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Analysis of Rainfall Trends and Extreme Precipitation in the Middle Adriatic Side, Marche Region (Central Italy)

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Abstract: Extreme precipitation trends and events are fundamental for the definition of the region's climate and allow the subsequent analysis of the risk for the territory and the possible countermeasures. This study takes into account the Marche Region (Central Italy) with 128 rain gauges from 1921 to 2017. Initially, in order to obtain a rainfall overview, the dominant trend of the period 1921–2017 was evaluated. Initially, in order to obtain a rainfall overview, the dominant trend of the period 1921–2017 was evaluated. In addition, to obtain a comparable analysis, the average precipitations grouped in climatological standard normals were analyzed. Finally, the main purpose of the research was achieved by analyzing extreme events in the middle Adriatic side. In addition, forecasts of extreme precipitation events, with a return period of 100 years, were made using the theory of "generalized extreme value" (GEV). The innovation of this research is represented by the use of geostatistics to spatialize the variables investigated, through a clear and immediate graphic representation performed through GIS software. This study is a necessary starting point for the study of climate dynamics in the region, and it is also a useful tool for land use planning.

Keywords: precipitation; GIS; climate change; extreme events

1. Introduction

1.1. Aim of the Study and State of the Art

Climate change is currently generating more and more intense and frequent extreme rainfall. The causes that generate climate change are under investigation and are mainly attributable to pollutant emissions [1], so much so that many studies evaluate their reduction [2]. In particular the greenhouse gases have increased from 1970 to 2010 of 0.55 gigatons per year, with a growth in the last period 2000–2010 of 1 gigaton per year despite the increasing countermeasures adopted by nations [3]. CO_2 emissions derive mainly from fossil fuel combustion (78%) and the increase in the period 2000–2010 is due to diverse anthropogenic causes as energy supply (47%), industry (30%), transport (11%), and buildings (3%) [3]. The relationship between greenhouse gases and extreme events has been widely demonstrated on several occasions by the international scientific community [4]. Future emission scenarios are directly related to climate change scenarios [5]. In this context; however, it is very important to statistically evaluate the change in extreme events for each territory, in order to prepare immediate countermeasures. Extreme rainfall is very harmful to all human activities and this leads to a growing attention to the phenomenon. In fact, extreme rainfall generates an increase in hydrogeological risk as well as problems for cultivation activities; therefore, this topic is related with the economy and public health. Obviously, in order to reduce the effects of extreme events, it is necessary to know the magnitude and the frequency of these events by preparing appropriate response measures. In the world, the situation is not univocal, in fact, there are large areas where there is a growth of extreme events of precipitation, while in others, although less extended territorially, there is a reduction [6]. In particular, the situation in the Mediterranean area is very unusual, where there is a growth in the extreme values of precipitation and a decrease in the total amount of rain [7]. Other recent studies, on the other hand, show that rising temperatures in the Mediterranean Sea increase the risk of extreme summer precipitation events in central Europe [8]. In the recent years, the focus is shifting from simple monitoring to future forecasting of extreme events of precipitation [9] with special attention to global trends [10]. Large-scale analyses certainly have a global validity also with regard to atmospheric dynamics, but local situations can also differ considerably from them. This lack of detail induces the creation of a working methodology that can lead to a detailed mapping of the territory. In the study area there is no detailed literature on rainfall trends and also on extreme rainfall events or indices, but there are some important studies that deserve mention. There are studies that provide a report of rainfall on the Marche Region [11], others that highlight climate change analyzing the different standard periods through interpolations in small part of the Marche Region [12,13]. There are researches that have analyzed topographic variables to evaluate the correlation of precipitation with them [14,15], some investigate the extreme indices in this area [16,17]. It is important to provide a research that can assess extreme precipitation and trends in detail, in order to be a reference point for future research and a reliable prevention tool for the various purposes of slope stability analysis and resource management [18]. The Middle Adriatic Italian side is the watershed between a Mediterranean climate more typical of the coasts of southern Italy and continental climate specific of the North Adriatic, because of its position. It is; therefore, interesting to analyze changes in precipitation given the sensitivity of the area to them. The results of the study can be summarized in the following three points:

1. Trend analysis: this part analyzes the period 1921–2017 in order to assess the general tendency.
2. Variations in average precipitation: general and territorial changes are assessed on the basis of three climatological spatial normal that are non-overlapping (1931–1960, 1961–1990, 1991–2020).
3. Extreme precipitations: in order to detect a return period for a rainfall event of a particular intensity, analyzed as extreme indices over a period of approximately 60 years from 1961 to 2017 (period of data availability).

1.2. Geographical Framework

The middle Adriatic Italian side can be approximated with the Marche Region (a region of Italy), which has a spatial extension of 9694 km^2. One third of this area is mountainous and two third is hilly, while the plains are almost non-existent and are located only in the coastal area. In the eastern part of the Region there are the Apennines, a mountain chain that in this area is close to 2500 m above sea level with Mount Vettore (2476 m a.s.l.). From east to west, the peaks gradually smooth until reaching the Adriatic Sea, an arm of the Mediterranean Sea. The river valleys are all developed perpendicularly to the Apennines and flow into the Adriatic Sea, even if there is only one river that flows into the Tyrrhenian Sea (Nera river, tributary of the Tevere river) [19] Figure 1.

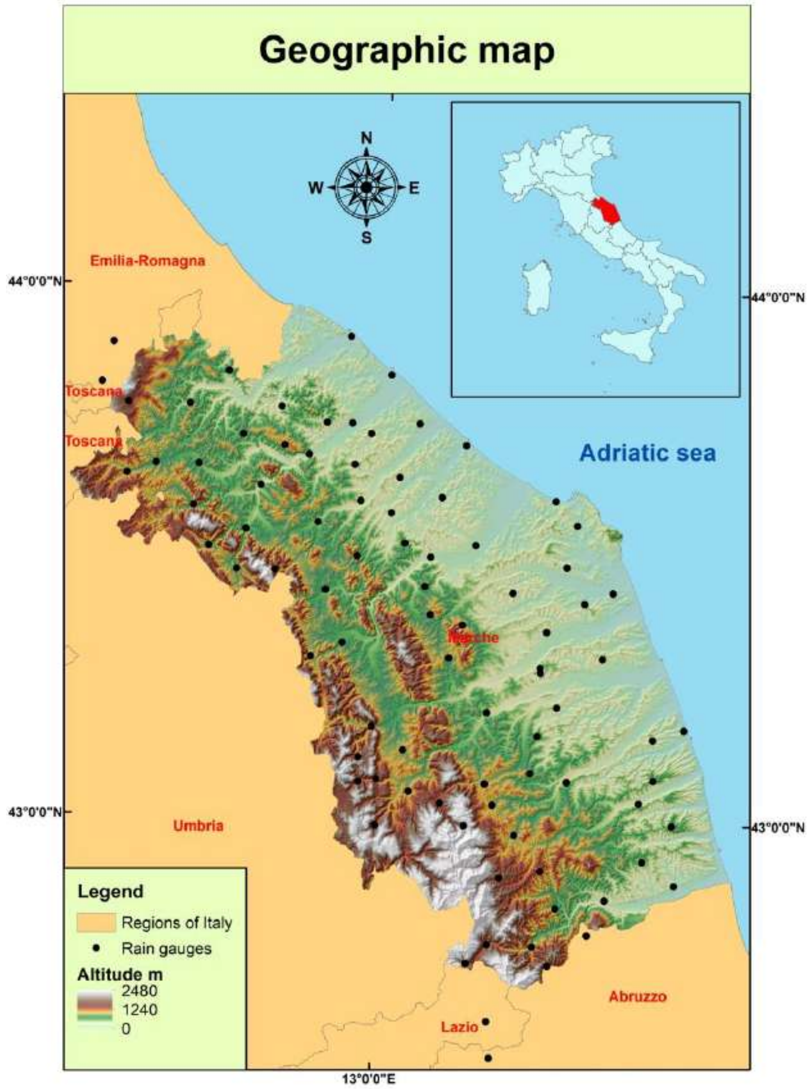


Figure 1. Geographical map of the Marche region [15].

2. Materials and Methods

Pluviometric data have been collected by several institutions: The former National Hydrographic Service (SIMN), Multiple-Risk Functional Centre of the Civil Protection, Italian Air Force, Functional Centre of Umbria and Experimental Geophysical Observatory of Macerata (OGSM). The total number of rain gauges collected was 128 for the whole Marche region and surrounding territories (Figure 1) which are part of the middle Adriatic side, over different periods. Monthly precipitation data were collected from 1921 to 2017, extreme precipitation data at 1, 3, 6, 12, 24 h were collected from 1961 to 2017 as well as daily precipitation data. Data quality controls were subsequently carried out, with validation primarily [20] and secondarily with homogenization [12]. The trend of the rainfall data from 1921 to 2016 were analyzed through MAKESENS procedure [21], with regard to both the amount of rainfall and the number of rainy days. In order to evaluate the trend from a graphic point of view with maps, the data were interpolated with the statistical method radial basis function using GIS software:

$$f(x) = \sum_{j=1}^{m} w_j h_j(x)\,, \tag{1}$$

where w are the coefficients for linear combinations, x is the viewpoint, h is the radial function that can be of different types (gaussian, completely regularized spline, spline with tension, multiquadric, inverse multiquadric, thin plate spline, etc.).

At the same time rainfall analysis was performed considering the climatological standard normal periods (1931–1960, 1961–1990, and 1991–2020) both for precipitation and number of rainy days. The data were interpolated with the geostatistical method simple co-kriging based on altitude, most correlated topographic variable, in order to obtain a better spatialization at the points where there are no rain gauges.

$$Z_{SCK}(u) - \mu_1 = \sum_{\alpha_1=1}^{n_1(u)} \lambda_{\alpha_1}^{SCK}(u)[Z_1(u_{\alpha_1}) - m_1] + \sum_{\alpha_2=1}^{n_2(u)} \lambda_{\alpha_2}^{SCK}(u)[Z_1(u_{\alpha_2}) + m_2], \tag{2}$$

$\lambda_{\alpha_1}^{OCK}(u)$ and $\lambda_{\alpha_2}^{OCK}(u)$ = weights of data; $Z_1(u_{\alpha_1})$ *e* $Z_1(u_{\alpha_2})$ = primary and secondary data; m_1 *e* m_2 = mean of primary and secondary data.

The maps of the various reference periods were compared with the mathematics between rasters, creating maps that highlight the spatial differences between the periods. The analysis has been further improved by the study of extreme precipitation, in order to know the maximum extreme events that occurred, the mean of extreme events, and the return period to 100 years. All these results have been summarized by several maps created with GIS software and the calculation of the return period was carried out using the GEV (generalized extreme value distribution) model [22]. Probability density function is as follows:

$$f(x) = \begin{cases} \frac{1}{\sigma}\exp(-(1+kz)^{-1/k}(1+kz)^{-1-1/k},\ k \neq 0 \\ \frac{1}{\sigma}\exp(-z-\exp(-z)),\ k = 0 \end{cases}, \tag{3}$$

where $z = \frac{(x-\mu)}{\sigma}$ (4)

The range of definition of the GEV depends on k:

$$\begin{array}{c} 1 + k\frac{(x-\mu)}{\sigma} > 0\ k \neq 0 \\ -\infty < x < +\infty\ k = 0 \end{array}. \tag{4}$$

The "shape" parameter k sets 3 types of distribution:

$k = 0$ Gumbel distribution [23].
$k > 0$ Fréchet distribution [24].
$k < 0$ Weibull distribution [25].

The values of the parameters were obtained with the "maximum likelihood" method (MLE) [26]. The goodness of the adaptation of the distribution to the selected model, in this case the GEV, was the Kolmogorov–Smirnov test [27] through the software EasyFit (©Math Wave Technology 2004–2015, Dnipropetrovsk, Ukraine) and graphically with the package of R "in2extRemes" [28], analyzing the quantile plot and the histogram of frequency. In addition, the confidence interval for the considered return time has been calculated [29] through the "bootstrap" method [30] with 1000 remissions. The research was carried out on the annual maximum values of precipitation for the duration ranges 1–3–6–12–24 h, from 1961 to 2016. Finally, the single rain gauges were analyzed with the Mann–Kendall test [31] to assess whether they are affected by significant trends.

3. Results

Trend analysis on 128 weather stations of the database, from 1921 to 2017, has showed some important results. In fact there are 36 rain gauges with a significant trend at 95% for precipitation amount and 31 for rainy days. From the 36 significant rain gauges, 32 out of them (equal to 89% of the total significant rain gauges) show a downward trend, while for rainy days there is not a clear tendency because increasing trend at 16 rain gauges and decreasing trend at 15 gauges are obtained in the annual amount of rainy days in the period. In Figure 2 there is an innovative histogram that shows a clear evidence of downward trend for precipitation and a stationarity for the amount of rainy days.

Moreover, to obtain a spatial evaluation of the trend magnitude, two explanatory maps were drawn up (Figure 3a,b) and two other maps show the rain stations that have significant trends (Figure 3c,d).There is a strong downward trend in rainfall for the Marche Region, although there are some countertrend areas located in the central–southern part of the Region (Macerata and part of the Sibillini Mountains). Instead, for rainy days there is no univocal trend, in fact the north–center part of the Region seems to be affected by a slight decrease, while in the southern part a slight increase of rainy days prevails.

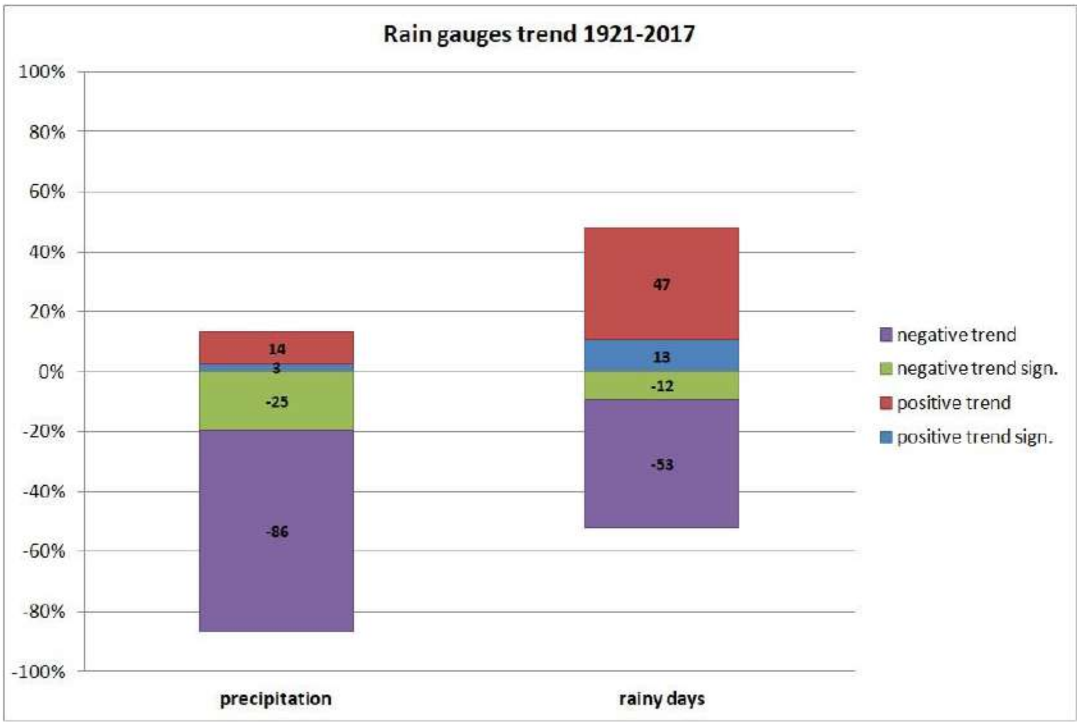
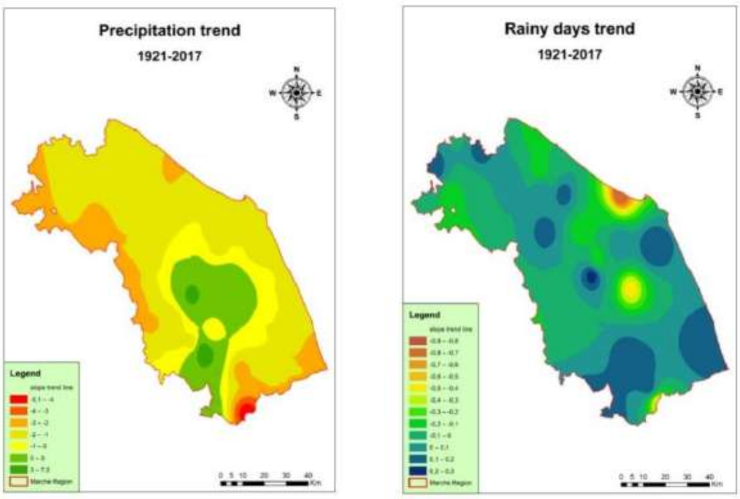
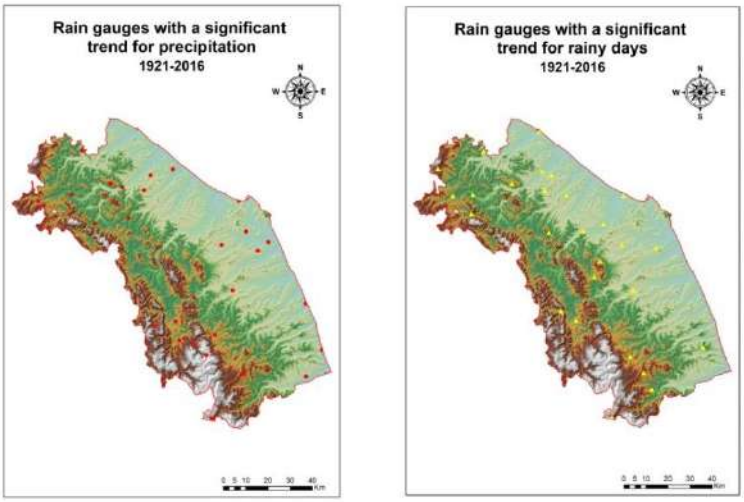


Figure 2. Percentage of rain gauges that have a significant negative, significant positive, negative or positive trend [15].



(**a**) (**b**)

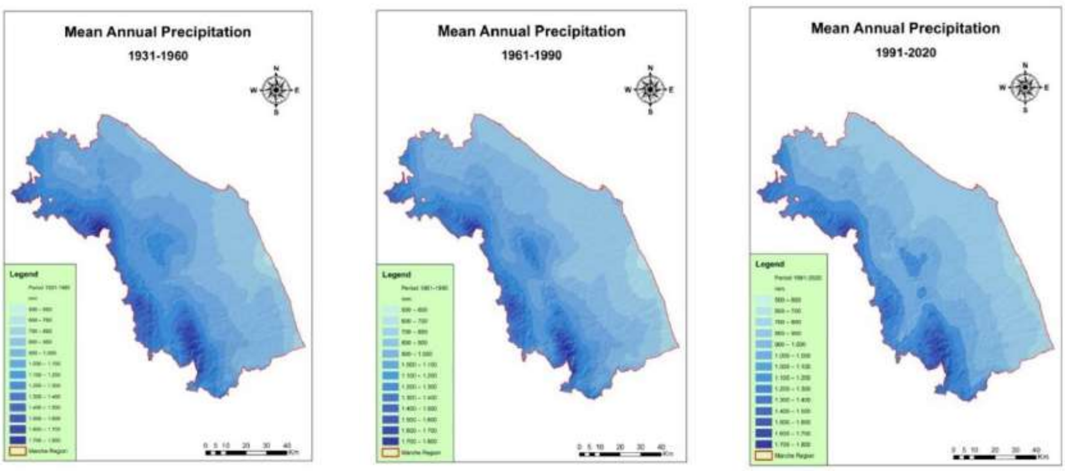
Figure 3. *Cont.*



(**c**) (**d**)

Figure 3. Trend magnitude for (**a**) precipitation and (**b**) rainy days in the period 1921–2017. Rain gauges with a significant trend for (**c**) precipitation (red circle) and (**d**) rainy days (yellow triangle).

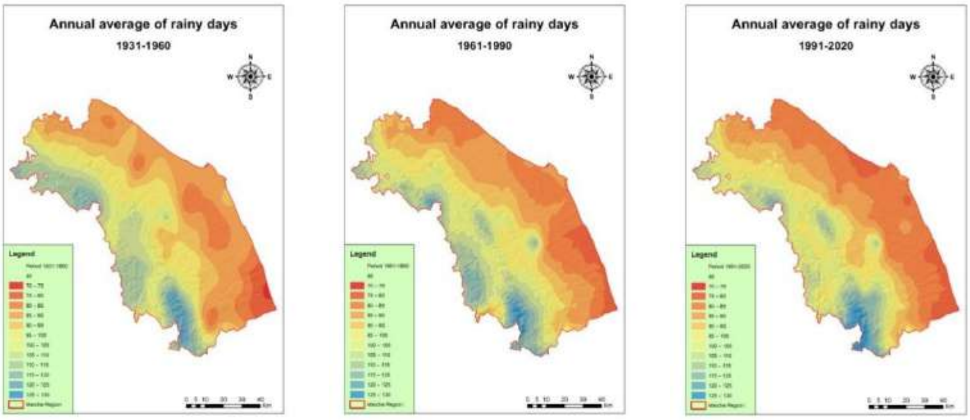
The trend analysis was accompanied by a climate report for the various standard climate periods: 1931–1960, 1961–1990, and 1991–2020. Maps of annual and seasonal precipitation (Figure 4) and rainy days were drawn up for each period, in order to obtain a complete assessment of both the past and the present rainfall in the Marche Region. The method of interpolation was simple co-kriging, with altitude as the independent variable and it is interesting to observe the distribution of precipitation on the regional territory. In fact, for all periods (1931–1960; 1961–1990; 1991–2020) the precipitation increases from the east (in front of the Adriatic Sea) to the west (Apennine Mountains). The lowest value of precipitation occurs in the southeastern part of the Marche Region.



(**a**) (**b**) (**c**)

Figure 4. Maps of mean annual precipitation for all standard periods ((**a**) 1931–1960; (**b**) 1961–1990; (**c**) 1991–2020).

Rainy days were interpolated with the same method of precipitation, a co-kriging based on altitude. The highest number of rainy days is located on the western part of the region (Apennines), with a peak in the southwest area (Sibillini Mountains). The lowest number of rainy days is located in coastal areas and especially in the southeast (Province of Ascoli Piceno). Observing the maps in Figure 5, it is possible to notice a decrease of rainy days, especially in the last period (1991–2020).



(**a**) (**b**) (**c**)

Figure 5. Maps of annual average rainy days for all standard periods ((**a**) 1931–1960; (**b**) 1961–1990; (**c**) 1991–2020).

The results of interpolation are summarized in two histograms (Figure 6; Figure 7), which highlight the annual and seasonal values of precipitation. On average the precipitation of the Marche Region is decreased between the past and the present from an annual point of view. Summer shows a fluctuating trend with a peak precipitation in the thirty-year period 1961–1990, while autumn is the opposite with a minimum in 1961–1990 and similar values comparing the other two standard periods (1931–1960; 1991–2020).

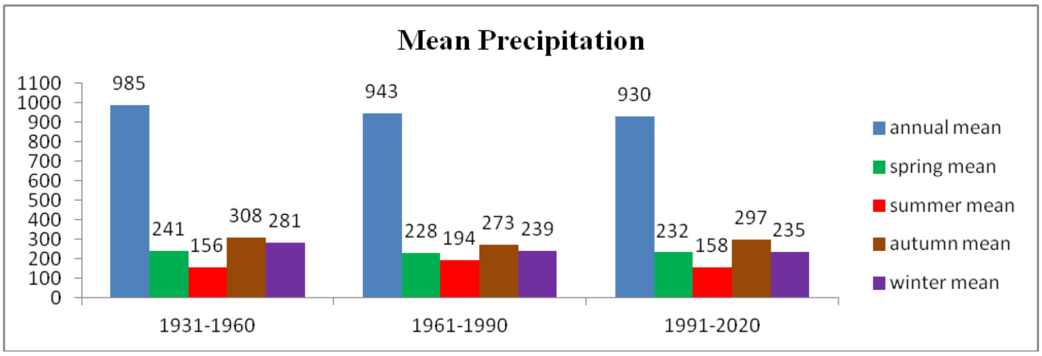


Figure 6. Mean precipitation (mm) of the Marche Region, from interpolation in the GIS environment for the years and all seasons of each standard period (1931–1960; 1961–1990; 1991–2020).

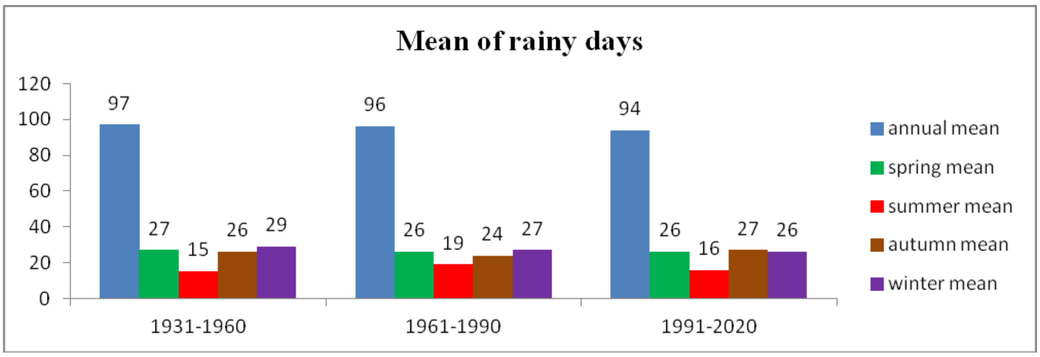
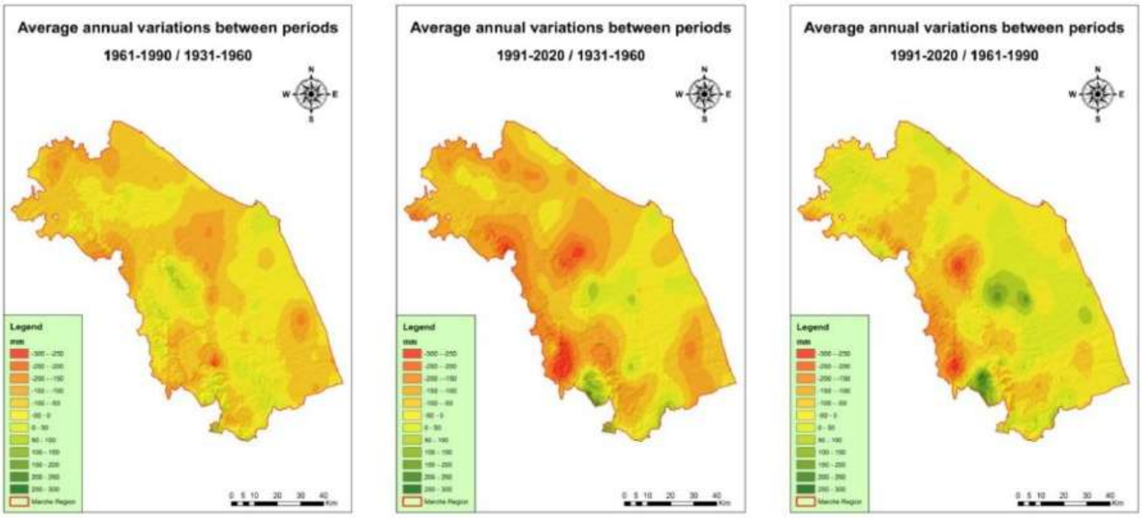


Figure 7. Mean of rainy days (dd) of the Marche Region, from annual interpolation of each standard period (1931–1960; 1961–1990; 1991–2020).

The average number of rainy days per year (Figure 7) decreased slightly from 1931–1960 to 1961–1990 (only one day), and more strongly between 1961–1990 and 1991–2020 (two days). For the other seasons it is significant to observe that there are lower values in summer for the periods 1931–1960 and 1991–2020, compared to 1961–1990.

In order to understand climatic changes, not only on average through the histograms (Figure 6; Figure 7), but also from the spatial point of view, some maps were created by subtraction between rasters in the GIS environment. From these maps it is possible to evaluate, graphically, the areas more or less subject to precipitation and changes in rainy days. In this context, a general decrease in precipitation from the past to the present prevails; however, there are some important countertrends that affect the most recent standard period 1991–2020, in which it is possible to see an increase of precipitation in the southwest (Sibillini Mountains) and in a small central part (territory of Macerata) (Figure 8).

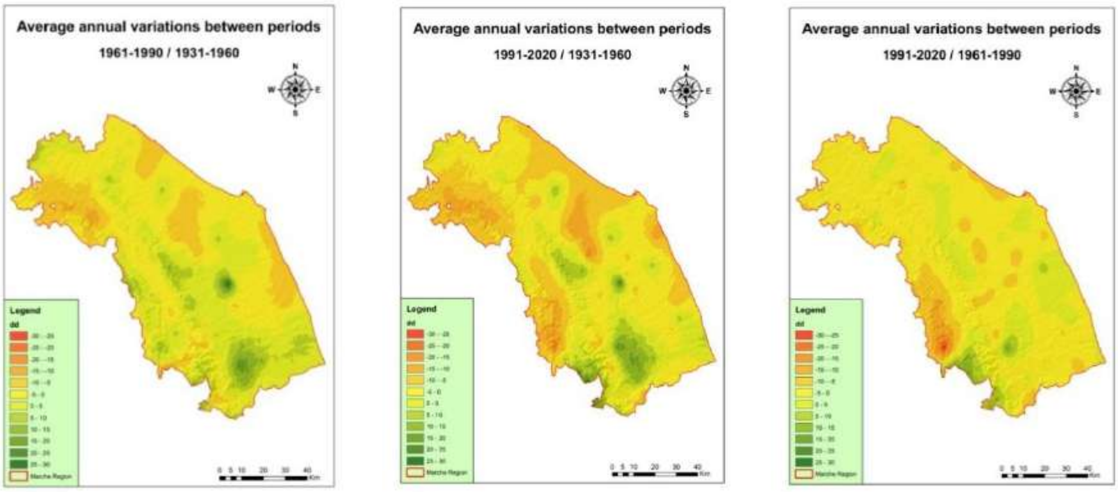


(**a**) (**b**) (**c**)

Figure 8. Variations in average annual precipitation (mm) for the periods ((**a**) 1931–1960; (**b**) 1961–1990; (**c**) 1991–2020).

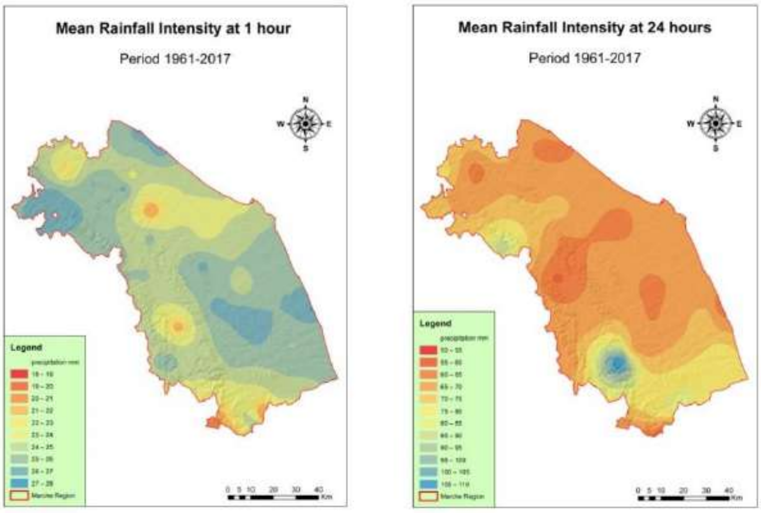
As far as rainy days are concerned, the comparison between 1961–1990 and 1931–1960 (Figure 9) shows a heterogeneous solution with an increase in the southern part and in the central hilly part, while the decrease is positioned in the remaining areas. The comparison between 1991–2020 and 1931–1960 from the point of view of areal distribution is very similar to what was previously observed with the comparison between 1961–1990 and 1931–1960 (Figure 9). Finally, between 1991–2020 and 1961–1990 there is a slight and homogeneous decrease, with only two different areas, located in the central–southern Apennine zone (in the south there is an increase, while in the center there is a more important decrease, in the last period).

In order to complete the rainfall analysis, a certain knowledge of extreme events is fundamental. Extreme events were assessed with the GEV method, after collecting data from about 60 years from 1961 to 2017. Initially, some correlation between the topographic variables and the extreme events that occurred was evaluated through linear regressions, in order to allow a more accurate interpolation; however, none of the topographic variables showed significant correlations, so that the method of interpolation used was changed to radial basis function instead of co-kriging. Before assessing extreme precipitation with a return time of 100 years, the available historical data were evaluated both for maximum intensity and mean intensity (calculated as an average of all the annual extreme precipitation of the period) over the period 1961–2017. The investigated intervals are the canonical 1–3–6–12–24 h; however, for practical reasons only the 1 and 24 h maps were shown. It is significant to observe the difference between the extreme average rainfall at 1 and 24 h, as they present a change in the reciprocal relationships between the rain gauges. In fact, in some cases the parts of the region with little rainfall for 1 h, compared to the average, become the rainiest (southwest) for 24 h and vice versa (southeast, northwest) (Figure 10).



(**a**) (**b**) (**c**)

Figure 9. Variations in average annual rainy days (dd) between periods ((**a**) 1931–1960; (**b**) 1961–1990; (**c**) 1991–2020).

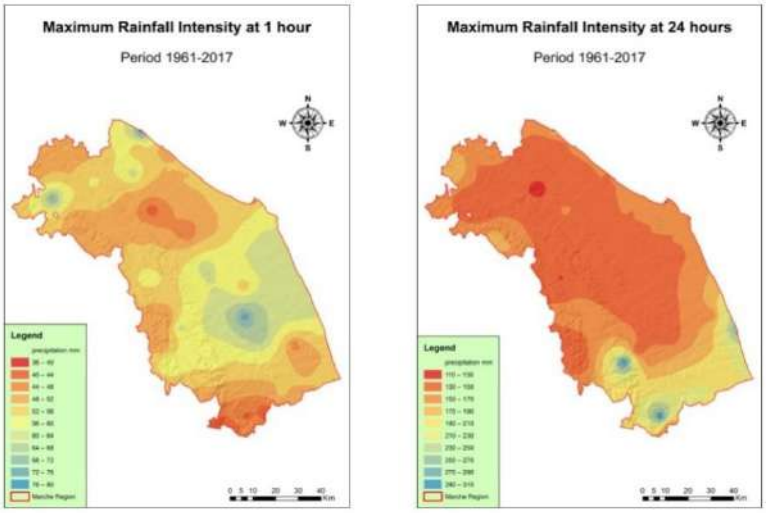


(**a**) (**b**)

Figure 10. Mean rainfall intensity (mm) in the period 1961–2017: (**a**) at 1 h, (**b**) at 24 h.

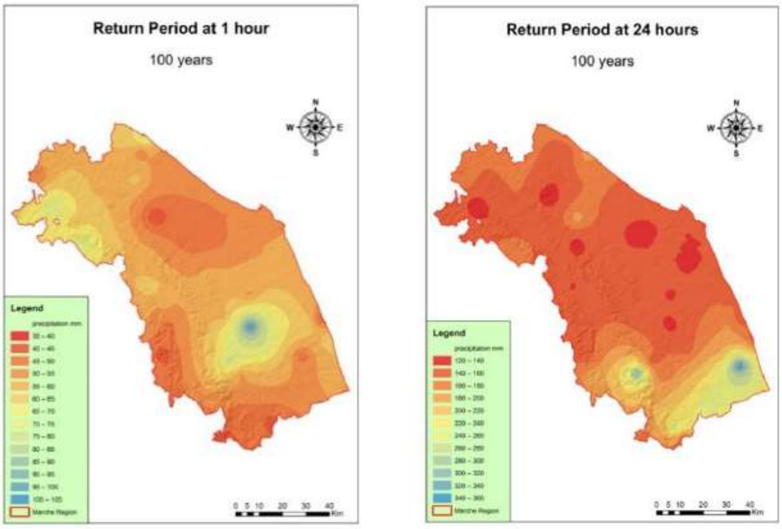
Additionally, when analyzing the maximum extreme rainfall in the period 1961–2017, it is possible to notice that there are changes in the reciprocal relationship between the rain gauges by analyzing the map at 1 and 24 h (Figure 11). There was a peak precipitation in the 1 h maps for the south–central part of the region (Province of Macerata), while in the 24 h map it returns to a low value compared to the rest of the region.

Finally, the values of extreme precipitation were calculated on the basis of the return period of 100 years, using the model GEV. In the 1 h map there is a large homogeneous area in which precipitation is contained, while in the 24 h map there is an increase in the extreme rainfall potential in the central–southern area (Figure 12). Therefore, it is interesting to note that in the 24 h map, the southern part of the region is potentially the wettest, up to more than 300 mm.



(**a**) (**b**)

Figure 11. Maximum rainfall intensity (mm) in the period 1961–2017: (**a**) at 1 h, (**b**) at 24 h.



(**a**) (**b**)

Figure 12. Estimated extreme precipitations (mm) with 100 years as the return period using (**a**) 1 h and (**b**) 24 h precipitation data.

4. Discussion

This research is an important climate report about precipitation for the Marche Region and the middle Adriatic side. Rainfall and rainy days were analyzed in three different climatological standard normals (1931–1960, 1961–1990, and 1991–2020), an example of completeness of the analysis that allows an in-depth evaluation of the latest climate changes [32]. The characterization of the precipitation of an area is a common practice that must be performed in order to have a correct framework [33,34]. This is significant because it is possible to identify the homogeneous areas and divide them into classes of precipitation or rainy days. The rainiest areas are the Apennines and pre-Apennines areas to the west, where the highest altitude of the region is located, as also found by Fratianni and Acquaotta, 2017 [35]. Then there is a hilly band with rainfall that decreases until it reaches the minimum in the coastal area, particularly in the southeastern part. The average number of rainy days follows the same pattern as rainfall, with more rainy days in the mountains and less in the coastal areas. Worldwide, research on mean rainfall and rainy days are usually carried out only on one climatological standard normal period [36] or over longer non-standard periods, which are difficult to compare with the rest of the world [34,37]. The results observed in this study are in agreement with other research previously carried out in the Mediterranean basin [38,39] and show a decreasing trend in the average annual precipitation. In this study a strong relationship with altitude was observed, which justifies spatial variations in precipitation distribution [40]. In any case, there is a good relationship between the climatic variable also with the distance from the sea because of its mitigating influence. The precipitation–altitude relationship is often used worldwide in order to improve data interpolation, although it assumes different ratios depending on the area investigated [41,42]. In the twentieth century, rainfall increased slightly overall [43], although conditions on the continental level [44] and even more so on the local level differ greatly. In this study, a strong downward trend in the amount of precipitation from 1921 to 2017 has been identified, with 86% of rain gauges declining and 25% of the total having a significant negative trend [45,46]. The same decrease was observed by comparing the different climatological standard normals, as can be seen in other parts of Europe [46]. In the last period, some studies have shown the influence of Arctic ice on the precipitations that take place in Europe in the summer season [47]. This condition determines an increase in northern Europe and a decrease in the southern part, including Italy, reflecting the situation observed in this study in the last climatological standard normal. The rainy days are decreasing in accordance with other studies on the Italian peninsula [48]. In addition, the evaluation by interpolation of the countertrend in the Macerata area (south–central part of the region) and in the Sibillini mountains was significant (southwestern part) (Figure 8), in the last standard period, is significant. In fact it follows that, even in a context of a general decrease in rainfall averages by decreasing the scale of observation, there may be climatic dynamics that determine reversals in the trend [49]. Although it has been shown that extreme precipitation is affected by topography [50,51], no significant relationships have been found in this study, although it is not excluded that they may exist. The analysis of extreme events in this area, in the last 60 years, show a similarity for 1 and 3 h intervals, with a large amount of precipitation in the coastal area and especially without a quantitative prevalence of the mountain area, as would be expected. For subsequent intervals (6, 12, 24 h) there is a homogeneity in the spatial distribution with a clear prevalence in the amount of precipitation for the southern part of the Region, for both maximum and average extreme events of the period. The growth of extreme precipitation events is significant, especially in the southern part of the Marche Region, characterized mainly by a Mediterranean-type climate which promotes extreme events [52], as compared with the central–northern part of it. In any case, recent researches show, through regional climate models, that there will be a generalized increase in extreme events in the next 100 years [53]. Instead the values obtained on the basis of the return period set at 100 years show a peak for 1 and 3 h near Macerata (central–southern area of the region), while for 6, 12, and 24 h the peak is displaced on the southern part of the region.

5. Conclusions

The analysis of trends of rainfall and rainy days has produced satisfactory results, in fact all the data of the rain gauges existing in the Marche Region since 1921–2017 have been collected. In addition, the relationship of rainfall and rainy days with altitude has allowed an accurate interpolation using the co-kriging methods. Instead, for extreme precipitation we can conclude that they are not particularly influenced by geotopographic parameters, but, rather, above all by weather and climate dynamics, although it would be interesting to investigate this further in the future. The innovation of this method is aimed at a detailed mapping of the territory with the definition of trends and amounts for each single area. Generalizations over large areas are very important; however, small-scale applications allow for the preparation of immediately operational systems, aimed at reducing the problems associated with extreme events. However, all these climate considerations are part of the consequences, hence it would be very important in the future to evaluate the atmospheric dynamics that generate these events, in order to better understand the causes and complete the climate framework of the region investigated.

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