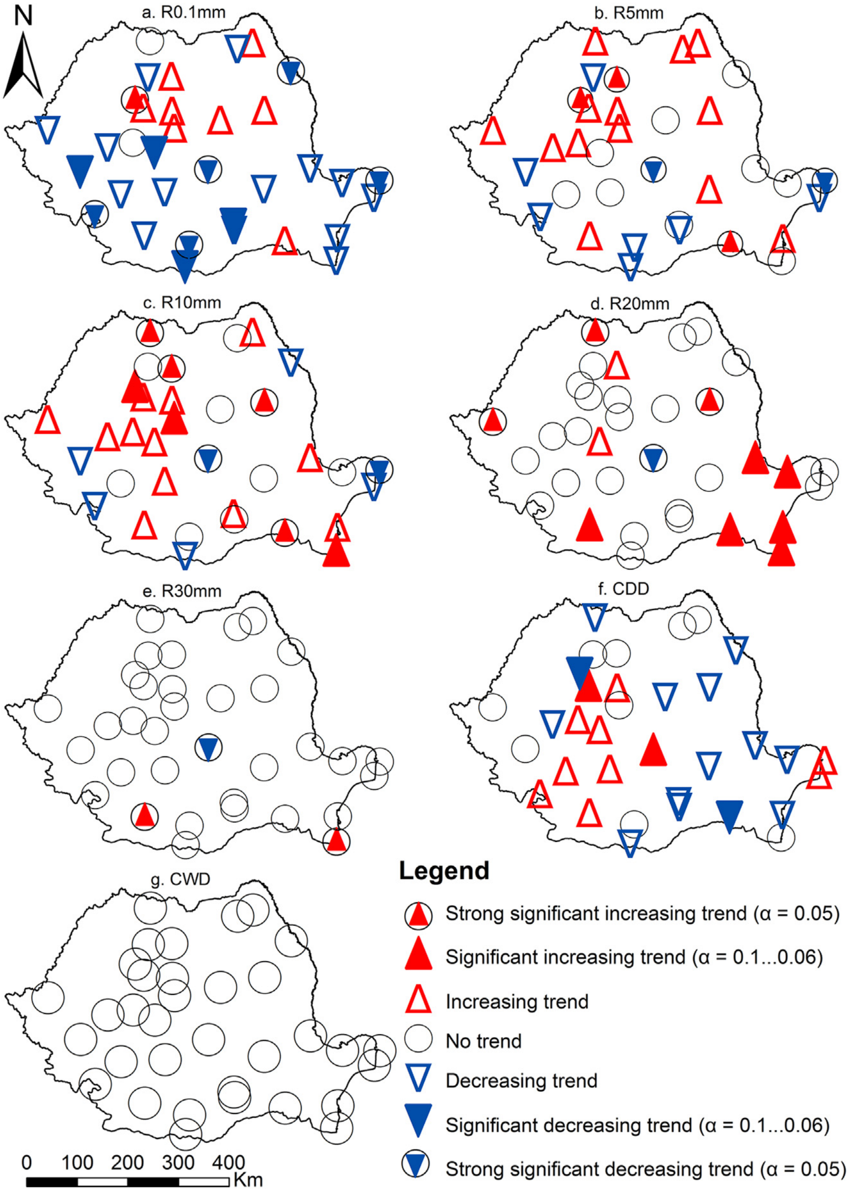

Fig. 3. Trends identified in indices based on fixed thresholds.

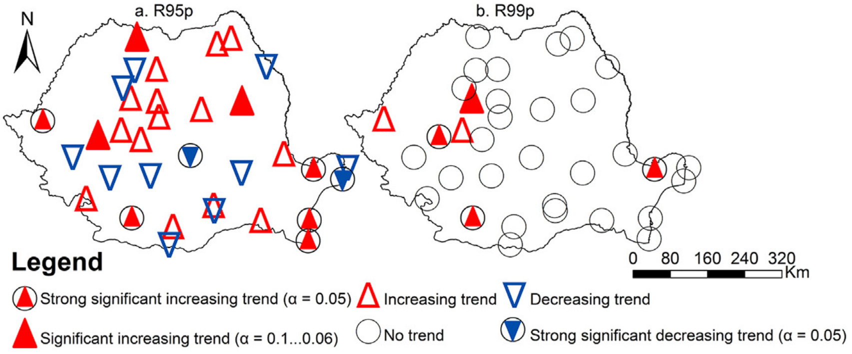

Fig. 4. Trends identified in indices based on station-related thresholds.

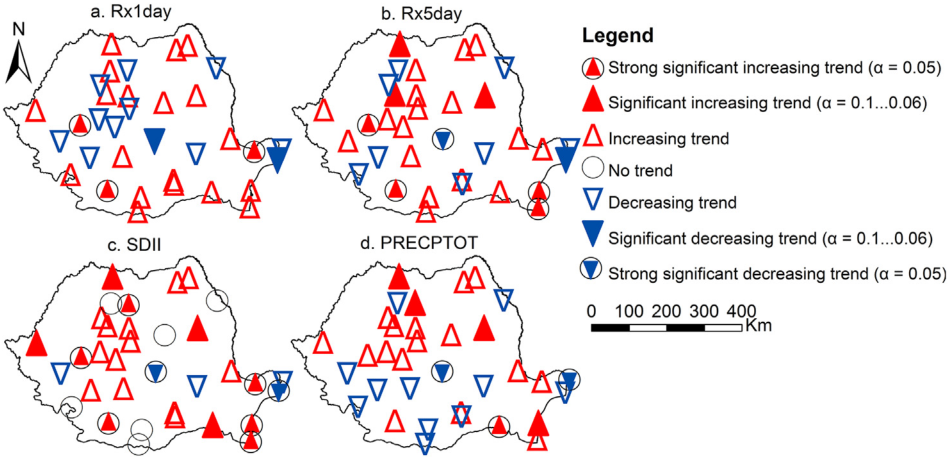

Fig. 5. Trends identified in non-thresholds indices.

Analysis of R99p index emphasizes that no trend was detected in the great majority of the locations under consideration (about 80%). All the other series are increasing and among them more than 11% are significant or strongly significant. They seem to be more concentrated in the central region of the country, but this cannot be assumed as a general rule (Table 3, Fig. 4b).

The rainfall amount in the very wet days (R95p) increased by 3.17 mm per decade, as an overall average for the whole country over the period 1961–2013. One can notice that the decreasing rate (between −0.3 and −38.0 mm/decade) suffered more variations than the increasing one (between 0.2 and 17.5 mm/decade) (Table 4). The intensity of the precipitation amounts increase in the extremely wet days (R99p) was lower compared to that of the very wet days. It varied from 0.00 mm to less than 9.00 mm/decade.

Table 4
Slopes of the extreme precipitation indices (slopes are computed per decade).

Location	R0.1	R5	R10	R20	R30	CDD	CDW	R95p	R99p	Rx1d	Rx5d	SDII	PRCPTOT
1.	−1.28	0.56	0.39	0.49**	0.00	0.00	0.00	11.72**	0.01	1.16	1.48	0.11*	12.97
2.	1.00	0.62	0.93**	0.47**	0.00	−1.00	0.00	13.04*	0.00	1.91	3.69*	0.16*	19.34*
3.	1.36	1.76**	1.18**	0.26	0.00	0.00	0.00	6.27	0.00	−0.76	2.41	0.14**	25.39*
4.	1.36	0.27	0.51	0.00	0.00	0.00	0.00	4.08	0.00	1.02	2.29	0.08	6.66
5.	−2.22*	0.00	0.32	0.00	0.00	−0.96	0.00	1.47	0.00	1.46	0.02	0.13	1.97
6.	−1.51	−0.38	0.00	0.00	0.00	−0.71	0.00	−1.39	0.00	0.88	−2.90	0.08	−7.46
7.	−0.50	0.46	0.00	0.00	0.00	−0.26	0.00	−5.56	0.00	−0.30	−1.42	−0.02	−2.05
8.	0.22	2.00**	1.06**	0.48*	0.00	−1.61*	0.00	9.91	0.00	2.35	3.91	0.19*	28.56**
9.	−3.08*	−0.91	−0.90	0.00	0.00	0.00	0.00	−4.14	0.00	−0.10	0.91	−0.05	−23.10
10.	3.57**	2.12**	0.91*	0.00	0.00	−0.97*	0.00	−0.29	0.00	−0.64	−0.31	0.07	19.60
11.	−1.03	0.53	0.38	0.27*	0.00	−0.63	0.00	14.80**	0.00	2.25	4.03**	0.32**	14.47*
12.	−1.18	0.71	0.50	0.43*	0.29**	0.63	0.00	17.51**	8.56**	3.67**	4.94**	0.31**	17.92
13.	−1.45	−0.22	0.00	0.00	0.00	0.00	0.00	−6.64	0.00	0.19	−0.90	0.00	−6.34
14.	−2.75	0.44	0.67	0.00	0.00	−0.51	0.00	10.29*	2.95**	2.41**	4.51**	0.17**	11.83
15.	−3.29**	−1.25	−0.43	0.00	0.00	0.62	0.00	5.26	0.00	0.29	−0.39	0.00	−10.17
16.	1.16	0.53	0.95*	0.00	0.00	0.00	0.00	6.01	0.00	−0.87	3.17	0.09	9.13
17.	−1.38	0.00	0.40	0.33*	0.00	−0.89	0.00	4.20	0.00	0.03	0.91	0.15	3.31
18.	−3.83**	0.00	−0.27	0.00	0.00	−0.86	0.00	−2.17	0.00	−0.82	−1.10	0.00	−9.55
19.	−0.33	0.00	0.56*	0.33*	0.25**	0.00	0.00	17.51**	0.00	3.00	5.42**	0.29**	13.80
20.	2.12	0.00	0.00	0.21	0.00	−0.29	0.00	7.81	0.00	0.52	1.95	0.00	2.86
21.	0.00	1.11	1.33**	0.56**	0.00	−0.42	0.00	12.63*	0.00	1.00	4.25*	0.13*	25.43*
22.	−1.05	0.00	0.28	0.00	0.00	0.61	0.00	−0.47	0.00	1.09	0.41	0.09	−1.29
23.	−3.67**	−0.74	0.00	0.00	0.00	0.00	0.00	2.56	0.00	0.41	0.62	0.00	−7.43
24.	0.00	0.31	0.33	0.00	0.00	0.80	0.00	5.04	0.10	−0.16	2.15	0.10	6.93
25.	−1.25	−0.83	−0.53	0.00	0.00	0.38	0.00	−10.96**	0.00	−2.81*	−4.13*	−0.27**	−15.86
26.	−2.00*	0.00	0.57	0.27	0.00	0.22	0.00	5.93	0.00	−0.22	0.49	0.11	5.46
27.	−1.25	0.37	0.00	0.00	0.00	0.00	0.00	6.14	0.00	0.63	1.59	0.04	4.75
28.	−5.26**	−0.83**	−0.62**	0.00	0.00	1.00	0.00	−4.48	0.00	−0.15	−1.67	−0.09	−15.87**
29.	−1.67	0.00	0.00	0.00	0.00	0.71	0.00	−1.60	0.00	−0.30	−2.76	0.05	−2.93
30.	0.49	0.32	0.40	0.00	0.00	0.32	0.00	0.17	0.00	0.44	0.36	0.06	5.85
31.	−2.69*	−0.72	−0.39	0.00	0.00	−0.50	0.00	−1.60	0.00	0.94	0.38	0.00	−8.71
32.	−1.25	0.00	0.00	0.40*	0.00	−0.71	0.00	17.23**	1.06**	3.25**	3.11	0.21**	9.16
33.	0.56	0.24	0.49	0.00	0.00	1.33*	0.00	5.64	3.22*	1.50	2.90*	0.06	2.00
34.	−8.45**	−5.16**	−3.64**	−1.54**	−0.67**	0.49*	0.00	−38.22**	0.00	−3.43*	−7.34**	−0.46**	−90.81**
Mean	−1.19	0.04	0.16	0.09	0.00	−0.09	0.00	3.17	0.47	0.58	0.97	0.07	4.14
Max.	3.57	2.12	1.33	0.56	0.29	1.33	0.00	17.51	8.56	3.67	5.42	0.32	28.56
Min.	−8.45	−5.16	−3.64	−1.54	−0.67	−1.61	0.00	−38.22	0.00	−3.43	−7.34	−0.46	−23.10

Note: ** is for $\alpha = 0.05$; * is for $\alpha = 0.1 \dots 0.06$.

Similar to other regions (Wong et al., 2011), the results indicate that the contribution of extreme rainfall events to the annual rainfall amount increased with time. They confirm the concentration of precipitation in single events or a higher concentration in shorter periods, which has been also reported in other regions in Europe (Ramos and Martínez-Casasnovas, 2006; Croitoru et al., 2013).

3.4. Changes in non-thresholds indices

This category consists of four indices, all being intensity-related indices. *Rx1day* and *Rx5days* are fixed-period indicators (one day and respectively, five consecutive days) and may be calculated for each month of the year. In this study, we kept only one value for each year (the highest amount recorded). The other two indices series (SDII and PRCPTOT) refer to cumulative values recorded in each year.

As a general remark, mainly increasing trends were detected in the time series of the non-thresholds indices (more than 66% of the total series considered for those indices) and about 10% experienced significant or strong significant change. In spatial distribution, 56% of the locations indicated similar evolution (increasing or decreasing trends) for all the four indices in this category, while 44% of the stations had different slope signs.

For maximum precipitation amount cumulated in one day (*Rx1day*), increasing trends were found in more than 64% of the locations considered. About 9% indicated strong significant changes. Decreasing trends are mainly statistically insignificant (Fig. 5a). The slopes varied between −3.5 and 3.5 mm/decade, with an average increase of less than 1 mm/decade for the whole country.

For the amount cumulated in five consecutive days (*Rx5days*), changes seem to be more consistent: the increasing trends were significant and strong significant in more than 20% of the locations (Fig. 5b). The decreases, both significant and strongly significant, did not exceed 6% of the series. The magnitude of the slopes ranged from −7.0 to 5.0 mm/decade (Table 4). The results are consistent to those projected by RCMs for Central and Eastern Europe (Beniston et al., 2007). The spatial distribution of this index reveals that most of the downwards trends are specific to southern locations, while upward trends are more specific in the northern half of the country, as for the R95p index.

The amount of precipitation calculated as wet day average (SDII) or cumulated amount during the year in wet days (PRCPTOT) are also increasing in Romania in 68% and respectively 62% of the locations, especially in northern regions (Fig. 5c and d, Table 3). In the southern half of the country, a combination of upward, downward, and no trends was detected (Fig. 5c, d). Statistically, about 35% and 15% respectively of the slopes were significant or strong significant, both increasing and decreasing. Decadal slopes in the SDII are in agreement with the results revealed at global scale by Kiktev et al. (2003) and Alexander et al. (2006). The slope magnitude varied between −0.50 and 0.30 mm/decade with a country overall average of 0.07 mm/decade.

The highest magnitude in case of PRCPTOT index was calculated for the summit weather station (34) located at 2500 m (−91 mm/decade). The other stations had much lower slopes, both negative and positive (−23.0 … 28.0 mm/decade).

4. Discussions and conclusions

This study aimed to investigate whether the climate in Romania is getting more extreme in terms of precipitation. Many results obtained suggest that the trends in the daily extreme weather variables are consistent with the observations made in the majority of the countries located in the Northern Hemisphere (Hundecha and Bárdossy, 2005).

This paper emphasizes the large spatial variability of trends in extreme precipitation indices for Romania. The analysis of the 13 indices, characterizing both wet and dry conditions, does not show a clear pattern of significant trends, but rather indicate different trend signals at local scale. Generally, decreasing trends are dominant in the southern regions, whereas increasing trends are more specific in the northern regions, but most of them are statistically insignificant. For some indices, a mixed pattern of increasing and decreasing trends is specific.

At global scale, as well as for Central, Southern or Eastern European regions, the analysis indicated mixed pattern of positive and negative changes for daily precipitation extremes (Easterling et al., 2000; Frich et al., 2002; Osborn and Hulme, 2002; Hundecha and Bárdossy, 2005; Schmidli and Frei, 2005; Ramos and Martínez-Casasnovas, 2006; Costa and Soares, 2009; Kysely, 2009; López-Moreno et al., 2010; Łupikasza et al., 2011; Ivanova and Alexandrov, 2012; Croitoru et al., 2013). This finding is common also for other regions (Caesar et al., 2011; Fan et al., 2012).

However, most of the trends detected are statistically insignificant, which is also a general feature at global scale (Alexander et al., 2006). Compared to extreme temperature indices calculated for the Romanian territory (Busuioc et al., 2010; Croitoru and Piticar, 2013, 2014), the spatial coherence of significant trends for precipitation indices is relatively low.

Generally, the climate of Romania has become wetter over the 53-yr period (1961–2013), especially in the northern regions, where the increasing trends are slowly dominant. One can conclude that the weather became “more” extreme in terms of precipitation magnitude and frequency, indicating consistent trends towards wetter conditions across most of the indices, even though the great majority are not statistically significant. These results are in agreement with the outputs of the most recent global and regional climate models simulations that project a general increasing trend for extreme precipitation events over Europe north of about 45°N (Frei et al., 2006; Kundzewicz et al., 2006).

Based on the annual values, the trends indicate more extreme rain days and increased contribution of extreme events to the total amount of precipitation. Thus, the highest frequency of strong significant changes was detected in the SDII index followed by R95p, R10, and Rx5day.

In Romania, analysis of extreme precipitation indices showed 9–29% of the considered locations have exhibited significant increases, depending on the index. The largest change detected over the 53-yr period is the significant or strongly significant increase in the SDII index at 29% of stations. Two indices showed dominant downward trends: R0.1 and CDD. Based on fixed threshold indices analysis, extreme precipitation events are characterized by a decrease in total number of precipitation days (R0.1) and an increase in isolated days with moderate and heavy precipitation (R5, R10), rather than concentrated in longer periods or in heavy and extreme heavy precipitation days (CWD, R20, R30). For the last three mentioned indices, no changes have been detected for the great majority of the locations considered.

The increase in frequency of occurrence and intensity of short-term moderate and heavy rainfall events could be attributed to climate warming that could enhance the surface evaporation and increase the moisture holding capacity in the atmosphere, resulting in higher chance of the occurrence of heavy rainfall events (Solomon et al., 2007; Archer and Rahmstorf, 2010; Wong et al., 2011). In addition, under warming conditions, the convective processes are expected to become more intense and the amount of precipitation generated by convective super-cells or simple cells to be higher. Such studies have been conducted both in Romania or in other regions in Eastern Europe (Ćurić and Janc, 2011a; Tudose et al., 2013) Also, special attention has been given to rainfall intensity–duration–frequency relationships (Gert et al., 1987; Koutsoyiannis et al., 1998; Trefry et al., 2000, 2005; Raiford et al., 2007; Okonkwo and Mbajiorgu, 2010). Some authors identified increasing precipitation as consequence of urban heat islands sources (Shepherd et al., 2002; Dixon and Mote, 2003; Mok et al., 2006; Wong et al., 2011), but we assume that in the analyzed area, urbanization is not an important factor because most of the significant and strong significant changes are more frequent in small locations rather than in large cities.

In Romania, the isolated high areas, as is the case of the mountain station Varfu Omu (located at 2504 m), seem to have significant or even strong significant decreasing trends for most indices (10 out of 13). Unfortunately, for this study, data from only one high altitude weather station were available, but in the future, another study with detailed investigation should be conducted to identify if this is a general feature of the high mountain area or it is specific only to that station.

Moreover, the high percentage of trends with the same direction within the individual regions (northern or southern) indicates the influence of large-scale drivers (atmospheric circulation) on the occurrence and the temporal changes of extreme precipitation (Łupikasza et al., 2011). These drivers are significantly modified, in general, by local factors as topography (by altitude, wind exposure, precipitation shadow, direction of mountain range), and determine the regional features. Thus, in Romania, in terms of extreme precipitation indices decreasing trends are dominant in the southern regions, whereas increasing trends are more specific to northern regions.

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