Extreme rainfall statistics in the Marche region, Italy

Luciano Soldini and Giovanna Darvini

ABSTRACT

A statistical analysis of the rainfalls is carried out for detecting a possible trend in the observed data. The rainfall dataset refers to the historical series collected in the hydrographic basins of the Marche region. On the one hand, the annual maximum daily, hourly and sub-hourly rainfalls have been analysed, on the other hand Climate Change Indices by Expert Team on Climate Change Detection and Indices (ETCCDI) (R1 mm, Rx1day, R20 mm, R95pTOT, PRCPTOT) have been computed to verify an eventual variation of the frequency of the rainfall regime in the Marche region. The time series, selected in the reference period 1951–2013, have been processed by using the non-parametric Mann–Kendall test. The results confirm that most of the series relating to the annual maximum rainfalls do not exhibit any trend. The absence of trend or the presence of negative trend prevail also in the analysis of the ETCCDI indices. The annual average anomalies of the same indices computed with respect to the climatological reference period 1961–1990 are negative since the mid-1980s, but they appear to show an increasing behaviour in the period 2009–2013.

Key words | central Italy, extreme rainfall, historical rainfall series, Mann–Kendall test, trend analysis

Luciano Soldini (corresponding author)
Giovanna Darvini
Department of Civil and Building Engineering and Architecture,
Università Politecnica delle Marche,
via Brecce Bianche,
Ancona I-60131,
Italy
E-mail: *l.soldini@univpm.it*

INTRODUCTION

Climate change is one of the most complex and critical challenges for the international community. An increase of extreme climate events (e.g., heat waves, sea level rise, heavy rainfall events) has been observed since about 1950 and some of these have been attributed to human influence (IPCC 2014). A problem of this type requires thorough analyses, as possible variations in rainfall and thermometric regime may have significant impacts on the availability of water resources, but also on the ecosystem and on human activity in general.

One of the most known and evident effect of the changes in climate is represented by a rise in temperature (IPCC 2014), while it is more difficult to individuate a well-defined signal in precipitations because of the complexity of the atmospheric circulation and the influence of the orography of different areas.

In recent years, several studies have been carried out at local and continental extent, mainly focused on the statistical analysis of annual, seasonal and extreme precipitations. Trend detection on large spatial scales has evidenced a significant increment in precipitation in northern and central Asia, North America and northern Europe. Conversely, a decrease in rainfall was observed in the Mediterranean area, southern Africa and southern Asia (IPCC 2007). However, in some areas of the Mediterranean, such as the central-western Mediterranean basin, Italy and Spain, an increase of heavy precipitation has been observed with a simultaneous decreasing trend in total precipitation (Alpert *et al.* 2002). This result is confirmed also by some local analysis for northern Italy (e.g., Brunetti *et al.* 2001).

In Italy, many other studies have been available regarding the trend detection in daily, seasonal and extreme rainfall. Brunetti *et al.* (2000) analysed some daily precipitation datasets of northern Italy. They found that the number of rainy days has a strong negative trend which is more significant than the corresponding precipitation amount and, as a consequence, the precipitation intensity has a positive trend. Similar results are also found in

doi: 10.2166/nh.2017.091

north-eastern Italy. In fact, the analysis of daily precipitation data by Brunetti *et al.* (2001) shows that the average annual number of wet days has a significant negative trend, mainly in spring and autumn. Moreover, a weak reduction in total precipitation indicates an increase in intensity which is not significant. In particular, extreme events exhibit a strong increase while non-extreme events exhibit a decreasing behaviour. For the annual maximum daily rainfall in the same region, Bovo *et al.* (2004) show the presence of positive and negative trends and seem to individuate a spatial pattern of the series affected by the trend.

In Tuscany, Caporali *et al.* (2014) analysed maximum annual daily rainfall and the maximum annual rainfalls of 1, 3, 6, 12 and 24 h duration recorded in 149 stations and showed a substantial absence of significant changes in precipitation regime, as only few changes were detectable near the coasts and in the north-west area. Increasing trends in some extreme events of 1, 3, 6, 12 and 24 h duration since the 1970s were also found by Crisci *et al.* (2002). Bartolini *et al.* (2014a) also found a slight increase of the extreme daily rainfall over the last two decades in central-southern Tuscany; conversely, in the northwest region, annual rainfall, extreme daily precipitation and the number of wet days exhibited a downward trend. Moreover, Bartolini *et al.* (2014b) also analysed changes in indices derived by daily and hourly data of two sites and detected a decrease of total rainfall and wet hours occurring in winter and spring, although an increase of hourly average rainfall was observed during wet hours.

In Sicily, the analysis of monthly rainfall by Cannarozzo *et al.* (2006) showed that significant negative trends are present in annual and winter data and only a few stations in summer months exhibit a positive trend. This result is confirmed by the analysis of the annual maximum rainfall events of 1, 3, 6, 12 and 24 h duration by Arnone *et al.* (2013). The authors conclude that only the rainfalls of short duration exhibit an increasing trend; conversely, the precipitation events of long duration are affected by a decreasing trend. The total annual precipitation is characterised by a significant negative trend, mainly in the winter season.

Besides the previously cited studies involving the Tuscany region, not many works are available for the detection of trend in the rainfall amount or frequency in central Italy. Recent studies on the time series of monthly precipitations from 40 rainfall stations located in Emilia-Romagna show a significant decreasing trend in the winter season during the 1960–1995 period (Tomozeiu *et al.* 2002) and an increasing trend with a systematic significant upward shift around 1962 in the summer time (Tomozeiu *et al.* 2000).

For the Marche region, an extended analysis was developed to define a regional model for estimating a design storm (Castellarin *et al.* 2005), but no explicit information about the rainfall statistics changes were provided. Appiotti *et al.* (2014) presented an integrated analysis of recent climate change by considering meteorological, oceanographic and river gauges during the period 1961–2009. The trend analysis of the annual and seasonal rainfall shows that total precipitation decreases for almost the entire year, except the autumn, influencing river flow change.

In the present study, a statistical analysis of rainfalls is carried out for detecting and quantifying changes in intense precipitation regime in the Marche region. The study analysed the historical series of annual maximum daily rainfall and annual maximum rainfalls for 1, 3, 6, 12 and 24 h, 15 and 30 minutes' duration from 1918 to 2013 at 156 stations. To define the temporal variability of precipitation, the time series of every station are analysed by using a non-parametric statistical test (Mann–Kendall) for detecting any significant trend. In addition, five ETCCDI Climate Change Indices (Rx1day, R1 mm, R20 mm, R95pTOT, PRCPTOT) have been computed to identify any variation in terms of intensity and frequency of the rainfall regime. Both the methodology of the analysis and the criteria for the selection of the dataset are detailed in the next sections.

METHODOLOGY

Trend detection

To detect any trend the time series of rainfall have been processed by using the non-parametric Mann–Kendall test (Mann 1945; Kendall 1975). This test does not require the data to be normally distributed and it is less influenced by the presence of outliers in the data. According to this test, the null hypothesis H_0 assumes that there is no trend (the data are independent and randomly ordered) and this is tested against the alternative hypothesis H_1, which assumes that there is a trend.

The computational procedure for the Mann–Kendall test considers the time series of n data points and y_i and y_j as two subsets of data where $i = 1,2,3,\ldots, n-1$ and $j = i+1, i+2, i+3, \ldots, n$. The data values are evaluated as an ordered time series. Each data value is compared with all subsequent data values. If a data value from a later time period is higher than a data value from an earlier time period, the statistic S is incremented by 1.

On the other hand, if the data value from a later time period is lower than a data value sampled earlier, S is decremented by 1. The net result of all such increments and decrements yields the final value of S.

The Mann–Kendall S statistic is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(y_j - y_i) \tag{1}$$

$$sign(y_j - y_i) = \begin{cases} 1 & \text{if } (y_j - y_i) > 0 \\ 0 & \text{if } (y_j - y_i) = 0 \\ -1 & \text{if } (y_j - y_i) < 0 \end{cases} \tag{2}$$

where y_j and y_i are the annual values in years j and i, $j > i$, respectively.

For $n \geq 10$, the statistic S is approximately normally distributed with zero mean and variance defined by:

$$\sigma^2 = \frac{n(n-1)(2n+5) + \sum_{i=1}^{g} t_i(i)(i-1)(2i+5)}{18} \tag{3}$$

in which t_i denotes the number of ties (equal observations) to extent i and g is the number of tied groups. The summation term in the numerator is used only if the data series contains tied values. The standard test statistic Z_S is calculated as follows:

$$Z_S = \begin{cases} \dfrac{S-1}{\sigma} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sigma} & \text{if } S < 0 \end{cases} \tag{4}$$

Positive Z_S values indicate an upward trend in the hydrologic time series; negative Z_S values indicate a negative trend. If $|Z_S| > Z_{1-\alpha/2}$, the hypothesis H_0 is rejected and a statistically significant trend exists in the hydrologic time series. The critical value of $Z_{1-\alpha/2}$ for a p-value of 0.05 from the standard normal table is 1.96.

In this analysis, significance level $\alpha = 0.01$, 0.05 and 0.1 were considered.

The magnitude of trends is given by the Sen's slope estimator determined, according to Theil (1950) and Sen's (1968) approach, by:

$$\beta = \text{Median}\left(\frac{y_{j-}y_l}{j-l}\right) \forall l < j \tag{5}$$

where y_l is the l-th observation antecedent to the j-th observation x_j.

ETCCDI indices

The joint CCl/CLIVAR/JCOMM ETCCDI has a mandate to address the need for the objective measurement and characterisation of climate variability and change. The team provides international coordination and collaboration on climate change detection and indices relevant to climate change detection, and encourages the comparison of modelled data and observations (Karl *et al.* 1999; Peterson *et al.* 2002; Peterson 2005; Klein Tank *et al.* 2009). The ETCCDI has recently revisited its definitions of indices by selecting some core indices (see http://etccdi.pacificclimate.org/list_27_indices.shtml). Some are based on fixed thresholds that are of relevance to particular applications, other indices are based on thresholds that vary from location to location. In these cases, thresholds are typically defined as a percentile of the relevant data series.

We have considered five indices, described in Table 1, based on daily precipitation amount. Each index has been computed on an annual basis.

R1 mm is defined as the number of so-called wet days, that is, the number of days with precipitation ≥1 mm, Rx1day is the maximum daily precipitation, defined conventionally as the rainfall cumulated between 9 a.m. of the day at which the measurement is attributed and 9 a.m.

Table 1 | Climate change indices (ETCCDI)

Acronym	Description	Unit
R1 mm	Annual count of days with precipitation ≥1 mm (wet days)	(days)
Rx1day	Annual maximum 1-day precipitation	(mm)
R20 mm	Annual count of days with precipitation ≥20 mm	(days)
R95pTOT	Annual total precipitation when the daily precipitation amount on a wet day *RR* > *RR95p*, where *RR95p* is the 95th percentile of precipitation on wet days in the 1961–1990 period	(mm)
PRCPTOT	Annual total precipitation	(mm)

of the previous day, and PRCPTOT is the annual total precipitation.

Anther two indices concerning extreme events are also considered, the very heavy precipitation days R20 mm (i.e., the number of days with precipitation ≥20 mm) and R95pTOT, defined as the total precipitation when the daily rainfall on a wet day is higher than the 95th percentile of precipitation on wet days in the reference period 1961–1990 specified by the World Meteorological Organization WMO (2011).

DATASET

The rainfall dataset refers to the historical series collected in the hydrographic basins of the Marche region, in Central Italy (Figure 1(a)). The Marche region extends over an area of 9,694 km^2. The main features are the Apennine chain along the internal boundary and an extensive system of hills descending towards the Adriatic Sea. With the exception of the southern part of the region, mountains do not exceed 2,000 m of altitude. The hilly area covers two-thirds of the region and is interrupted by wide gullies with numerous rivers and alluvial plains perpendicular to the principal chain. The coastal area is 172 km long and is relatively flat and straight except for two hilly areas in the northern and central parts of the region.

Rainfall data have been selected from the regional database of the Centro Funzionale Multirischi per la Meteorologia, l'Idrologia e la Sismologia. This institution has been responsible for the collection and management of regional meteorological data since 2002. The period of observation for the daily rainfall is the interval 1918–2013 and an overview of the recording rain gauges in this time is depicted in Figure 1(b). Grey pixels indicates working rain gauges, white pixels refer to not-working stations and

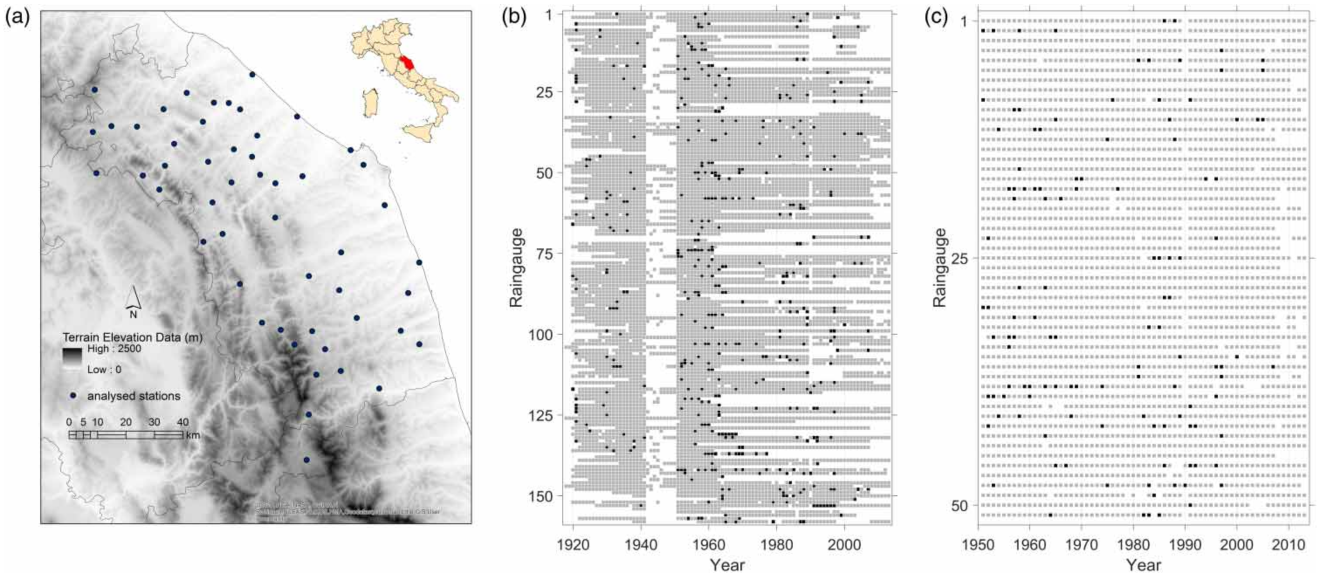

Figure 1 | (a) Study area and location of the analysed stations over the Marche region; working (grey), not-working (white) and intermittently recording (black) rain gauges; (b) all the rain gauges in the period 1918–2013; and (c) selected dataset in 1951–2013.

black pixels are used for intermittently recording rain gauges.

Since 2007 the monitoring network has been extended and modernised by turning conventional weather stations into remote meter reading stations. This operation has involved the outage of some stations and the lack of stationarity of certain data series of precipitations.

A preliminary analysis was made for identifying the time period with the highest number of running rain gauge stations. In order to identify the final dataset, the selection was based on two criteria. Stations must have recorded for more than 50 years (WMO 1988) and the total missing data could not be greater than 10%. Furthermore, for daily rainfall the number of missing data in the annual series had to be smaller than 10% of the length of the series (36 missing days maximum).

The selected time period is the interval 1951–2013, in which more than 50 rain gauges passed the adopted criteria (see Figure 1(c)). All the series refer to one basic common period with a length variable from 57 to 63 data. The choice of this period involved the elimination of the interval 1942–1949 in which most of the stations were not working, as shown in Figure 1(b). Furthermore, in the period 1951–2013, digital data useful for the computation of the ETCCDI indices are available.

The final subset is shown in Table 2 for the different types of analysed rainfall and indices.

The dataset counts 51 stations for the annual maximum daily rainfall with an average sample size of 59.7 years, as suggested for investigation of climate change by Kundzewicz & Robson (2000). The numbers of analysed stations for the PRCPTOT, R1 mm and R95pTOT indices are different because some data have been reconstructed during the validation phase of the series.

In comparison with the dataset of the daily rainfall, the number of stations selected for the analysis of the rainfall for 1, 3, 6, 12 and 24 h duration in the period of observation 1951–2013 drops to 23 with an average sample size of 59.8 data.

Unlike the daily and the annual maximum hourly rainfall, the period of observation for the precipitation of 15 and 30 minutes' duration, was identified in the interval 1990–2013 and the length of the series had to be greater than 20 years. The selection was required as only in this period are annual maximum data of rainfall of 15 and 30 minutes' duration available. It is well known that 20 years of records are not enough to draw any kind of conclusion on climate change. At the same time, a detection of any trend can be considered as a hypothesis of the existence of a tendency since those are the more recent available data for rainfall of sub-hourly duration. Thus, 48 stations were selected with an average sample size of 22.7 years.

Table 2 | Dataset selected for the analysis

Parameter name	Period	Number of analysed stations	Minimum sample size (years)	Average sample size (years)
Rx1day	1951–2013	51	57	59.7
PRCPTOT	1951–2013	54	57	60.2
R1 mm	1951–2013	52	57	59.9
R20 mm	1951–2013	51	57	59.6
R95pTOT	1951–2013	50	57	59.6
1, 3, 6, 12 and 24 h duration maximum annual rainfall	1951–2013	23	57	59.8
15–30 minutes' duration maximum annual rainfall	1990–2013	48	21	22.7

In spite of the advantage of the Mann–Kendall test, which has low sensitivity to abrupt breaks due to inhomogeneous time series (e.g., Jaagus 2006), the CUSUM and Pettitt (Pettitt 1979) tests were used to detect any inhomogeneity in the series of annual maximum daily rainfall. Among selected time series, six revealed the existence of change points in both tests. Considering both the difficulties and uncertainties in the detection of a possible break point in the time series and the absence of historical metadata for the involved rain gauge stations, the series have not been eliminated.

The application of statistical tests requires verification of the absence of serial correlations that may alter the outcome. This analysis was omitted for historical series consisting of only annual maximum values, as these data series are devoid of any correlation (Bovo *et al.* 2004).

For the series of daily rainfall, in the case of incomplete series different techniques may be applied to estimate missing data (e.g., Karl *et al.* 1995; Cannarozzo *et al.* 2006).

After the data check, in the selected dataset, missing values amount to less than 5% and are evenly distributed along the series without long periods of more consecutive years of missing data. Due to the exiguous number of missing data and considering that the substitution of an arbitrarily chosen value will likely give biased estimates of the trend, we have not replaced missing values. The presence of only a few not detected values in a record (less than about 5%) is not likely to affect the accuracy of the trend slope magnitude significantly (Helsel & Hirsch 2002).

Location of the 51 selected stations for the analysis of the annual maximum daily rainfall distributed over the whole region is reported in Figure 1(a). The spatial distribution over the whole region of the average value and the coefficient of variation of annual maximum daily rainfall with reference to the entire period of observation 1951–2013 is depicted in Figure 2. Rainfall data were spatially interpolated by means of inverse distance weighted (IDW) technique and the production of the maps was carried out by use of ArcGIS software. This technique has been largely used in the spatial interpolation of rainfall data over a wide region (Cannarozzo *et al.* 2006; Fatichi & Caporali 2009; Appiotti *et al.* 2014).

The average value of the annual maximum 1-day rainfall varies from 46 mm to 97 mm, the low values being registered in the central part of the region and the high values localised in the mountain areas. The coefficients of variation vary from 0.25 to 0.55 and the maximum variability is observed in the southern part of the region.

The Mann–Kendall test was applied to series of annual maximum precipitation with durations of 1 day, 1, 3, 6, 12 and 24 hours, 15 and 30 minutes and to the series of R1 mm, R20 mm, R95pTOT and PRCPTOT indices.

Besides the Mann–Kendall test, for these indices we also analysed the time series of the annual average anomalies computed over all the rain gauges from 1951 to 2013 in comparison with the normal value of the climatological reference period 1961–1990 recommended by the WMO (2011). For each index, a single time series of the anomalies representative of the Marche region was computed. This series was obtained by first calculating the annual values of the deviations of the index from the average value obtained in the climatological normal 1961–1990 period for each station and then calculating the arithmetic average of the anomalies of all stations year by year (Desiato *et al.* 2012).

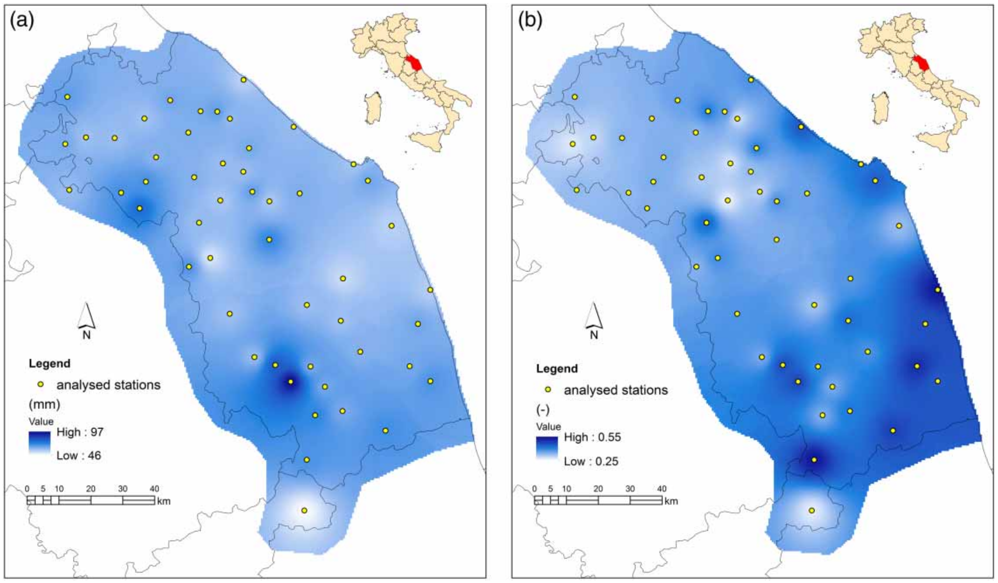

Figure 2 | Spatial distribution of the annual maximum daily rainfall in the period 1951–2013 over the region, reconstructed by IDW technique: (a) mean value and (b) coefficient of variation.

RESULTS

Analysis of the annual maximum rainfall

The results of the Mann–Kendall test applied to annual maximum rainfall for 1, 3, 6, 12 and 24 hours and 15 and 30 minutes are depicted in Figure 3(a) for the respective observation periods (Table 2). The graph provides the percentage of stations with a trend, positive or negative, or no trend for each duration and for a significance level $\alpha = 0.05$. Figure 3(a) shows that there is no trend in most of the analysed rain gauges. No stations have negative trend for the rainfall for 15 and 30 minutes and 6 h duration. In detail, for the rainfall of hourly duration, the percentage of stations with positive trend is non-null for durations greater than 3 h, while the percentage of stations with negative trend is 4.35% for 3, 12 and 24 h duration. There is no difference between results obtained for the 12 h and the 24 h duration. For the rainfall of sub-hourly duration, no stations exhibit a negative trend and the percentage of stations with positive trend is larger for the smaller duration. The latter finding should be regarded with caution because the average sample size are 22.7 data, as shown in Table 2.

Such conclusions are confirmed by increasing the significance level. The results obtained for $\alpha = 0.1$, here not reported, show that there is a general tendency of increasing the number of stations with positive trend, for the sub-hourly durations, whose percentage becomes twice as great. On the contrary, the number of rain gauges with negative trend increases for the precipitation of hourly duration.

No relevant results were obtained for the Mann–Kendall test with reference to the significance level $\alpha = 0.01$, since only the sub-hourly rainfall show a limited number of rain gauges with positive trend (three and two stations for 15 and 30 minutes, respectively).

Spatial distribution of the Mann–Kendall test results of the annual maximum rainfall for all the durations is illustrated in Figure 3(b)–3(h) for a significance level $\alpha = 0.05$. Triangles indicate stations exhibiting a trend. The upper or lower vertex of the triangles indicates positive or negative trend and the triangle size is proportional to the magnitude β of the trend given by Equation (5). The remaining stations do not exhibit statistically significant variation.

As already stated, the dataset used for the analysis of the rainfall with duration smaller than 1 h is different from that adopted for the larger durations. In the first case, the number of analysed stations is 48, while in the latter one it is 23. For this reason, while the percentage of the stations exhibiting a trend could be similar, the number of rain gauges showing a tendency for the rainfall of short duration could be twice the number of stations with a trend for the hourly precipitation.

For the rainfall with a duration of 15 and 30 minutes, stations exhibiting a variation show only a positive trend with larger values of magnitude β. In particular, for the 15 minute duration, the stations are distributed along the eastern band of the region. In the mountain areas, only two stations show a positive trend and are located in the northern part of the region. Similar outcomes along the eastern coastal band are obtained for the rainfall with 30 minutes' duration, while in the mountain areas only one station exhibits a positive trend in the south-west part of the region.

As the duration increases, the number of stations showing a tendency drastically reduces and no spatial behaviour can be observed. Only the rain gauge of Pioraco has a positive trend for the rainfall of 6, 12 and 24 h duration with a constant magnitude of the trend. As regards the decreasing trend, only the station of Diga di Carassai seems to show the existence of a reduction of the rainfall of hourly duration.

Analysis of the ETCCDI indices

Application of the Mann–Kendall test to the climate indices allows to individuate the existence of trend in the frequency and intensity of daily rainfall. The general results are reported in Figure 4(a), where the percentage of the stations with a positive or negative or no trend is provided for a significance level $\alpha = 0.05$. Most of the stations have no trend in their time series. When a trend is present it is negative and only for the two indices, R95pTOT and R1 mm, at some stations, has a positive trend been detected.

With reference to the annual maximum daily rainfall (Rx1day), a negative trend was detected at about 12% of the stations and no stations manifested a positive trend. This result is different from those obtained for the annual

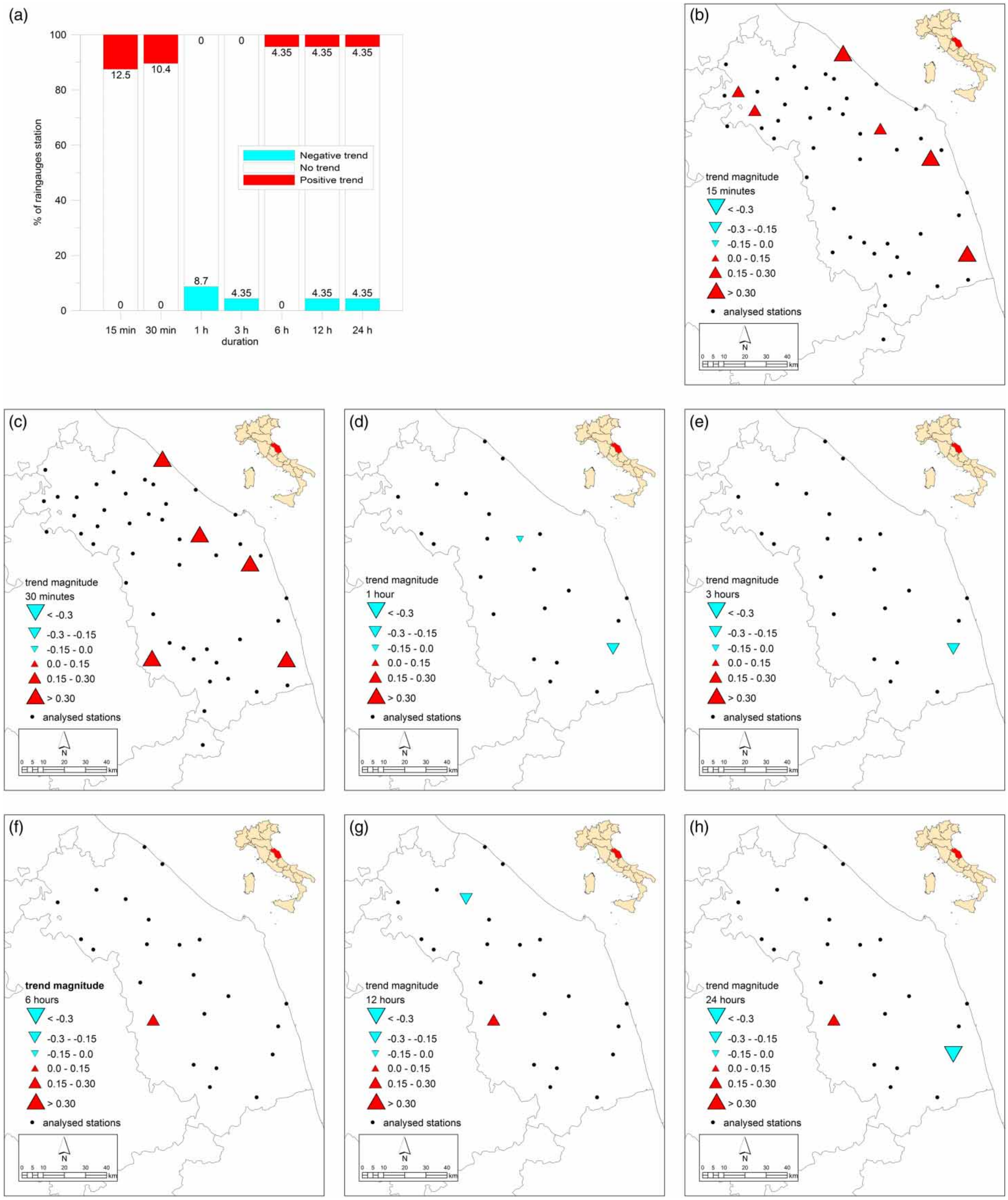

Figure 3 | Results of the Mann–Kendall test for maximum annual rainfall for 1, 3, 6, 12 and 24 hours and 15 and 30 minutes' duration for a significance level $\alpha = 0.05$. (a) Percentage of rain gauges showing a positive, negative and no trend; (b)–(h) spatial distribution of the trend sign and magnitude in the analysed stations exhibiting evidence of a tendency.

Figure 4 | Results of the analysis of ETCCDI indices. (a) Percentage of rain gauges showing a positive, negative and no trend according to the Mann–Kendall test for a significance level $\alpha = 0.05$. (b)–(f) Time series of the annual average anomalies for over the period 1951–2013 computed with respect to the average value of the climatological normal 1961–1990: (b) Rx1day, (c) R20 mm, (d) R95pTOT, (e) R1 mm and (f) PRCPTOT. Dashed lines represent the moving average computed over 9 years.

maximum rainfall of 24 hours. The explanation for this is that the statistics concerning the index were computed over 51 stations with the average size of the sample being 59.7 years, while the results of the maximum annual value of 24 hours' duration refer to 23 stations with an average sample size of 59.8 years. In addition, although the duration of the precipitation of the two time series is the same, the rainfall amount was computed during different time intervals, according to the definitions of the Italian Hydrographic Service. The index Rx1day considers the daily rainfall being defined as the precipitation falling between 9 a.m. and the same hour of the previous day, while the 24-hour maximum rainfall is the maximum value of the precipitations regardless of the initial time of the event.

The percentage of stations showing a negative trend is similar for R1 mm and R20 mm, while no station shows a positive trend for the annual number of rainfall events with precipitation ≥20 mm. Therefore, the frequency of the daily precipitation seems to reduce regardless of the rainfall intensity. This reduction of the wet days confirms the results obtained in most of the studies carried out in the Italian territory, in which the number of wet days in the year has a clear negative trend (Brunetti *et al.* 2001; Bartolini *et al.* 2014a).

As regards extreme precipitation, for the total annual amount in days with rainfall higher than 95th percentiles of the reference period (1961–1990), a negative trend was detected at about 22% of the stations, while 2% of the rain gauges manifested a positive trend. Therefore, for extreme events, the percentage of the stations in which no trend is observed reduces in comparison with the value observed for Rx1day, even if both cases of positive and negative trends increase and a general tendency cannot be defined.

Finally, a negative trend in the PRCPTOT was observed at 50% of the stations, which represents the most evident result from a quantitative point of view. Similar results were observed in the work of Appiotti *et al.* (2014), in which a negative trend of the annual total rainfall was detected over the period 1960–2009 in 35 of the 51 stations analysed with a percentage of about 68%. Seasonal data highlighted that the negative annual trend was driven mainly from the winter negative trend and no trend was detected in autumn in any station. An analogous conclusion may be attained throughout the Italian territory, in which a general decrease of the total precipitation was observed in northern regions (Brunetti *et al.* 2001) and an important reduction in annual rainfall was observed in Tuscany (Bartolini *et al.* 2014a) and Sicily (Cannarozzo *et al.* 2006; Arnone *et al.* 2013).

No particular differences were detected in the presence of trend by increasing the significance level from α = 0.01 to α = 0.10. All the analysed indices show that the percentage of rain gauges with any trend increases with the value of α, the greater gain being from α = 0.01 to α = 0.05. Data reported in Table 3 show that, in the case of global indices R1 mm and PRCPTOT, more than 50% of stations have a negative trend for α = 0.10. At the same time, the rain gauges with positive trend are practically negligible at any significance level.

Besides the detection of trend, the time series of the annual average anomalies of the ETCCDI indices was computed for all the analysed stations over the period 1951–2013 with respect to the normal value of the climatological reference period 1961–1990 recommended by the WMO (2011). Results, plotted in Figure 4(b)–4(f), show an irregular behaviour of the data oscillating between positive and negative values, therefore no evidence of either increasing or decreasing tendency could be extrapolated. In a global analysis, it could be considered a general prevalence of positive anomalies until 1980 for all ETCCDI indices except for R95pTOT, while negative values are prevalent in the last three decades. A particular result can be found for the maximum annual daily rainfall that has positive anomalies in the last 5 years (2009–2013), in which 2013 is the highest value over the entire period

Table 3 | Number of rain gauges with trend for climate change indices (ETCCDI)

Index	R1 mm			Rx1day			R20 mm		
Significance level α	**0.01**	**0.05**	**0.10**	**0.01**	**0.05**	**0.10**	**0.01**	**0.05**	**0.10**
Positive trend	0	2	2	0	0	0	0	0	1
Negative trend	6	19	26	1	6	10	13	19	21

Index	R95pTOT			PRCPTOT		
Significance level α	**0.01**	**0.05**	**0.10**	**0.01**	**0.05**	**0.10**
Positive trend	0	1	2	0	0	0
Negative trend	4	11	17	15	27	33

1951–2013. Moreover, the interval 2009–2013 is the longest one with positive anomalies of Rx1day. A certain prevalence of positive anomalies can be observed in the same years for other indices also.

Since no more results of particular evidence can be observed from the anomalies' values, the time series were interpolated by a moving average computed over 9 years to highlight their evolution over the reference period. Results are discussed below. It is evident that all the indices are characterised by a decreasing phase in the interval 1965–1974 and in the recent past from 1981 to the mid-1990s, while in the last decades the moving average of all indices has an alternate behaviour between increasing and decreasing tendency, although it assumes negative values.

Figure 4(b) shows that the anomalies of the maximum annual daily rainfall were decreasing initially from 1960 to 1975 and from 1981 to 1995. They start to increase in 1976 and become positive from 1977 to 1985; then, the anomalies of Rx1day have a stationary behaviour with negative values in 1994–2008, and only in the last years have they shown an increasing positive behaviour.

Results obtained for two indices referring to the extreme precipitation, R20 mm and R95pTOT, illustrated in Figure 4(c) and 4(d) are very similar. In both cases, the anomalies are characterised by decreasing tendencies in the 1960s and 1980s. The increasing period is from 1974 to 1980 and the moving average has positive values from 1976 to 1986 and then becomes negative. In the recent period 1999–2008, negative anomalies have become more negative and only since 2009 does there seem to be an increasing behaviour of the anomalies of both indices.

The results obtained for the rainy days of Figure 4(e) highlight a decrease of the anomalies from the 1965 to the mid-1990s and then a rising phase, still in progress. The more evident growth of positive anomalies of R1 mm is observed from 1959 to 1965.

Finally, Figure 4(f) shows that the moving average of the anomalies of the annual precipitation computed with respect to the climatological normal 1961–1990 is similar to that of extreme indices R20 mm and R95pTOT, with negative values of moving average from 1983 to 2013. In the last years, the anomalies of PRCPTOT seem to increase, as observed for the other indices. Similar results were observed in the work of Appiotti *et al.* (2014), in which the percentage anomaly was calculated with respect to the climatological normal 1971–2000. Their results show that the winter data of annual precipitation decreased from the decade 1960–1970 up to the period 1990–1999, while the decade 2000–2010 showed a certain precipitation recovery, except for the coastal areas and in the mountainous south-west part of the region. It is to be noted that the increase of the indices observed since 2009 seems to depend heavily on the values observed in 2013, which is a year of particularly intense and frequent rainfall and which was not considered by Appiotti *et al.* (2014).

To define the temporal and spatial evolution of the indices Rx1day, R1 mm and PRCPTOT, a spatial interpolation of the average values of the three indices was carried out by means of IDW technique for four reference periods of 30 years: 1951–1980, 1961–1990, 1971–2000, 1981–2010.

The map of the average values of the annual maximum daily rainfall in all considered periods, reported in the left column of Figure 5, shows that in the past the rainfall was distributed unevenly throughout the region and there is not an evident correlation between daily rainfall and the geographic location of the stations. As partial confirmation of this fact, the rain gauges with the maximum and minimum average values are both located in the southern Apennine area. By considering the development over the years, a progressive reduction of Rx1day is evident throughout the region, with particular reference to the maximum value: it varies from 100 mm in 1951–1980 to 89 mm in 1981–2010, while the variation of the minimum is less evident and not uniform with respect to the time and ranges between 43 mm and 47 mm. Therefore, the variation of Rx1day over the region tends progressively to reduce and the spatial distribution of Rx1day in the last 30-year period 1981–2010 (see Figure 5(j)) seems more uniform except for the extreme values located in a few stations of the mountain area. A similar result was obtained by computing the average value over the entire observation period, as illustrated in Figure 2(a). Finally, the reduction of Rx1day between two subsequent 30-year periods appears not to be constant in time; the more important variation is observed between the first two analysed 30-year periods and in the last years this effect is less noticeable.

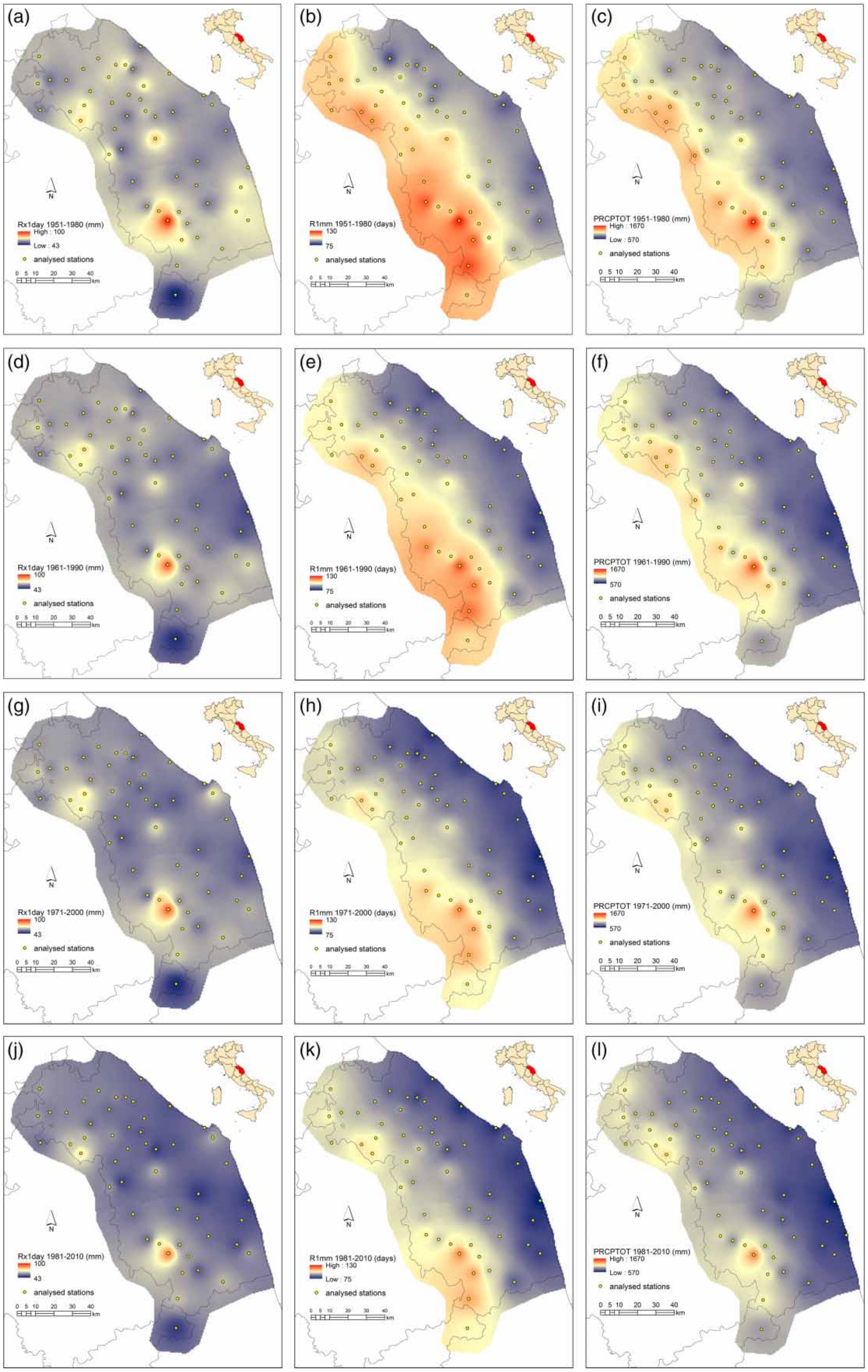

Figure 5 | Spatial distribution of the average value of the ETCCDI indices Rx1day (left column), R1 mm (middle column) and PRCPTOT (right column) during different four 30-year periods: (a)–(c) 1951–1980; (d)–(f) 1961–1990; (g)–(i) 1971–2000; (j)–(l) 1981–2010. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2017.091.

The central column of Figure 5 shows the map of the spatial distribution of rainy days (R1 mm). It can be observed that, as expected, the value of R1 mm reduces moving from mountain areas toward the coast, regardless of the 30-year period. The comparison among maps for a reference period of 30 years shows a generalised reduction of rainy days throughout the region. During the four 30-year periods, the maximum value reduces from about 131 to 117 days and the minimum one from 81 to 75 days. This means that both the maximum and minimum values reduce albeit to different extents and, as time goes on, the gap between the two extreme values tends to reduce and the distribution over the region becomes more uniform. Moreover, the reduction of R1 mm with time was more pronounced in the past and from the 30-year period 1971–2000 to 1981–2010 this effect appears to have stopped (see Figure 5(h) and 5(k)).

The results of the spatial and temporal evolution of the PRCPTOT index are illustrated in the right-hand column of Figure 5. The map of the average values confirms that the annual total precipitation is strongly dependent on the altitude. In all the 30-year periods, we can distinguish three bands corresponding to the mountainous, hilly and coastal areas, characterised by decreasing precipitation values. The maps confirm that the stations that have the highest PRCPTOT values are the same that exhibit the peaks of Rx1day and R1 mm indices.

As in the previous cases, PRCPTOT reduced from 1951–1980 to 1981–2010 and the reduction of the maximum values was larger than that of the minimum ones. The maximum value reduced from 1,670 mm to 1,415 mm, while the minimum changed from 736 mm to 570 mm. However, unlike the variation of the maximum values which seemed to be more gradual in time, the reduction of the minimum values seemed to increase in the last 30-year period.

Comparing the maps of the three indices, there is not an evident difference between the southern and northern coastal areas of the Marche region and thus no correlation can be identified between precipitation regime and latitude.

CONCLUSIONS

The statistical analysis of the annual maximum daily rainfall and those for a duration of 1, 3, 6, 12 and 24 hours, 15 and 30 minutes reveals that there is no clear evidence of the increase of these events.

The results of the Mann–Kendall test show that more than 91% of the analysed historical time series of hourly maximum precipitations do not have any trend. No stations have negative trend for the rainfall for 15 and 30 minutes' duration. The latter result, obtained in the period 1990–2013, could represent an indicator of maximum events' increase in the last years, although it could be influenced by the reduced dimension of the statistical sample (24 years). Anyway, there is not a preferential spatial distribution of the rain gauges with positive or negative trend over the Marche region.

The analysis of indices relevant to climate change detection confirmed that no increasing trend exists in the frequency and intensity of daily rainfall. On the contrary, the global indicators R1 mm and PRCPTOT have a negative trend for 36.5% and 50% of the analysed stations. Also, indices over a certain threshold (R20 mm and R95pTOT) have percentages of decreasing trend greater than 37% and 22% respectively. These results were partially confirmed by the time series of the annual anomalies of the same indices that are mainly characterised by negative values since about 1981. The behaviour of the moving average showed an increasing tendency for Rx1day in the interval 2009–2013, as confirmed by the positive values in the anomalies time series since 2009. However, this result could be influenced by the data measured in 2013, that are the highest of the time series in any rain gauge. Therefore, confirmation of the tendency should be considered with the last data acquisitions which are not available yet.

The temporal and spatial evolution of the indices Rx1day, R1 mm and PRCPTOT revealed a reduction of both maximum and minimum average values during the period of analysis; as a consequence, the present distribution of the data over the Marche region is more uniform. This variation is evident from 1951 to 2000, then the differences between average values of indices in the interval 1971–2000 and those calculated in the period 1981–2010 seem to reduce or be cancelled. Since the variations are negative, this result could be considered an indirect confirmation of the increasing tendency of the anomalies in the last years (2009–2013) observed for Rx1day, while there is not a direct correspondence between positive values of anomalies and reduced variations in the other two indices (R1 mm and PRCPTOT).

These results reveal that if there is no evidence of a positive trend of maximum annual rainfall events at regional scale, at the same time, a possible variation in the climatic indices is taking place. This aspect could have some consequences in the definition of the design storm. A specific analysis of the temporal evolution of the rainfall intensity-duration–frequency curves, due to variation of the maximum annual rainfall of the last years (2009–2013), could represent a possible development of the present work.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Maurizio Ferretti and all the staff of the 'Centro Funzionale Multirischi per la Meteorologia, l'Idrologia e la Sismologia' of the Marche region for collaboration in the dataset collation and the referees for their helpful criticisms and suggestions.

REFERENCES

Alpert, P., Ben-Gai, T., Baharad, A., Benjamini, Y., Yekutieli, D., Colacino, M., Diodato, L., Ramis, C., Homar, V., Romero, R., Michaelides, S. & Manes, A. 2002 The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. *Geophys. Res. Lett.* **29**, 1–31.

Appiotti, F., Kržélj, M., Russo, A., Ferretti, M., Bastianini, M. & Marincioni, F. 2014 A multidisciplinary study on the effects of climate change in the northern Adriatic Sea and the Marche region (central Italy). *Reg. Environ. Change* **14**, 2007–2024.

Arnone, E., Pumo, D., Viola, F., Noto, L. V. & La Loggia, G. 2013 Rainfall statistics changes in Sicily. *Hydrol. Earth Syst. Sci.* **17**, 2449–2458.

Bartolini, G., Messeri, A., Grifoni, D., Mannini, D. & Orlandini, S. 2014a Recent trends in seasonal and annual precipitation indices in Tuscany (Italy). *Theor. Appl. Climatol.* **118** (1), 147–157.

Bartolini, G., Grifoni, D., Torrigiani, T., Vallorani, R., Meneguzzo, F. & Gozzini, B. 2014b Precipitation changes from two long-term hourly datasets in Tuscany (Italy). *Int. J. Climatol.* **34** (15), 3977–3985.

Bovo, V., Gaetan, C. & Villi, V. 2004 Massimi annuali delle piogge giornaliere del triveneto (Annual maximum daily rainfall in the Triveneto). *L'Acqua* **5**, 19–27 (in Italian).

Brunetti, M., Buffoni, L., Maugeri, M. & Nanni, T. 2000 Precipitation intensity trends in northern Italy. *Int. J. Climatol.* **20**, 1017–1031.

Brunetti, M., Maugeri, M. & Nanni, T. 2001 Changes in total precipitation, rainy days and extreme events in Northeastern Italy. *Int. J. Climatol.* **21**, 861–871.

Cannarozzo, M., Noto, L. V. & Viola, F. 2006 Spatial distribution of rainfall trend in Sicily (1921–2000). *Phys. Chem. Earth* **31**, 1201–1211.

Caporali, E., Manetti, S., Chiarello, V. & Fatichi, S. 2014 Changes in precipitation regime in Tuscany Region (Italy). *Geophys. Res. Abstr.* **16**, EGU2014-15247-2.

Castellarin, A., Di Baldassarre, G., Brath, A. & Galeati, G. 2005 Legame sperimentale tra piovosità annuale e regime di frequenza degli estremi di precipitazione (A regional model for estimating the design storm in northern-central Italy). *L'Acqua* **3**, 9–22 (in Italian).

Crisci, A., Gozzini, B., Meneguzzo, F., Pagliara, S. & Maracchi, G. 2002 Extreme rainfall in a changing climate: regional analysis and hydrological implications in Tuscany. *Hydrol. Process.* **16**, 1261–1274.

Desiato, F., Fioravanti, G., Fraschetti, P., Perconti, W. & Piervitali, E. 2012 *Elaborazione delle serie temporali per la stima delle tendenze climatiche, Rapporto ISPRA, Serie Stato dell'Ambiente 32/2012*, p. 60 (in Italian).

Fatichi, S. & Caporali, E. 2009 A comprehensive analysis of changes in precipitation regime in Tuscany. *Int. J. Climatol.* **29**, 1883–1893. DOI: 10.1002/joc.1921.

Helsel, D. R. & Hirsch, R. M. 2002 *Statistical Methods in Water Resources Techniques of Water Resources Investigations*, Book 4, chapter A3. US Geological Survey, p. 522.

IPCC 2007 Climate change 2007: the physical science basis. In: *Contribution of working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller, eds). Cambridge University Press, Cambridge.

IPCC 2014 Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R. K. Pachauri and L. A. Meyer (eds)]. IPCC, Geneva, Switzerland, p. 151.

Jaagus, J. 2006 Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. *Theor. Appl. Climatol.* **83**, 77–88.

Karl, T. R., Knight, R. W. & Plummer, N. 1995 Trends in high-frequency climate variability in the twentieth century. *Nature* **377**, 217–220.

Karl, T. R., Nicholls, N. & Ghazi, A. 1999 CLIVAR/GCOS/WMO workshop on indices and indicators for climate extremes: workshop summary. *Climatic Change* **42**, 3–7.

Kendall, M. G. 1975 *Rank Correlation Methods*, 4th edn. Griffin, London.

Klein Tank, A. M. G., Zwiers, F. W. & Zhang, X. 2009 *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation. Climate Data and Monitoring. WCDMP-72, WMO-TD No. 1500.* WMO, Geneva, Switzerland.

Kundzewicz, Z. W. & Robson, A. (eds) 2000 *Detecting Trend and Other Changes in Hydrological Data. World Climate Programme – Water, World Climate Programme Data and Monitoring, WCDMP-45, WMO/TD No. 1013*. WMO, Geneva, Switzerland.

Mann, H. B. 1945 Non-parametric tests against trend. *Econometrica* **13**, 245–259.

Peterson, T. C. 2005 Climate change indices. *WMO Bulletin* **54** (2), 83–86.

Peterson, T. C., Folland, C. K., Gruza, G., Hogg, W., Mokssit, A. & Plummer, N. 2002 *Report on the Activities of the Working Group on Climate Change Detection and Related Rapporteurs 1998–2001*. WMO, Rep. WCDMP-47, WMO-TD No. 1071, Geneva, Switzerland.

Pettitt, A. N. 1979 A non-parametric approach to the change-point problem. *App. Statist.* **28**, 126–135.

Sen, P. K. 1968 Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* **63** (324), 1379–1389.

Theil, H. 1950 A rank-invariant method of linear and polynomial regression analysis. In *Proceedings of the Royal Netherlands Academy of Sciences*, Amsterdam, The Netherlands, 53 (1950) Part I: 386–392, Part II: 521–525, Part III: 1397–1412.

Tomozeiu, R., Busuioc, A., Marletto, V., Zinoni, F. & Cacciamani, C. 2000 Detection of changes in the summer precipitation time series of the region Emilia-Romagna, Italy. *Theor. Appl. Climatol.* **67**, 193–200.

Tomozeiu, R., Lazzeri, M. & Cacciamani, C. 2002 Precipitation fluctuations during the winter from 1960 to 1995 over Emilia-Romagna, Italy. *Theor. Appl. Climatol.* **72**, 221–229.

WMO 1988 *Analyzing Long Time Series of Hydrological Data with Respect to Climate Variability. Project description. WCAP-3, WMOTFD No. 224*, Geneva, Switzerland.

WMO 2011 *Guide to Climatological Practices (Updated Version at 19 January 2016). WMO No. 100*, Geneva, Switzerland.

First received 17 March 2016; accepted in revised form 6 March 2017. Available online 6 April 2017