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Mapping the uneven temporal changes in ordinary and extraordinary rainfall extremes in Italy

Paola Mazzoglio *, Alberto Viglione, Daniele Ganora, Pierluigi Claps

Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino 10129, Italy

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ABSTRACT

Study region: Italy
Study focus: The impact of climate change on the hydrological cycle is a debated topic, especially in complex areas such as the Mediterranean. Among all the European countries, Italy represents a challenging study area due to its complex topography, variable climate conditions, and the presence of fragmented datasets produced by different regional services. In this work, time series of sub-daily annual maximum rainfall depths coming from the "Improved Italian – Rainfall Extreme Dataset" are used to shed light on the possible presence of trends in rainfall extremes and their magnitude. Two different approaches are used: an at-site application of the Mann-Kendall test, combined with the computation of the Sen's slope estimator, and a distributed application of quantile regressions, which allows to cover the entire period of the analysis and to investigate the rate of change in the largest extremes.
New hydrological insights for the region: The median values of short-duration annual maxima show an increase all over the country, especially when considering 1 h extremes. Negative trends emerge in some areas when moving to longer durations (24 h). The quantile regressions show that higher quantiles (0.95–0.99 exceedance probability) are characterized by larger variations with respect to lower quantiles (i.e., the median). The non-uniformity of the observation records, finally, demonstrates the need for caution in deriving ultimate conclusions in emerging trends all over the country.

1. Introduction

In recent decades, the frequency and intensity of extreme rainfall events have gathered increasing attention globally (Alexander et al., 2006; Westra et al., 2014; Guerreiro et al., 2018; Papalexiou and Montanari, 2019; Fowler et al., 2021a, 2021b; Poschlod and Ludwig, 2021). Among all the countries of the Mediterranean area, Italy represents an interesting but also challenging case study because of its complex topography: elevation ranges from a few meters under sea level in the Po river floodplain up to more than 4800 m a.s.l. in the Alps (Fig. 1). The country's shape, with wide areas protected by the Alps and 2/3 of the region exposed to the Mediterranean Sea, makes it difficult to imagine homogeneous results in countrywide analyses. Studies related to the whole of Italy were also impossible before the reconciliation of multiple regional datasets (Libertino et al., 2018b; Mazzoglio et al., 2020). Several regional-scale studies were indeed conducted over the past 20 years, which all agree on the lack of statistical significance of the trends over large parts of the investigated areas (Crisci et al., 2002; Bonaccorso et al., 2005; Arnone et al., 2013; Persiano et al., 2020; Avino

* Corresponding author.
E-mail address: paola.mazzoglio@polito.it (P. Mazzoglio).

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et al., 2021, 2024; Treppiedi et al., 2021; Roseto et al., 2023).

Evidence for consistently increasing rainfall extremes remain elusive over large portions of the country: data suggested that, for the same rainfall duration, separate tendencies emerge in different sectors, even at close distances (Crisci et al., 2002; Libertino et al., 2019; Mazzoglio et al., 2022; Roseto et al., 2023; Avino et al., 2024). Moreover, the different rainfall durations typically used to define rainfall extremes (1, 3, 6, 12, and 24 h) seem to be often affected by opposite changes over time for the same region (Crisci et al., 2002; Libertino et al., 2019; Mazzoglio et al., 2022). The entity of the change, moreover, seems to depend on the observational period used in the investigation (Crisci et al., 2002; Persiano et al., 2020). As an example, Crisci et al. (2002) detected a change point in the 1970s in Tuscany when investigating time series covering a period ending in 1994: when considering data starting from the 1970s, a change towards increasing extreme events at any duration emerged in several stations. When investigating the complete series (1951–1994), negative trends prevail over positive ones, especially for shorter durations.

The research on changes in short-duration rainfall extremes in Italy was characterized by a diverse set of methodologies applied over different periods (Caporali et al., 2021). Even if each investigation contributes valuable insights into the intricate dynamics of rainfall extremes, the heterogeneity inherent in these approaches, both in terms of methodology and temporal intervals analyzed, poses a significant challenge in conducting robust comparisons and synthesizing findings coherently. In light of these challenges, it becomes evident that further research is imperative to deepen our understanding of the patterns of changes in short-duration rainfall extremes across Italy.

The present work provides a comprehensive evaluation of the possible presence of trends in short-duration (1–24 h) rainfall extremes in Italy and their magnitude. The dataset is described in Section 2. Different methodologies are used: the classical at-site application of the Mann-Kendall test and computation of Sen's slope estimator in Section 3, and a distributed application of quantile regression in Section 4. In Section 5 we compare our results to other research works conducted over smaller areas or with partial datasets, and discuss the potential implication of the work for hydrological design. Section 6 contains the main conclusions of this analysis.

2. Dataset

The dataset that we use consists of short-duration ($d = 1, 3, 6, 12$, and 24 h) annual maximum rainfall depths coming from the most recent version of the Improved Italian – Rainfall Extreme Dataset or I^2-RED (Mazzoglio et al., 2020). The different durations considered in this work, from 1 up to 24 hours, represent different types of phenomena: annual maxima of 1 h duration are generally measured

Fig. 1. Map of the Italian elevation, with an indication of the administrative regions.

during convective events, while 12 h and 24 h annual maxima are representative of stratiform events.

The dataset represents the most up-to-date collection of information regarding extremes that occurred in Italy in the past 100 years and consists of 5563 time series covering the 1916–2022 period. The elevation of the rain gauges ranges from −3 m a.s.l. up to more than 3000 m a.s.l. With respect to Libertino et al. (2019), this new version includes more than 28000 additional records for each of the 5 durations. Despite this inclusion, discontinuities due to station relocation, sensor upgrade and malfunctionings are still present in the dataset. From Fig. 2 it is possible to have a general understanding of the period covered by the measurements: in the graph, each grey line represents a different time series, while the red line shows the number of stations active in each year. While, for some time series, discontinuities are sparse and spread over the entire time window, for others the missing data are concentrated at the beginning or at the end of the time window.

3. At-site trend analysis

3.1. Methodology

Similarly to other studies on this region (Libertino et al., 2019; Mazzoglio et al., 2022), an at-site investigation has been performed here by using the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1948) for assessing trend significance, integrated by the Sen's slope (Sen, 1968) for the trend magnitude. By using the same methodology on an up-to-date dataset we aim to assess the influence of newly observed extremes and thus the sensitivity of the methodology. Results can have implications on the evaluation of a rate of update which can be suggested to at-site analyses.

Trend analyses require time series with at least 30 years of records (WMO, 2023). In order to increase the number of time series analyzed, we merged all the time series acquired by rain gauges located at distances smaller than 1 km. If, for a specific year, two rain gauges located at a distance < 1 km present two different values, the merged time series has been constructed by inserting the maximum between the two values. This preprocessing represents an attempt to soften the problems induced by the extreme fragmentation and lack of continuity of the Italian hydrologic records. In the early 1990s, after the dismantlement of the Servizio Idrografico e Mareografico Nazionale (the National Hydrographic Service) and the creation of 21 different local agencies in charge of the management of the monitoring network, the Italian hydrologic service was significantly renewed. During this process, some rain gauges were relocated at very close distances (sometimes in the order of hundreds of meters). The time series merging from relocated sensors represents a simple but effective way to increase the length of data records. We obtained 1614 time series longer than 30 years (either continuous or discontinuous) instead of the 1562 that could be analyzed without this pre-processing step. Shorter time series were not considered, as in Libertino et al. (2019).

3.2. Results

The Mann-Kendall test has been applied to the 1614 time series with at least 30 years of data. On a total of 1614 time series

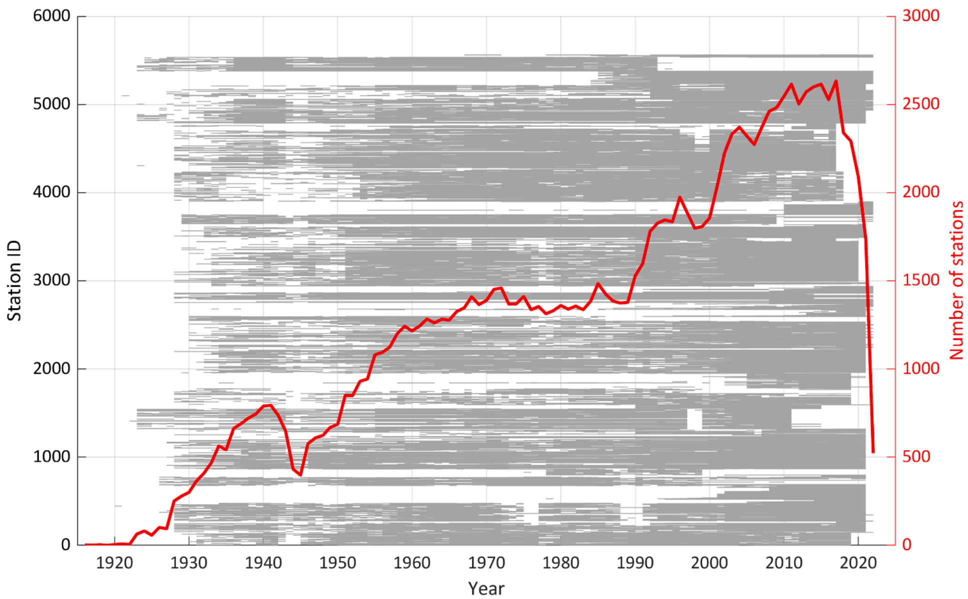

Fig. 2. Number of rain gauges active in each year, according to the I^2-RED dataset (red line). Time period covered by each time series (gray lines). The decline of station availability in the last few years (from 2018 onward) is due to the delay in data validation and publication by the regional hydrological agencies that manage the monitoring network.

considered, 279 of them (17 %) present a statistically significant trend (either positive or negative) at the 5 % level for the 1 h duration (Table 1), confirming that over a large portion of the nation the trend is not statistically significant. This is consistent with previous findings reported in the literature over Italy (Crisci et al., 2002; Bonaccorso et al., 2005; Arnone et al., 2013; Libertino et al., 2019; Persiano et al., 2020; Avino et al., 2021, 2024; Treppiedi et al., 2021; Mazzoglio et al., 2022; Roseto et al., 2023) or in the Mediterranean region (Sun et al., 2021). In our analysis, however, the percentage of stations with significant trend is higher than in the before-mentioned studies, indicating that by including the most recent years the signal of change is becoming stronger. In Libertino et al. (2019), as an example, only 163 time series out of more than 1300 presented a statistically-significant trend at the 5 % level. The number of locations with a statistically significant trend decreases to 214 (13 %) when considering the 24 h interval, while in Libertino et al. (2019) the number of statistically-significant trends at the 5 % level was 150. From Table 1 we can see that the percentage of stations with a statistically significant trend decreases with increasing rainfall duration. A similar decrease is also evident when considering the subset of stations with a positive statistically significant trend. The highest number of stations with a negative statistically significant trend is present in the 1 and 24 h durations, while intermediate durations are characterized by lower numbers. However, we cannot detect a clear positive or negative variation with the duration, since the numbers are quite similar.

In Fig. 3, panels a and b show the results obtained by considering the 1 h duration, while panels c and d show the results obtained by processing the 24 h annual maxima. Panels a and c show the trend significance from the application of the Mann-Kendall test, while panels b and d show the Sen's slope estimate. The triangles in Fig. 3a,c indicate the position of the time series with a statistically significant variation detected by the Mann-Kendall test (the size of the triangle is proportional to the entity of the Mann-Kendall test statistic Z). The background map is obtained by spatially interpolating with ordinary kriging all the at-site Z statistics without considering the significance of the trend. In Fig. 3b,d the triangles indicate the position of the time series with a statistically significant trend, while the size is proportional to the entity of the Sen's slope. The background map is, again, obtained by spatially interpolating with ordinary kriging all the at-site Sen's slope estimator without considering the significance of the trend.

Considering the sign of change, we can see that short-duration rainfall extremes are not increasing uniformly over Italy (Fig. 3) but a certain degree of spatial consistency exists. Opposite tendencies in the variation of 1 h extremes emerge in different geographic sectors of Italy: positive trends prevail in North-East and in Central Italy, while negative trends prevail in the North-West (Fig. 3a,b). For the 1 h duration, some areas show a clear reduction of the extremes over time, such as in most of Piedmont and in parts of Toscana, Sardegna, and Calabria, while in other regions the decreasing trends lose spatial coherence, as in the case of Emilia-Romagna (Fig. 3a, b). For longer durations (24 h), positive trends are visible in some areas, such as in the North-East, in Liguria, and in Campania (Fig. 3c, d). However, in most of the territory, the spatial variability is larger than for short duration extremes, and the extent of areas with equal sign is smaller. The lack of spatial coherence of the trends in precipitation extremes is in line with the findings already reported in global-scale studies (see e.g. Alexander et al., 2006, and Sun et al., 2021).

The application presented simultaneously investigates all the time series, not considering which specific period is covered by each of them. To better understand the period considered in each gauged location, Fig. 4 illustrates the spatial distribution of rain gauges with statistically significant trends, categorized by the ending year of their time series. Panels a and b are related to the 1 h duration, while Panels c and d refer to the 24 h data. For each row, the left panel shows the location of the series with negative trends (the lightest blue represents the time series ending before 1970, and the darker blue indicates the series ending in more recent years). The right panel shows the position of the time series with positive trends.

From Fig. 4a,c emerges that most of the stations with negative trends are characterized by time series that end more than 20 years ago, especially for the 1 hour duration. More specifically, for the 1 h duration, among all the 68 time series with negative statistically significant trend, only 17 end in 2010 or later. Conversely, Fig. 4b,d shows that most of the stations with a positive trend end in 2010 or later.

With this check, we understand that Fig. 3 compares trends related to different periods, which does not allow a consistent investigation over Italy. The problem becomes relevant in regions such as Piemonte and Campania, where most of the new stations were installed quite far from the old ones. In this case, the merging procedure described in Section 2 does not allow to solve the problem, at least using a threshold of 1 km to merge the series.

To tackle this relative inconsistency in time of the dataset, an additional technique (the quantile regression) has been considered.

Table 1
Number of stations with a statistically significant trend at the 5 % level for the 5 different durations, with the distinction between stations with positive and negative trends.

Duration (h)	Time series with a statistically significant trend (-)	Positive trends (-)	Negative trends (-)
1	279	211	68
3	252	202	50
6	256	199	57
12	236	182	54
24	214	144	70

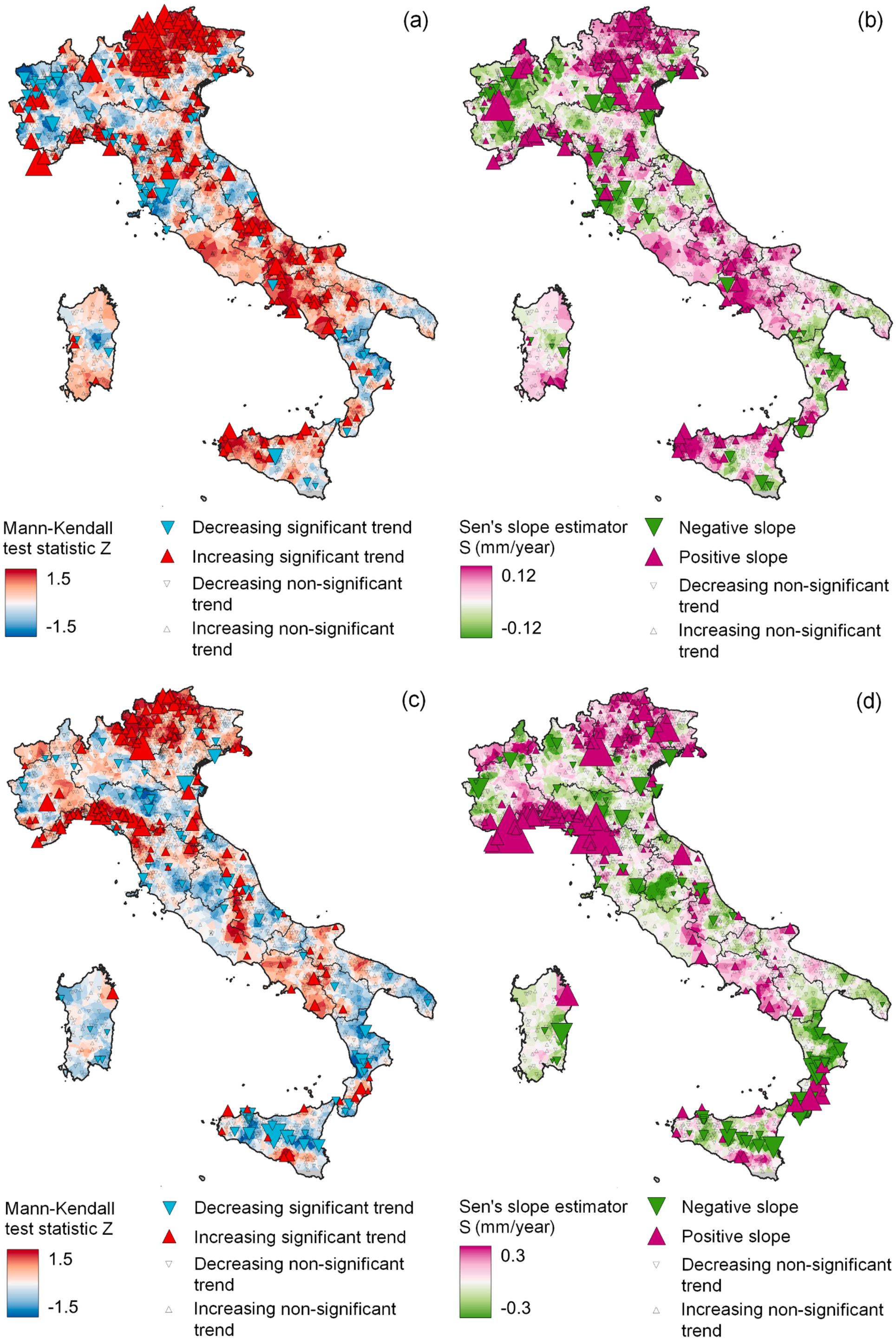

Fig. 3. Mann-Kendall test statistic for the 1 h (a) and 24 h (c) time intervals. Sen's slope estimator for the 1 h (b) and 24 h (d) time intervals. The background maps are obtained by spatially interpolating with an ordinary kriging the MK test statics (a, c) and the Sen's slope estimators (b, d) obtained in all the stations, without considering the significance of the trend. The size of the triangle is inversely proportional to the significance level in panels (a, c) and proportional to the Sen's slope estimator in panels (b, d).

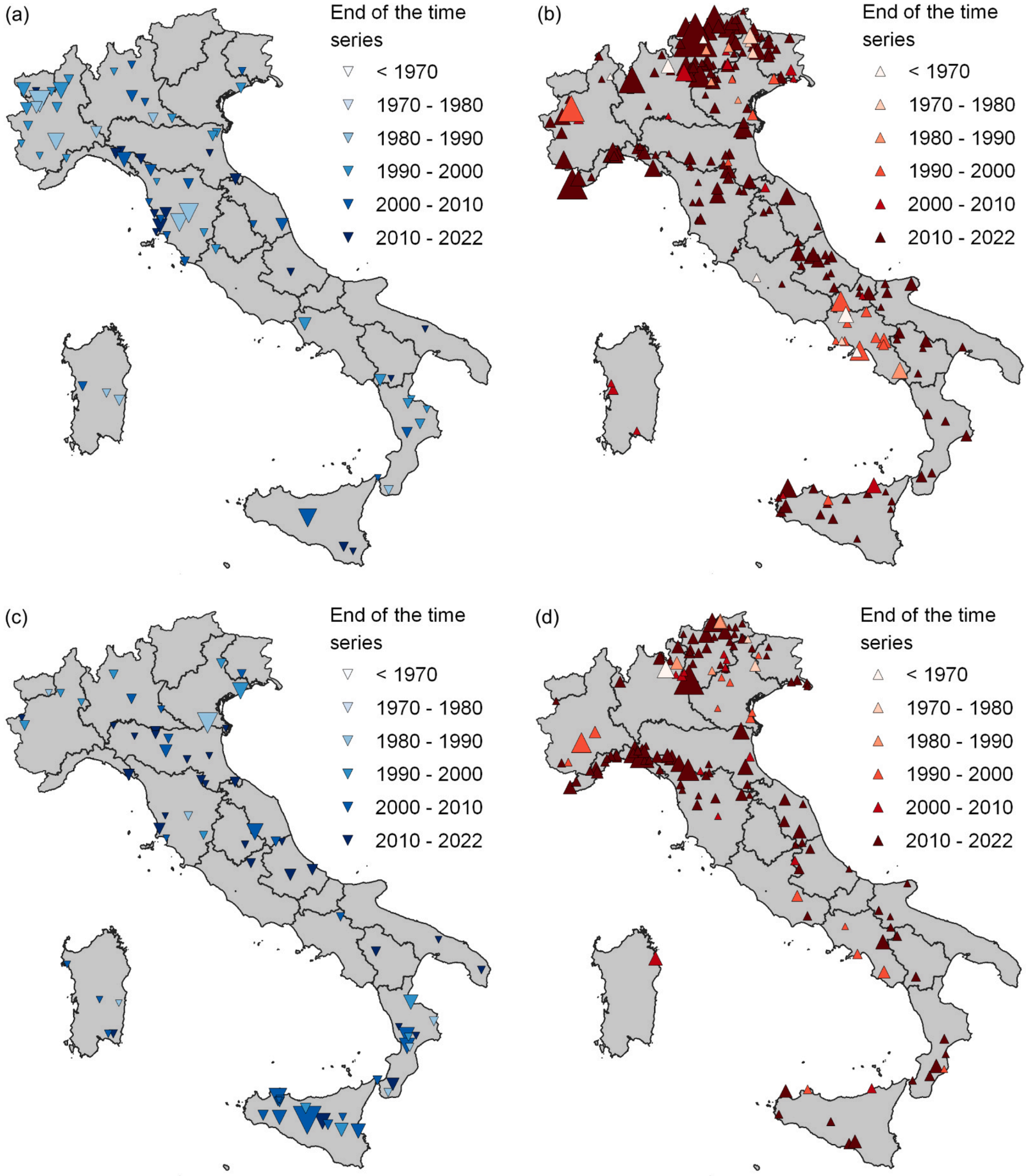

Fig. 4. End of the time series used in this work for the 1 h (a, b) and 24 h (c, d) durations. The left (right) column shows the end of the time series with decreasing (increasing) variations.

4. Quantile regression

4.1. Methodology

Since a large percentage of the time series do not cover the recent years due to a massive station relocation that occurred in the past, we consider here a distributed quantile regression approach that can cope with data fragmentation. Quantile regressions can be considered an extension of the classical linear regression model. They allow to perform a regression on each quantile, and not only on the mean, as performed by applying simple linear regression models. To overcome data fragmentation problems, the quantile regressions are applied pooling together data available in limited areas close to the target point. We segment Italy using a grid size of $s = 10$, 20 and 25 km resolution and, for each pixel, we apply a quantile regression by pooling together all the time series available within a circle centered on the pixel of interest. For each resolution s, the circle radius is $r = 1.5$ or 3 times the grid size s (see Fig. 5).

The R package *quantreg* was used to apply the quantile regression to each cell. In this work, we considered different quantiles: $q = 0.5$ (i.e., the median), 0.95 and 0.99.

By using this approach, a common period is used in each part of the Italian territory, allowing to obtain results that can be directly

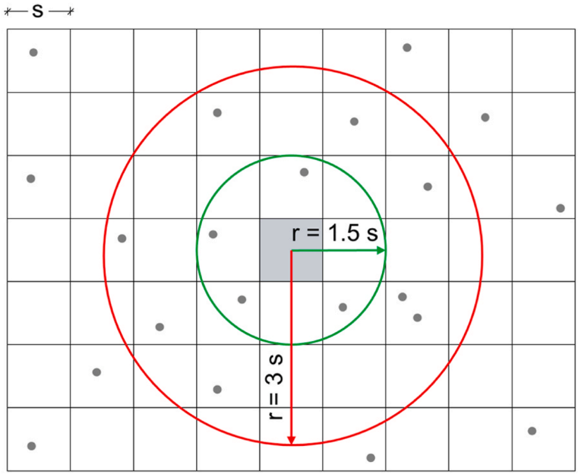

Fig. 5. Outline of the approaches used to select the rain gauges.

compared. We used the time window 1960–2022 since: a) before 1960, the number of active rain gauges was quite low (as visible in Fig. 2) and the series were interrupted due to the impact of the II World War; b) it is an interval almost coincident with the ones used in several European- and national-scale investigations (Blöschl et al., 2019; Persiano et al., 2020; Bertola et al., 2021), thus allowing comparisons among these works.

In Fig. 6 we can see the application of the quantile regression over a selected pixel located in North-West Italy, a region where very intense rainfall events occurred frequently. This cell represents an interesting case study, since in this area we observed two extreme rainfall events that occurred in 1970 and 2021 (with the first one being higher than the second one). Applying the quantile regression, for $q = 0.50$ we obtained a slightly negative slope (equal to −0.5 mm/year) while for higher quantiles, such as $q = 0.99$, we obtained a positive slope (2.6 mm/year). This result exemplifies that different quantiles can present different rates of change over time.

4.2. Results

The systematic application of the quantile regressions all over Italy allows us to build maps with observed variations in rainfall extremes. The new approach is no longer representative of very local variations of the extremes, but it is more robust and allows a national-scale comparison of the results. In this section, we focus on the results obtained using a grid size of $s = 20$ km and a search radius of $r = 60$ km. The results that we obtain using different resolutions are also briefly discussed but the related figures are not reported for the sake of brevity.

Fig. 7 shows the slopes of the quantile regressions obtained for 1 h (first row) and 24 h (second row) durations, expressed in mm/year. The first, second, and third column show the results related to $q = 0.5$, 0.95, and 0.99, respectively. The base color indicates the

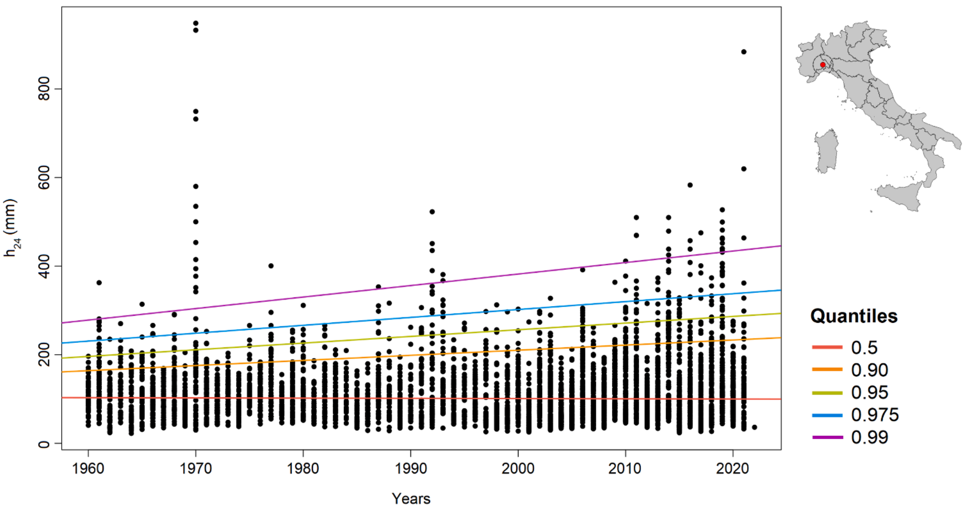

Fig. 6. Quantile regression applied over the 20 km size pixel indicated with a red dot on the map ($q = 0.5$, 0.9, 0.95, 0.975, 0.99). Data are pooled using a search radius of 60 km (dashed black circle centered on the red point).

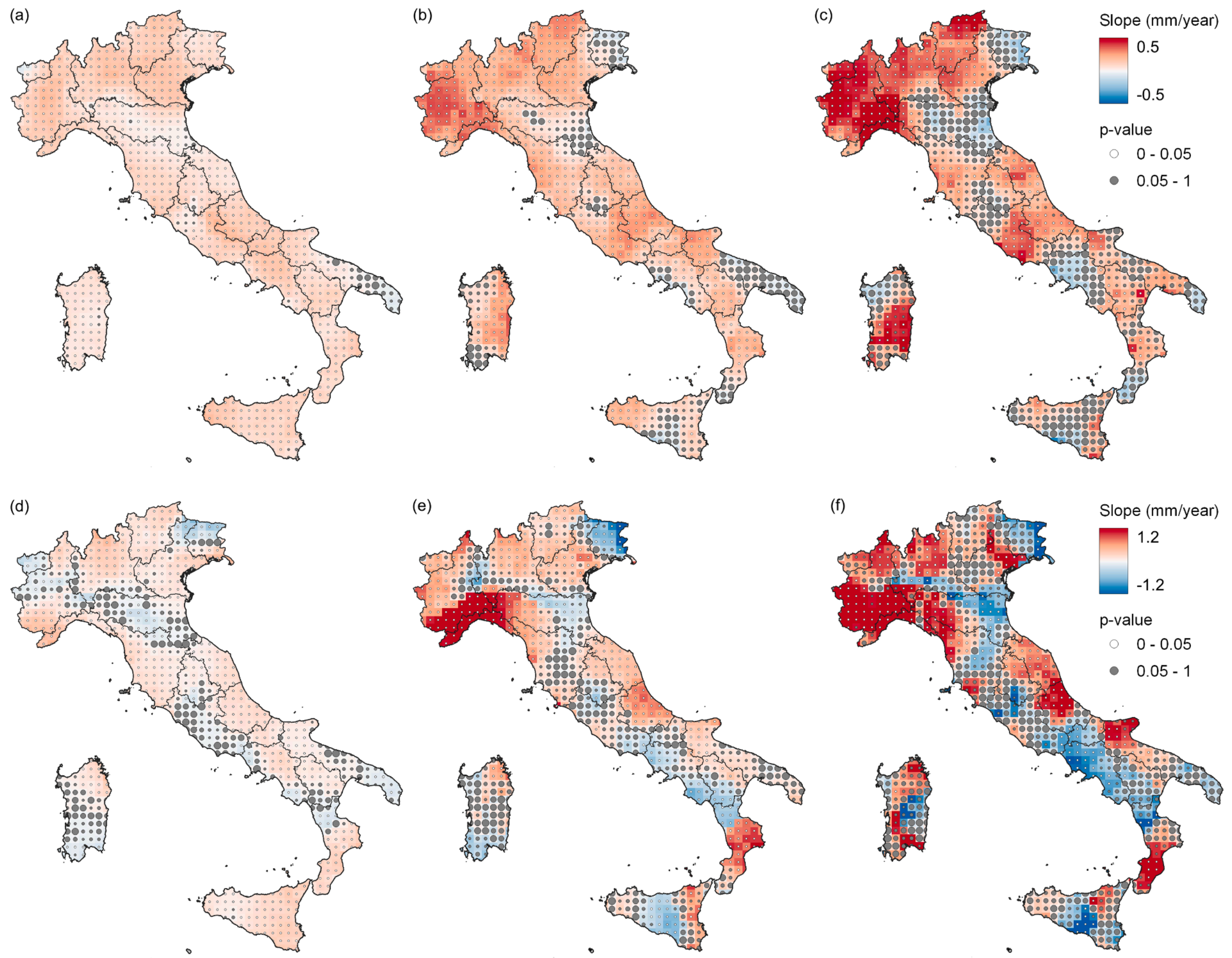

Fig. 7. Slopes of the quantile regressions obtained for: $d = 1$ h and $q = 0.5$ (a), $d = 1$ h and $q = 0.95$ (b), $d = 1$ h and $q = 0.99$ (c), $d = 24$ h and $q = 0.5$ (d), $d = 24$ h and $q = 0.95$ (e), $d = 24$ h and $q = 0.99$ (f). The basemap shows the slope of the quantile regression. Circles represent the p-value of the regression: white indicates a statistically significant regression (p-value lower than 0.05) while grey indicates not statistically significant regressions (p-value higher than 0.05). The size of the dot is proportional to the p-value.

slope (red is positive, blue is negative). The dots overlapping the base map indicate the entity of the p-value: small white points indicate p-values lower than 0.05 (i.e., a statistically significant regression), while grey dots represent cells where the quantile regression is not statistically significant at a 5 % level (the size of the dots is proportional to the entity of the p-value).

More in detail, Fig. 7a shows that the median values of 1 h rainfall extremes ($q = 0.5$) slightly increase all over Italy, except for two small areas in Valle d'Aosta (North-West of Italy) and Puglia (South of Italy). The latter area, Puglia, however, presents variations that are not statistically significant at a 5 % level. For almost all the other areas, the increase is statistically significant. The situation becomes more variable when considering longer durations, such as the 24 h one (Fig. 7d): in this case, for $q = 0.5$, the number and the extent of locations with negative trends increase. Also, the spatial distribution of the p-values, and their entity, presents some differences: for 24 h, the number of not statistically significant areas increases. The decrease in the number of areas with a statistically significant variation in the 24 h case is consistent with previous findings reported in the literature and the at-site analysis of Section 3 (a more in-depth discussion is reported in Section 5).

Another important piece of evidence that emerges when comparing these maps is the different rates of increase of ordinary ($q = 0.5$) and extraordinary ($q = 0.95$ and higher) extremes in places where both quantiles present positive variations. For the 1 h interval, over large areas of North and Central Italy, we observe more steep positive slopes when considering higher quantiles (Fig. 7b,c). These slope coefficients are all statistically significant. Fig. 7c also shows that in other areas, extraordinary rainfall extremes decrease, while ordinary ones show a slight increase (Fig. 7a). These areas, however, show high p-values (non-significant trends at the 5 % significance level).

When comparing the results obtained with a quantile regression able to cover the entire period under investigation (Fig. 7) with those obtained with the at-site analysis (Fig. 3) we can observe quite different behavior in terms of the sign of the trend when the time period covered by the record is limited. Marked positive trends that emerge in Trentino Alto-Adige (North-East of Italy) and at the border between Liguria, Toscana and Emilia Romagna visible in Fig. 3 are, in fact, still present in Fig. 7. This result was expected, since, as visible in Fig. 4, most of the time series of these areas reach recent years. The same is not true when comparing, e.g., the results obtained over Piemonte (North-West of Italy). In this case, the data pooling that we used in the quantile regression enables us to cover the entire time window, thus investigating the real entity of the change that is emerging as of today. The former at-site analysis shown in Fig. 3 was instead based on single time series that do not guarantee a complete temporal coverage in each site. By comparing the two analyses, however, we can see a similar behavior in the significance of the trends. For the at-site analysis, the 1 h duration is characterized by a higher percentage of series with statistically significant variations with respect to the 24 h case (the percentage decreases with increasing duration). The same is true when considering the quantile regression: even in this case, we can see, for all the quantiles, a higher percentage of pixels with a statistically significant regression in the 1 h duration with respect to the 24 h.

The results discussed so far are related to observed variations (expressed in mm/years). However, Italy presents significant spatial differences in rainfall regimes. Comparing the variations in relative terms (i.e., after a normalization) it is thus a valuable addition to the previous analyses. Fig. 8 shows the percentage of variation of rainfall extremes over 10 years, that is evaluated as the slope of the quantile regression computed over the 1960–2022 period divided by the mean of the rainfall extremes of the pixel in the 1960–2022 period, multiplied by 10. In this figure, orange indicates a positive variation, while violet a negative one. Also in this case, the dots overlapping the base map indicate the p-value of the quantile regression. As expected, these maps present patterns similar to the ones visible in Fig. 7. However, in this case, the relative variations are comparable at the national scale since they provided information related to a variation in relative terms, with respect to the mean value, rather than a variation in mm/years, that is not informative since the range of observed rainfall extremes is quite large in the Italian context.

Ordinary extremes (i.e., the median values) have an observed rate of change lower than 5 %, both for short and long durations. When considering higher quantiles, the entity of the variation increases in many areas. For the 1 h duration and $q = 0.99$, variations are higher than 15 % for selected areas in the North of Italy and in Sardegna. When considering the same quantile but the 24 h duration, similar variations are observed in the Southern part of Piedmont, Liguria, few coastal areas in Central Italy, part of Sardegna and the southern part of Calabria.

Both for the entity of the slope of the quantile regression and for the percentage of variations it could be interesting to briefly discuss the influence of the spatial resolution and the research radius. If we keep constant the resolution (20 km) and reduce the search radius

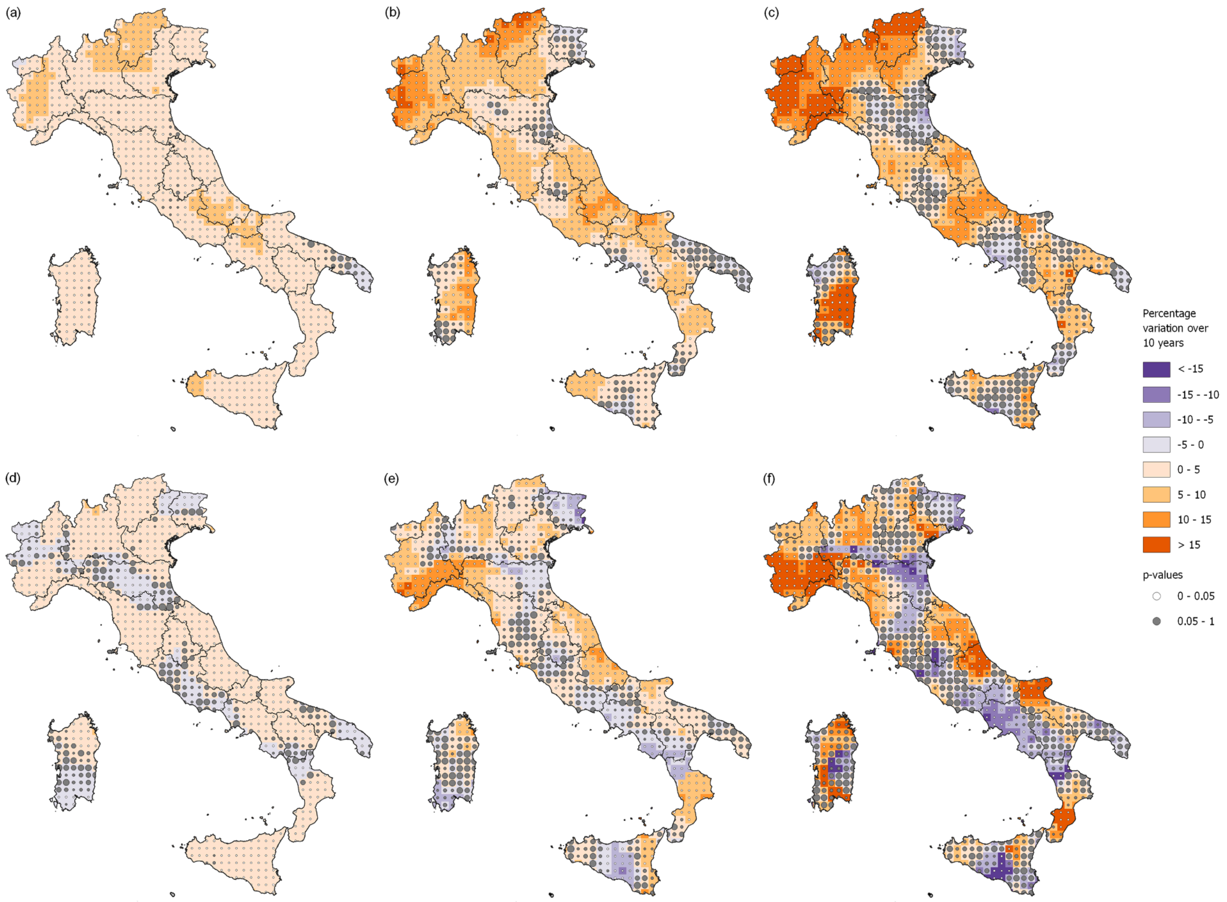

Fig. 8. Percentage variation obtained for: $d = 1$ h and $q = 0.5$ (a), $d = 1$ h and $q = 0.95$ (b), $d = 1$ h and $q = 0.99$ (c), $d = 24$ h and $q = 0.5$ (d), $d = 24$ h and $q = 0.95$ (e), $d = 24$ h and $q = 0.99$ (f).

(30 km in place of 60 km) we notice that the trend patterns remain quite similar. However, the number of pixels with non-statistically significant relationships increases, both for short and longer durations. For the 24 h, we notice that the trends of the higher quantiles are not statistically significant over almost the entire country, except for a few pixels. Results obtained with a 10 or 25 km resolution are quite similar to the ones obtained at 20 km. Also in this case, shorter research radius produces a lower number of pixels with statistically significant trends. Thus, changing the spatial aggregation does not have significant consequences on the overall results. While some local variations are observed when modifying the resolution, the overall quantile regression patterns remain consistent. Specifically, clusters of pixels that exhibit uniformly positive or uniformly negative trends continue to be evident, even when the resolution is altered. This consistency is particularly noticeable in regions where the trends are pronounced.

5. Discussion

The results obtained through the application of the at-site Mann-Kendall test (presented in Section 3) show a variation in the number of stations with statistically-significant trends with respect to previous studies, even if in the majority of the sites the trend is not statistically-significant (at a 5 % level). For all durations, positive trends prevail over negative ones. The analysis also shows that the number of series with significant trends is higher for shorter durations, and then decreases as the rainfall duration increases. This methodology, however, suffers the presence of fragmented time series (even after having merged time series closer than 1 km). Possible options that could be implemented to soften this problem could be: a) increasing the value to 2 or more km (however, this approach implies merging rainfall extremes that are recorded in different valleys, and we expect that the orographic effect could influence the rainfall amounts and thus the entity of the trend); b) lowering the threshold applied to the time series length from 30 to 25 years (but this approach will not solve the time misalignment between the series); c) selecting only the data of the most recent 30–40 years (however, in this case, wide areas of Italy will result to be poorly sampled). Approaches such as the application of the at-site Mann-Kendall test provide results that are not directly comparable when applied in a region with a marked fragmentation of the time series and a huge number of rain gauges relocated over time.

In the case of the spatial application of the quantile regression, it is essential to consider the inherent trade-offs involved in this approach. These trade-offs revolve around three key factors: spatial homogeneity, spatial correlation, and sample size. As the radius for pooling data increases, the likelihood of incorporating diverse and heterogeneous sites within the same analysis also rises. This increased heterogeneity can introduce variability in the data, as different locations within a larger radius may experience distinct climatic, topographical, and hydrological conditions. In regions where observations are spatially correlated, there is a risk of over-estimating the statistical significance of the observed trends. On the other hand, reducing the research radius and thus the number of measurements enhances spatial homogeneity but can lead to small sample sizes which may not capture the full variability of the data, leading to less precise estimates and lower statistical power. This can result in weaker or non-significant trends, even if underlying patterns do exist, simply because there are not enough data points to detect them. Balancing these three factors (spatial homogeneity, spatial correlation, and sample size) is crucial for the accuracy and reliability of the distributed application of the quantile regression analysis and requires careful consideration of the geographic and climatic characteristics of the study area.

The results obtained with the quantile regression reported in Section 4 represent, to our knowledge, the first assessment of changes in rainfall extremes performed all over Italy considering measurements that completely cover the most recent 60-year period (1960 – 2022). Some interesting comparisons can be made with other regional works already conducted in Italy with other methodologies or considering different periods.

Over Southern Trentino Alto Adige (the location of the Italian regions is reported in Fig. 1), Dallan et al. (2022) detected positive trends, consistent with the results visible in Figs. 3 and 7. These results were expected since both analyses were performed considering data that covered the entire period.

In the Emilia-Romagna region, Persiano et al. (2020) pointed out that most of the statistically significant trends are located in the Apennines, along the regional borders with Liguria and Toscana, and in the North-Eastern area close to Veneto. Similar results are visible in Fig. 7. Persiano et al. (2020) also pointed out that different trends emerge when considering a shorter period (1961–2015) in place of the entire one (1931–2015). Thus, for a more in-depth comparison, we refer to the shorter period (that is quite similar to the one used in this work, 1960–2022). The two studies generally agree for short durations. However, when comparing long durations, we observe some areas with statistically significant negative trends, that appeared to be not significant in Persiano et al. (2020). This difference could be caused by the different approaches used in the two works (at-site analysis vs distributed application of a quantile regression).

In Umbria, Cifrodelli et al. (2015) detected little increases in rainfall extremes in three rain gauges covering the period up to 2013. In this work, thanks to an increase in the time series length and a data pooling approach, we are able to identify a large portion, in the northern part of the region, characterized by a positive statistically significant variation that did not emerge in the previous work.

Over Campania, for the 1 h duration, positive trends were observed in small and defined regions by Avino et al. (2021), while we observed a positive trend for $q = 0.50$ over the entire region. For longer durations, they observed both positive and negative trends: similar results are obtained in this work, but the spatial distribution of these trends is different (probably due to the different datasets used).

Over Puglia, Roseto et al. (2023) pointed out that the number of series with a positive trend is greater than the number of series with a negative trend (for the time intervals between 1 h and 24 h, the average ratio is 60/30). Positive trends prevail also in our work. Moreover, in both studies, negative trends seem to be clustered in the southern parts of the region, while positive trends are generally observed in the northern areas.

Over the entire southern Italy, Avino et al. (2024) detected that, for the 1 h duration, only 28.4 % of the time series presents a statistically significant positive trend, while all the others are characterized by not significant variations (14.3 % negative, 57.3 % positive). From Fig. 7a we detect a positive statistically significant trend all over the area, with the exception of the southern part of Puglia, where not statistically significant negative variations emerge. Over this area, Avino et al. (2024) also highlighted the lack of significance. According to Avino et al. (2024), the percentage of stations with positive statistically significant trends decreases with increasing rainfall durations, while the percentage of negative trends (either significant or not significant) increases. The results presented in Fig. 7 are generally in line with those reported in Avino et al. (2024), but in our analysis we detect larger portions with positive statistically significant trends. The difference between the results of these two works could be induced by the different methodologies: Avino et al. (2024) applied the Mann-Kendall test in each gauged location considering reconstructed time series obtained by applying geostatistical techniques, while we apply a quantile regression only on observed extremes, without reconstructing rainfall measurement values that can introduce bias, especially in years with sparse observation (Libertino et al., 2018a; Avino et al., 2021).

Over Sicilia, three different works are available. Bonaccorso et al. (2005) investigated 16 time series of at least 50 years of data in the 1921–2000 period and pointed out different behavior according to the time scale considered: shorter durations (1 h) generally exhibit increasing trends while decreasing trends emerge when considering longer durations (24 h). Trends in the region were then investigated by Arnone et al. (2013): in this paper, the authors investigated a richer dataset of 57 time series covering the 1956–2005 period and detected increasing trends for short-duration extremes, especially for 1 h duration. Conversely, extremes of longer durations exhibited a decreasing trend. Over the region, an increase in short-duration extremes was detected near the coastline, even if no clear and well-defined spatial pattern was outlined. The results of a more recent study, performed by Treppiedi et al. (2021) considering the 2002–2019 period, are in line with most of the results performed before. In their work, Treppiedi et al. (2021) confirmed increasing trends in hourly (and sub-hourly) extremes, especially at higher quantiles (> 0.9). The increasing behavior of the 1 h extremes highlighted in these three works is confirmed by the results obtained here and shown in Fig. 7a, even if in some areas we detected different patterns in the type of change, probably due to the different periods covered. For the 24 h duration, the results obtained in our analysis, realized with a longer and most up-to-date dataset, is different: ordinary extremes tend towards an increase, while extraordinary ones both increase and decrease on the region. The latter variations are however not statistically significant (the lack of significance in higher quantiles was also pointed out by Treppiedi et al., 2021).

6. Conclusions

In this work, two different methodologies are applied to evaluate the possible presence of trends in the time series of short-duration rainfall extremes in Italy. The first method is an at-site application of the Mann-Kendall test, combined with the computation of the Sen's slope estimator. This first approach produces useful results at the local scale, but is not suited to providing an overview of trends on large areas. As Italy presents very fragmented time series, the results cannot be easily compared among them, even at close distances. To overcome this limitation and try to obtain wide-area trend information we used a distributed quantile regression approach, that allows to analyze data covering the entire 1960 – 2022 period and provides information valid for areas that coincide with the extent of the cells of a grid covering the country.

The results obtained suggest that the distributed approach should be preferred to the at-site one when the dataset is extremely fragmented both in space and in time, as in the case of Italy. The quantile regression approach is also able to investigate variations in extremes with different exceedance probabilities. Its application over Italy points out that extraordinary extremes appear to change more than ordinary ones, both in terms of the entity of the trend and in terms of spatial variability. Ordinary (low quantile) extremes are characterized by positive variations for the 1 h duration, while both positive and negative variations characterize the 24 h ones. Extraordinary extremes, instead, show both a positive and a negative variation, depending on the region and on the duration under investigation.

The findings presented in this study offer valuable insights into the magnitude of observed variations in rainfall extremes across Italy and of its spatial variability. These results are particularly relevant for the planning and design of new infrastructure, as they highlight both the increasing intensity of extreme rainfall events and the increasing number of stations with statistically-significant trends with respect to previous studies. Moreover, these results can be used as a baseline for testing trends in climate model output over the historical period.

It is worth underlying that all the results discussed here are obtained from observations and describe the trends observed on data recorded from 1916 (in the case of the at-site analysis) or 1960 (in the case of the quantile regression) up to now. Thus, it's important to acknowledge that while these observations offer valuable insights into historical trends, they may not entirely encapsulate the potential variations that could unfold in the future. As such, caution must be exercised in extrapolating these trends to predict future scenarios, as observed trends could potentially diverge from their current trajectories in the coming years.

CRediT authorship contribution statement

Mazzoglio Paola: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claps Pierluigi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Viglione Alberto:** Writing – review & editing, Methodology, Conceptualization. **Ganora Daniele:** Writing – review & editing, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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