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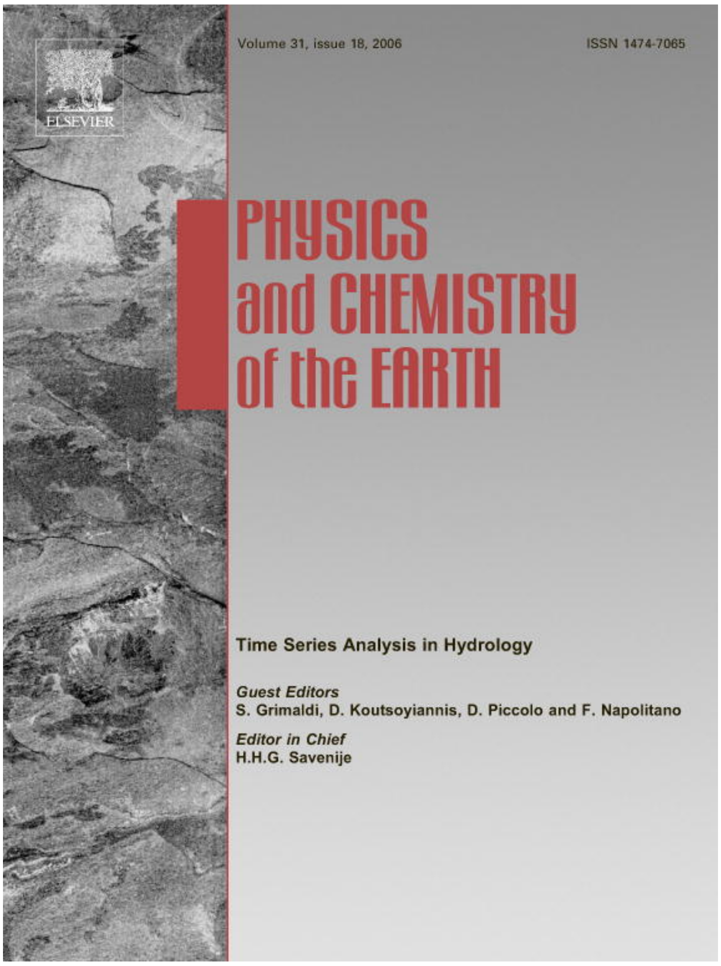

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Spatial distribution of rainfall trends in Sicily (1921–2000)

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Abstract

The feared global climate change could have important effects on various environmental variables including rainfall in many countries around the world. Changes in precipitation regime directly affect water resources management, agriculture, hydrology and ecosystems. For this reason it is important to investigate the changes in the spatial and temporal rainfall pattern in order to improve water management strategies.

In this study a non-parametric statistical method (Mann–Kendall rank correlation method) is employed in order to verify the existence of trend in annual, seasonal and monthly rainfall and the distribution of the rainfall during the year. This test is applied to about 250 rain gauge stations in Sicily (Italy) after a series of procedures finalized to the estimation of missing records and to the verification of data consistency.

In order to understand the regional pattern of precipitation in Sicily, the detected trends are spatially interpolated using spatial analysis techniques in a GIS environment.

The results show the existence of a generalized negative trend for the entire region.
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Keywords: Trend detection; Rainfall; Spatial analysis; Climatic change

1. Introduction

The historical observation of climatic variables is receiving a more and more considerable attention, as many scientists are attempting to verify whether or not there is a detectable climate signal change subsequent to the greenhouse effect. Indeed in recent years several extreme events have caused large losses of life, as well as a tremendous increase in economic losses from weather hazards. These life and property losses helped to raise the alarm over the possibility that the recent events were due to a climate change (Easterling et al., 2000). One of the most important necessities of research into climate change (IPCC, 1996) is to analyze and detect historical changes in the climatic system. In this general context, and especially in Mediterranean areas, rainfall is the most important climatic variable owing to its manifestation as a deficient resource (droughts) or a catastrophic agent (floods).

Several studies have been carried out at different temporal scales (from daily to annual) and in different world areas. Existing analyses of daily series show for some areas a positive trend in the daily precipitation intensity and a tendency toward higher frequencies of heavy and extreme rainfall in the last few decades (Houghton et al., 1996). The main areas where significant positive trends have been observed are the USA (Karl et al., 1995; Trenberth, 1998; Kunkel et al., 1999), eastern and northeastern Australia (Suppiah and Hennessey, 1998; Plummer et al., 1999), South Africa (Mason et al., 1999), the UK (Osborn et al., 2000) and northern and central Italy (Brunetti et al., 2000, 2001). In most of the areas with a positive trend in rainfall intensity, an increase in total precipitation has also been observed (Groisman et al., 1999). This relationship is,

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however, not universal, as in some areas (i.e. Italy) an increase in heavy precipitation has been observed together with a tendency toward a decrease in total precipitation (Brunetti et al., 2001). Besides the increase in precipitation intensity, there are some indications that the overall percentage of the Earth's surface affected by either drought and/or excessive wetness has increased (Dai and Trenberth, 1998). Gemmer et al. (2004) analyzed the annual rainfall series of 160 stations in China. They observed a spatial clustering of the trends in certain months, including district trend belts especially in east and northeast China.

Regarding the Mediterranean areas, previous studies have found an annual decreases in precipitation: eastern part (Amanatidis et al., 1993; Kutiel et al., 1996), central part (Giuffrida and Conte, 1989; Piervitali et al., 1998) and western part (Esteban-Parra et al., 1998; De Luis et al., 2000). Different previous studies analyzed trend of hydrological variables for the island of Sicily (Italy—Southern-center of Mediterranean sea). Among these Cannarozzo (1985) found a generalized decrease of annual rainfall while a decreasing trend has been detected for some rain gauges around Palermo area (Aronica et al., 2002). Bonaccorso et al. (2005) analyzed the trends in annual maximum rainfall series finding different behaviors according to the different time scale. In particular for shorter durations the rainfall series generally exhibit increasing trends while for longer duration more and more series exhibit decreasing trends.

In this context this study is aimed at quantifying the trends in rainfall series in about 250 locations of the island of Sicily (Italy) and to point out the presence of spatial pattern of these trends.

2. Dataset and methodology

Monthly rainfall data records for 1921–2000 from 247 stations across the Sicily, from the Ufficio Idrografico Regionale (UIR) dataset, have been analyzed to describe any changes in annual, monthly and seasonal rainfall amount. For rainfall trends investigation only homogeneous and complete series covering this period are used, so a method of spatial interpolation is used to create a complete data set (Bono et al., 2005). The percentage of missing data, which have been reconstructed, was around 16% and the largest percentage of missing data was present especially during the Second World War period (72% of missing data). For each station, annual (Fig. 1) and seasonal rainfall have been calculated.

Regional analysis of the trend, for the entire island of Sicily, was performed for all the above described variables. The presence of at site and regional trends was evaluated over three timeframes: first on a 80 years (1921–2000) temporal window, and second on two 30 years (1930–1960 and 1960–1990) suggested periods given by the WMO (World Meteorological Organization). The analysis carried out on the WMO periods was made with the aim to create a common scientific discussion field for Mediterranean climatologic studies and to test how the temporal position influences the at site and regional trends analysis.

Another hydrological variable was used in this study in order to analyze monthly heterogeneity of rainfall amounts. This variable is a modified version of Oliver's (1980) precipitation concentration index (PCI) (De Luìs et al., 1997). This index, described as

$$PCI = 100 \cdot \frac{\sum_{i=1}^{12} p_i^2}{\left(\sum_{i=1}^{12} p_i\right)^2} \quad (1)$$

where p_i is the rainfall amount of the ith month, has been calculated for each of the 247 locations and for each of the 80 years being considered. As described by Oliver (1980), PCI values below 10 indicate a uniform monthly rainfall distribution in the year, whereas values from 11 to 20 denote seasonality in rainfall distribution. Values above 20 correspond to climates with substantial monthly variability in rainfall amounts.

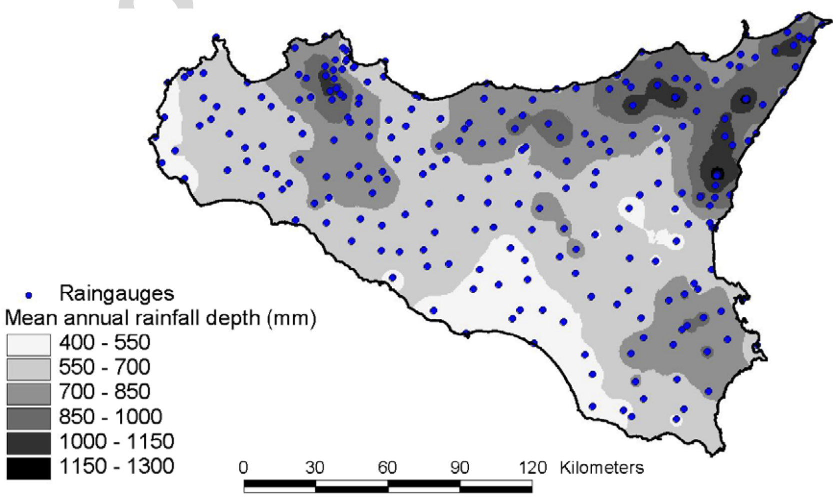

Fig. 1. Location of rainfall gauging stations and annual rainfall amount (1921–2000).

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2.1. Trend detection test

The time series of rainfall were analyzed using the Mann–Kendall non-parametric test for trend. Mann (1945) originally used this test and Kendall (1962) subsequently derived the test statistic distribution. This test allows to inquire on the presence of a tendency of long period in rainfall data, without having to make an assumption about its distributional properties. Moreover the non-parametric methods are less influenced by the presence of outliers in the data (Lanzante, 1996).

In trend test the null hypothesis H_0 is that there is no trend in the population from which the dataset is drawn; hypothesis H_1 is that there is a trend in the analyzed records.

Mann–Kendall test was applied to annual, monthly, and seasonal rainfall. The test statistic, Kendall's S, (Kendall, 1962) is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}(y_j - y_i) \tag{2}$$

where y are the data values at times i and j , n is the length of the data set and

$$\text{sign}(\vartheta) = \begin{cases} 1 & \text{if } \vartheta > 0 \\ 0 & \text{if } \vartheta = 0 \\ -1 & \text{if } \vartheta < 0 \end{cases} \tag{3}$$

The Mann–Kendall test has two parameters that are of importance for trend detection. These parameters are the significance level that indicates the test strength, and the slope magnitude estimate that indicates the direction as well as the magnitude of the trend. Under the null hypothesis that y_i are independent and randomly ordered the statistic S is approximately normally distributed when $n \geqslant 8$, with zero mean and variance as follows:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

The standardized test statistic Z, computed by

$$Z = \begin{cases} \frac{S-1}{\sigma} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sigma} & \text{if } S < 0 \end{cases} \tag{5}$$

follows a standard normal distribution (Kendall, 1962).

In this analysis confidence level at 90%, 95% and 99% were considered.

Local significance levels (p-values) for each trend test can be obtained from the fact that

$$p = 2[1 - \Phi|Z_s|] \tag{6}$$

where $\Phi(\cdot)$ denotes the cumulative distribution function (cdf) of a standard normal variate.

The non-parametric robust estimate of the magnitude of the slope, β of linear trend, determined by Hirsch et al. (1982), is given by

$$\beta = \text{Median}\left[\frac{(y_j - y_i)}{(j-i)}\right] \tag{7}$$

Confidence levels of the trend test and slopes of the trend were spatially interpolated using inverse distance weighted (IDW) interpolation method which gives a raster surface as output. IDW implies that each station has a local influence that decreases with distance by means of the use of a power parameter. This parameter controls the significance of measured values at the rain gauges on the interpolated value. The higher the power parameter, the more the importance for the nearest point. The power parameter in this study was set equal to three. The choice of a relatively high power ensures a high degree of local influence and gives the output surface increased detail (Gemmer et al., 2004).

2.2. Areal trend test

In order to evaluate the presence of a regional trend in rainfall we used the Regional Average Kendall's S (S_m) computed as

$$S_m = \frac{1}{m} \sum_{i=1}^{m} S_k \tag{8}$$

where S_k is the value of Kendall's S statistic in kth station in a region with m stations.

If stations are uncorrelated in space the standardized test statistic can be calculated with (Douglas et al., 2000):

$$Z_m = \frac{S_m - E(S_m)}{\sigma/\sqrt{m}} \tag{9}$$

where $E(S_m)$ is the expected value of S_m and σ is the same as defined above; the significance of Z_m can be computed from the cdf of a standard normal variate.

Lettenmaier et al. (1994) note that the effect of cross-correlation in space in the data is to increase the expected number of trends under the hypothesis of no trend in data. Livezey and Chen (1983) indicate the need to consider the field significance of the outcomes from a set of statistical test. The concept of field significance allows the determination of the percentage of tests that are expected to show a trend, at a given local (nominal) significance level, purely by chance. Douglas et al. (2000) adopted an approach in order to determine the field significance that involves calculating the regional value for the Mann–Kendall statistics.

A bootstrap, or resampling, approach (Efron, 1979) was used herein to determine the critical value for the percentage of stations expected to show a trend by chance. The null hypothesis for our trend tests was that the annual, monthly, seasonal rainfall data exhibit no trend, are spatially correlated and serially independent. We used the bootstrap method to determine the cumulative distribution function of S_m in Sicily, in order to determine the field significance associated with S_m computed from historical data.

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The bootstrap procedure can be summarized as follow (Burn and Hag Elnur, 2002):

- The first step is to extract randomly one year of the time series.
- For each station, rainfall data of this year are collected.
- The third step is the repetition of step 1 and 2 until a new data set, with the same dimension of the original one, is created.
- The statistic S_m is calculated for the new data set.
- The previous step are repeated for a number N of times, with the purpose to obtain N values of S_m that are used to define the cumulative distribution function F. In this work N was set to 1000.

The cumulative distribution function of S_m was obtained by ranking the 1000 values of S_m in ascending order and assigning a non-exceedence probability using the Weibull plotting position formula

$$F(S_{m,i}) = \frac{i}{1+N}; \quad i = 1, \ldots, N \tag{10}$$

The cumulative distribution function allows to define the level of significance associated with the historical S_m. The null hypothesis is accepted when this level of significance is greater than a prefixed confidence level.

3. Application of the methodology

3.1. At site analysis (1921–2000)

Initially the at site trends analysis was carried out using continuous series recorded in 247 Sicilian rain gauges from 1921 to 2000. Results obtained for annual data are summarized in Fig. 2 where, for assigned levels of significance (equal to 90%, 95% and 99%), the number of stations with negative or positive trends is reported.

The histograms show that most of rain gauges exhibits a negative precipitation trend, at all confidence levels. Particularly, 62% of analyzed stations (155 rain gauges) show significant negative trends at 95% confidence level. It is also remarkable that stations have no trend, vary from a minimum of 68 (90% confidence level) to a maximum of 141 (99% confidence level). The greatest decrease is detected in the East zone (Buccheri) where over the last 80 years reach 7.65 mm/year while the only one station showing a positive significant trend is Erice (2.86 mm/year) located in the North West.

The trend analysis has been led also using four seasonal datasets. The results (Fig. 3) show that winter season has the greatest number of negative trends. About 60% of the stations show a negative trend at 95% confidence level

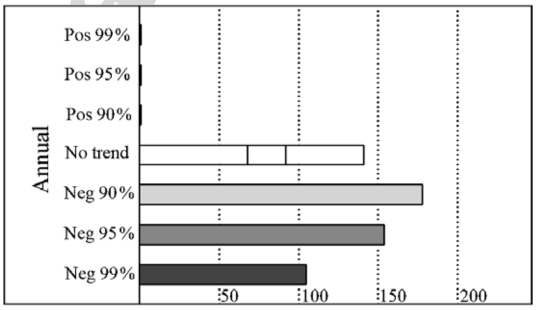

Fig. 2. Observed annual precipitation trends at the 90%, 95% and 99% confidence level. The *no trend* bar shows the number of stations with the three different confidence levels (the first vertical segment in the bar indicates the confidence level equal to 90%, the second one is for 95% while the third one is for 99%).

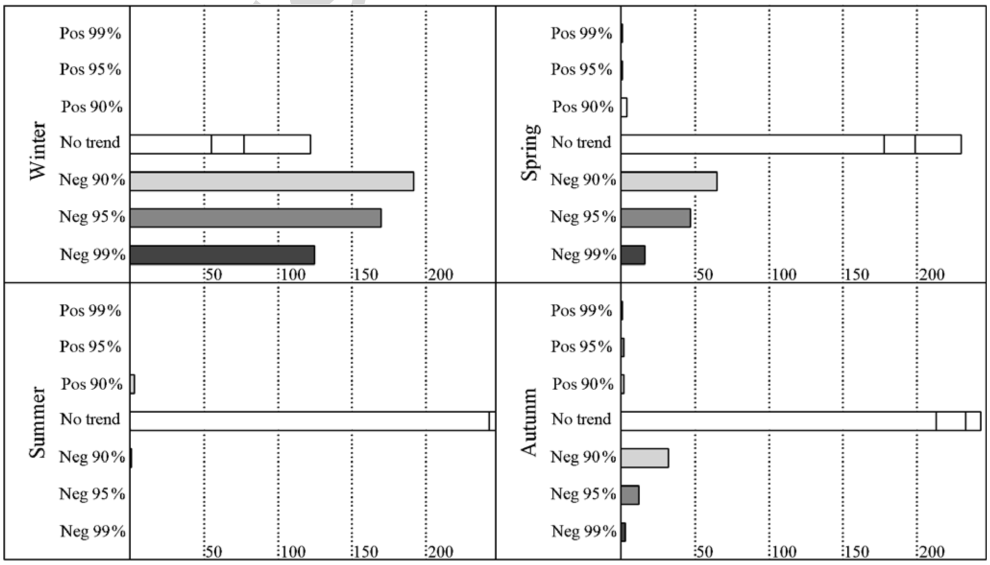

Fig. 3. Observed seasonal precipitation trends at the 90%, 95% and 99% confidence level. The *no trend* bar shows the number of stations with the three different confidence levels (the first vertical segment in the bar indicates the confidence level equal to 90%, the second one is for 95% while the third one is for 99%).

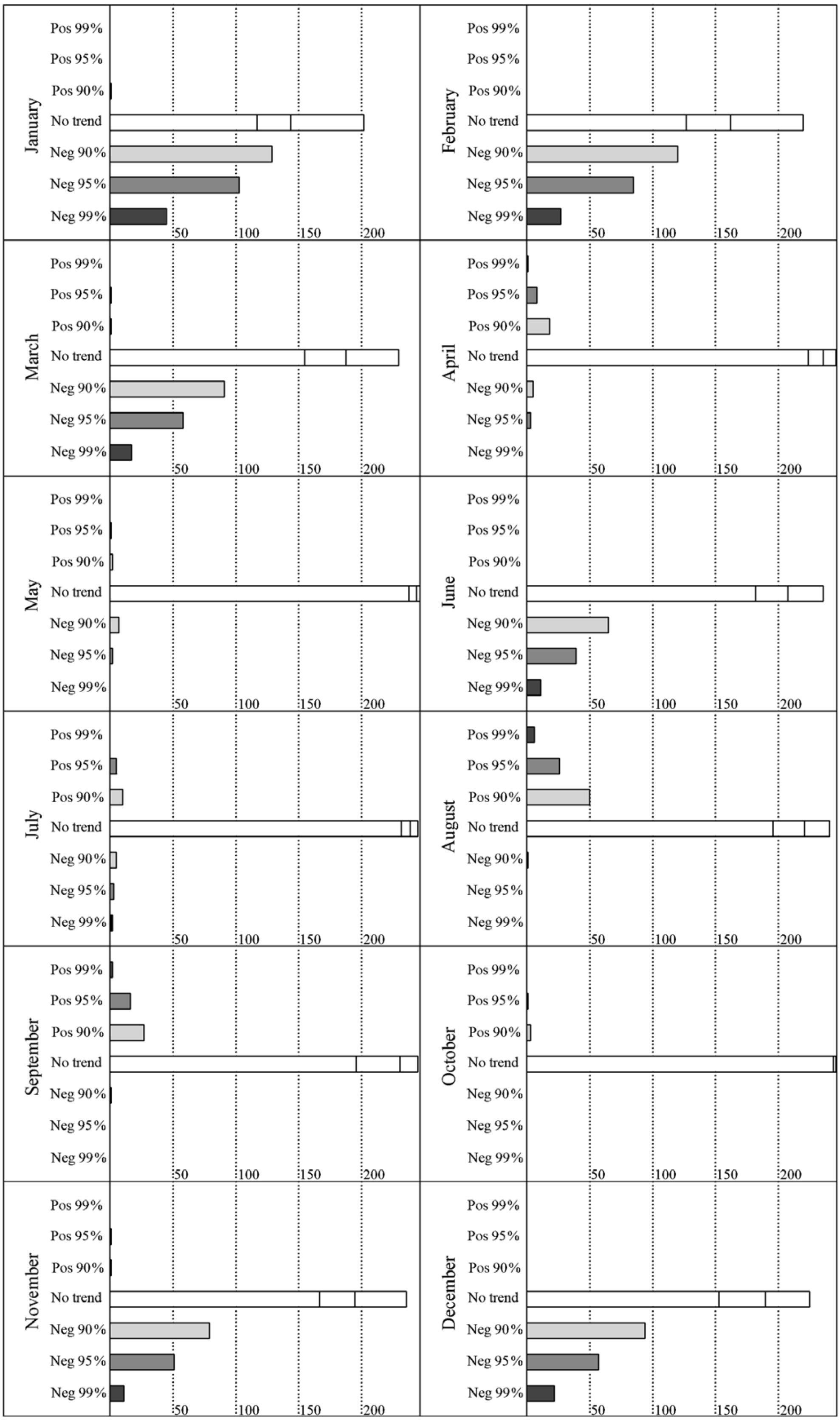

Fig. 4. Observed monthly precipitation trends at the 90%, 95% and 99% confidence level. The *no trend* bar shows the number of stations with the three different confidence levels (the first vertical segment in the bar indicates the confidence level equal to 90%, the second one is for 95% while the third one is for 99%).

and this percentage coincides almost exactly with the percentage of rain gauges which exhibits a negative trend at the same confidence level at the annual scale. Consequently it is possible to assert that precipitation reduction, whereas it exists, has regarded mostly the winter season. This behavior is due to the typical Mediterranean climate in which the most of annual precipitation (i.e. 40% in Sicily) is concentrated in the months of December, January and February. It is emphasized that at seasonal scale none positive trend has been found.

Several different situations have been found by analyzing the monthly rainfalls (Fig. 4). Particularly few months show a sizeable number of rain gauges with a statistically significant trend; among these ones, January and February exhibit 50% of stations with a significant negative trend at the 95% confidence level, while for March, June, November and December this percentage decreases to 35%. On the contrary, the only months which exhibit a positive trend are August and September with 10–20% of stations with a significant trend at the 95% confidence level.

3.2. Interpolated precipitation trends (1921–2000)

Local significance levels (*p*-values) for each trend test have been interpolated over the entire island of Sicily using the inverse distance weighting (IDW) method. Fig. 5 shows interpolated *p*-values for annual trend test; as the *p*-value decreases, the confidence level grows (i.e. low *p*-value corresponds to a low probability of making a mistake when asserting the presence of trends). The analysis of this figure shows that south-western part of Sicily is characterized by the presence of trend with high confidence level, while the eastern part has confidence level lower than the previous one. Fig. 5 is not able to point out the sign of the trend. This kind of information can be obtained from Fig. 6 which shows the interpolated precipitation trends for the annual

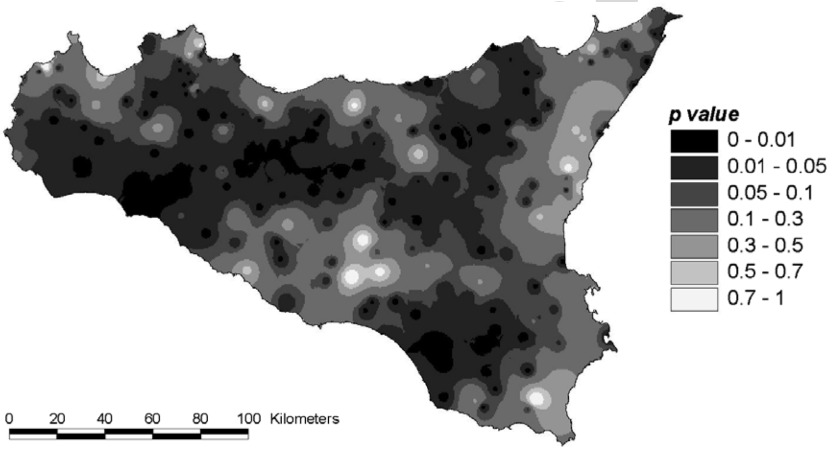

Fig. 5. Spatial distribution of *p*-value for annual precipitation (1921–2000).

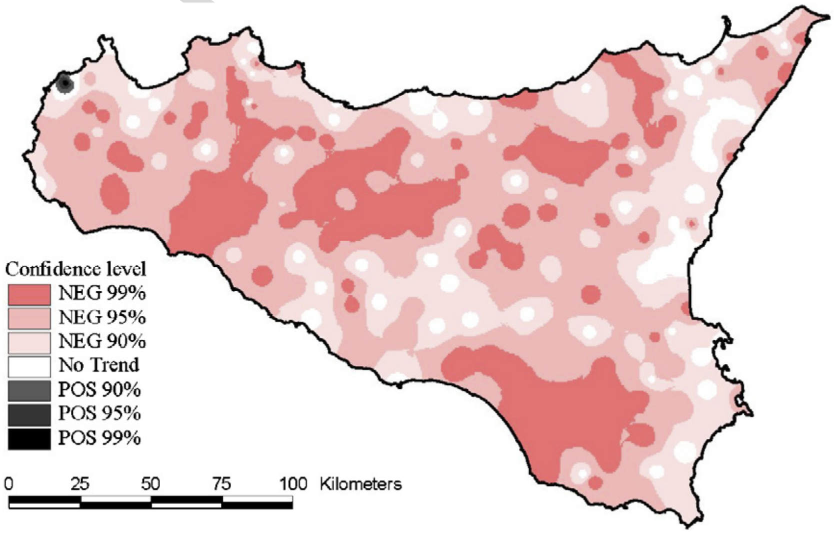

Fig. 6. Mann–Kendal precipitation test. Annual data (1921–2000).

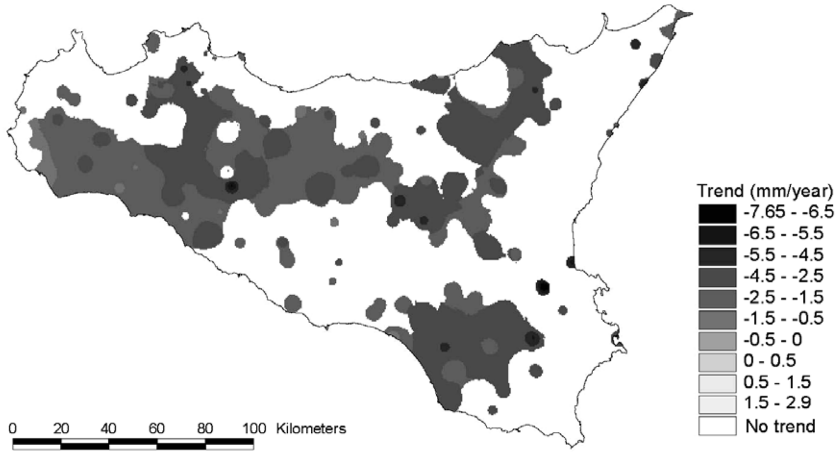

Fig. 7. Annual precipitation trend at 95% confidence level.

rainfall. The classes displayed are based on the confidence levels used in Figs. 2–4. This type of spatial presentation of detected precipitation trends enables a better understanding of climatic change in Sicily in the last 80 years, especially in terms of spatial pattern of these changes.

For a fixed significance level (i.e. 95%) the no trend area has been masked, and it is possible to show the magnitude of the trend in terms of slope magnitude β calculated using the (7) (Fig. 7). Many isolated points without a strong meaning and three large areas stand out from the masking operation. The detected three areas, covering the 35% of entire island, are somewhat irregular and seem to be not linkable to particular geographic conditions as morphology. The presence of these large contiguous areas with significant trend strengthen the at site results, even if the existence of a little number of sparse rain gauges without any apparent spatial correlation raises a legitimate doubt on the statistical and physical meaning of it. For this reason the spatial distribution of the magnitude of the trends, influenced also by the used interpolation method, is not still enough clear, nevertheless the high values of coefficient β lead to consider results as remarkable.

As mentioned above, in the winter season many stations exhibit negative trends, while in remaining seasons no remarkable tendency has been detected. For this reason the spatial distribution analysis of the trends for the winter season has been carried out. The results, shown in Fig. 8, highlight a different behavior between the eastern part of the island and the western – south western part. Even if almost the entire island shows a precipitation decrease in the winter season, this trend is less significant in the eastern part, while in the most part of western area the confidence level of this negative trend is equal to 99%.

The same spatial analysis was carried out using monthly rainfall data. As exposed in Section 3.1, January is the most remarkable month, with the highest number of significant negative trends and for this month spatial pattern of trends is shown in Fig. 9. As in the case of the winter season, the

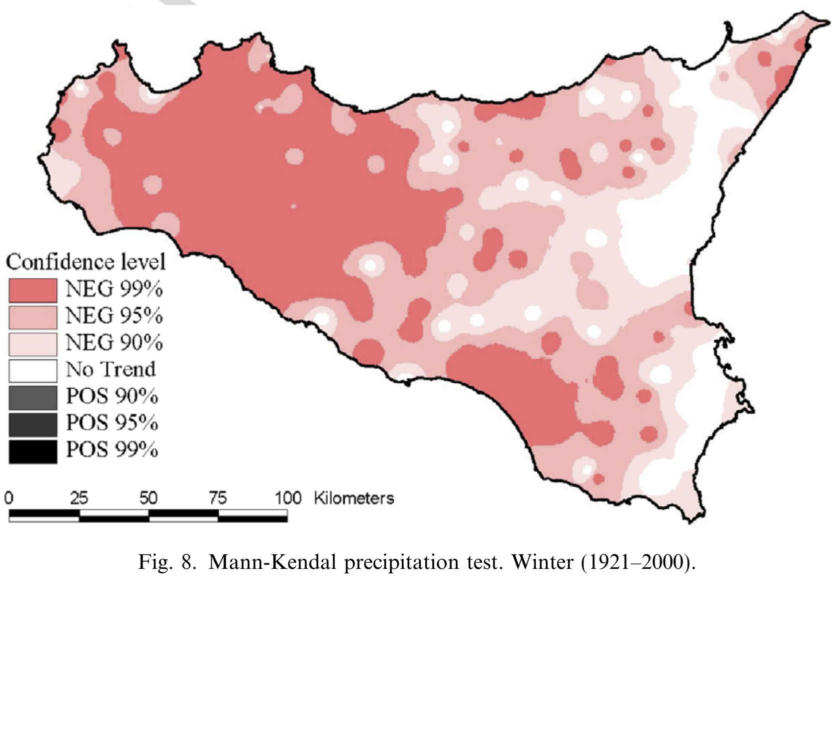

Fig. 8. Mann-Kendal precipitation test. Winter (1921–2000).

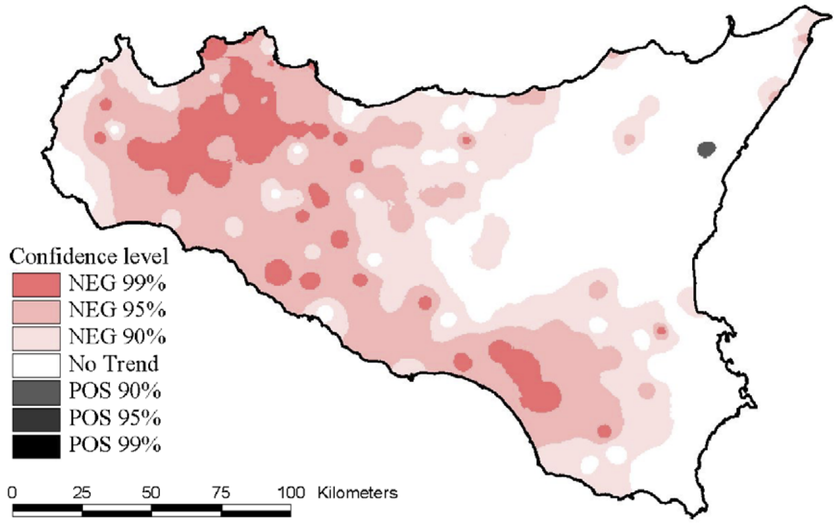

Fig. 9. Mann-Kendal precipitation test. January (1921–2000).

island appears distinctly divided in two main zone, the eastern, where no negative trend is found, and the western, where a significant precipitations decreasing trend is observed although with a strong spatial dependence. In this case the pattern of the negative trend is less pronounced than the case of the winter season.

The spatial distribution of rainfall trend in January, shown in Fig. 9, can be related to the one of the month of August (Fig. 10). This month is the only one presenting large areas with a significant positive trend and it is important to point out that for the areas with positive trends in August, no trends are detected in January.

The spatial distribution of the results of the application of Mann–Kendall test to the PCI at site (Fig. 11) points out a general steady situation in which the rainfall temporal distribution during the year has not been modified. Obviously the areas highlighted in Fig. 11 represent some exceptions. For these areas a negative trend involves a more and more uniform rainfall distribution during the year. This is a result not expected because it is general opinion that decreasing in annual rainfall involves a greater concentration of rainfall during the year.

In order to evaluate trends at regional scale the *regional average Kendall* coupled with *bootstrap analysis* based on annual, monthly and seasonal data have been employed. In Fig. 12 the empirical bootstrap cdf for annual precipitation is shown. The analysis carried out for the entire island leads to a value of S_m equal to -563; since this value is smaller than the S_m value (-298) related to the 95% confidence level, the null hypothesis must be rejected and for this reason the Sicily exhibits a negative regional trend with a confidence level of 95%.

All regional trends analysis results are summarized in Table 1, where "T_{MK}" indicate the Mann–Kendall statis-

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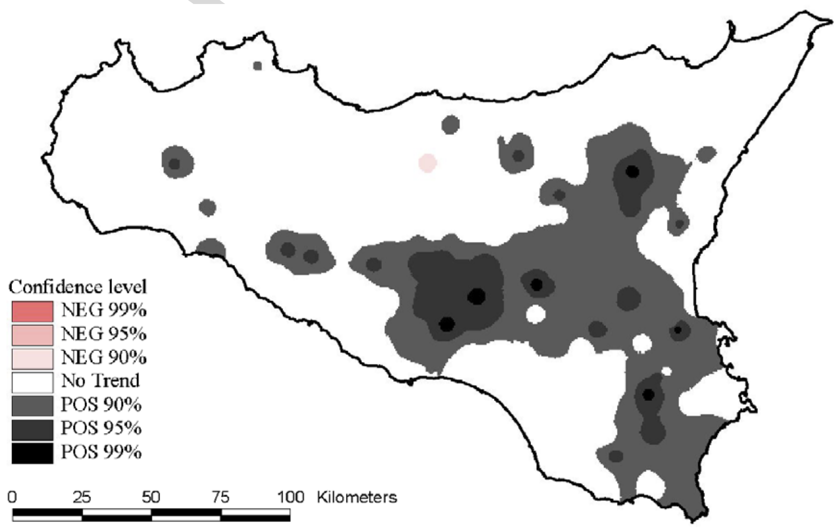

Fig. 10. Mann-Kendal precipitation test. August (1921–2000).

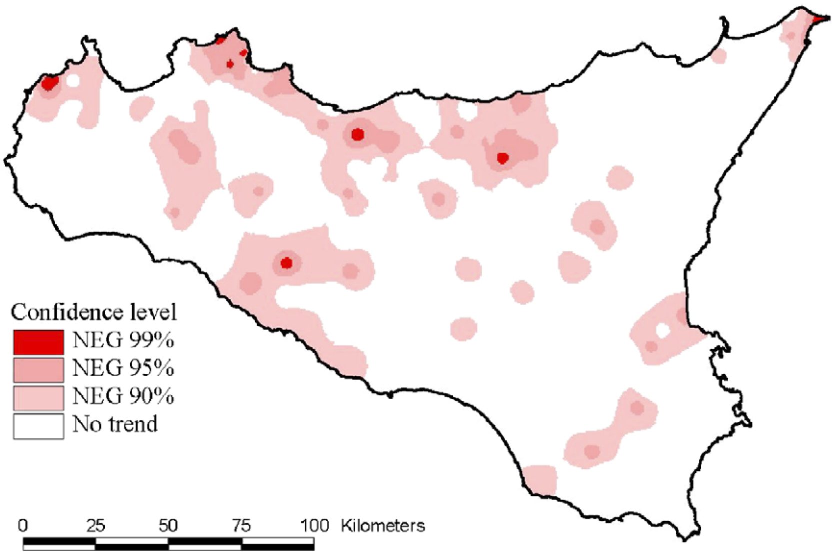

Fig. 11. Trends in monthly precipitation concentration index (PCI).

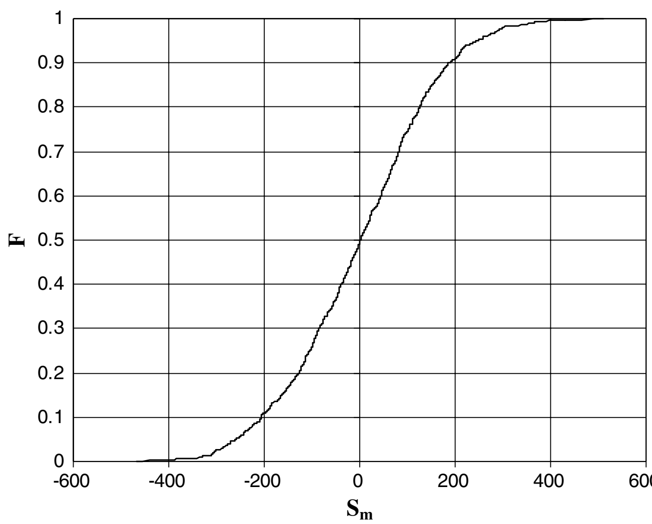

Fig. 12. Bootstrap cumulative distribution function (cdf) for annual precipitation.

tic, while "T_B" is related to the bootstrap analysis, and dots indicate that the null hypothesis must be rejected. The analysis of Table 1 shows that the regional average Kendall approach leads to detect more regional trends, at different time scale, than the bootstrap procedure. For January, February and winter data the presence of a regional trend is confirmed until the 95% confidence level.

Even if the use of bootstrap analysis should exclude the influence of spatial cross-correlation, further *regional average Kendall* and *bootstrap analysis* have been carried out using annual data coming from a subset of 50 stations with the lowest number of interpolated data, in order to dispel the doubt that the data reconstruction introduce spurious spatial correlations, that may affect the results of the trend analysis.

At the annual scale, regional trends exist at all considered confidence level for both procedures and for both the datasets analyzed; this result confirms the presence of a negative rainfall trend in Sicily in the last 80 years.

3.3. Rainfall trends analysis in suggested WMO periods

The precipitation trends analysis has been carried out considering 1931–1960 and 1961–1990 periods, that represent the reference periods indicated by the WMO (World Meteorological Organization) for climatologic studies. In general for both periods negative tendencies are observed. The number of station in which a significant trend is

Table 1
Regional trend analysis results

	$\alpha = 0.1$		$\alpha = 0.05$		$\alpha = 0.01$	
	T_{MK}	T_B	T_{MK}	T_B	T_{MK}	T_B
Annual	•	•	•	•	•	•
January	•	•	•	•	•	
February	•	•	•	•	•	
March	•	•	•		•	
April						
May						
June	•		•		•	
July						
August	•		•		•	
September	•		•			
October						
November	•	•	•		•	
December	•	•	•		•	
Winter	•	•	•	•	•	
Spring	•		•		•	
Summer						
Autumn						

Dots indicate trend existence.

detected is reported in Table 2 for the three considered periods, for a confidence level equal to 95%.

The analysis of the results, shown in the Table 2, points out a strong difference between the stations percentage presenting an annual trend for the three periods. As mentioned above in Section 3.1, for the 1921–2000 period, 62% of stations have significant trends at 95% confidence level for annual data. This high and meaningful percentage value is four time greater than the percentage of rain gauges presenting an annual trend for 1931–1960 and 1961–1990 periods. This deep difference has been also found in January and, less pronounced, in March, November and in the winter season.

These results has led in the belief that observed annual precipitations reduction in 1921–2000 period was not gradual, but sharp, keeping rainfalls practically constant in 1931–1960 and 1961–1990 periods. Nevertheless, more elaborations on rainfall data are required to verify such conclusion. It is common knowledge that natural changes are never abrupt, otherwise an external interference, sometimes shattering, exists.

Seasonal data analysis has demonstrated that the summer season in the 1921–2000 period is steady, while a number of significant trend in 1931–1960 and a few more in 1961–1990 periods are detected.

The analysis of the monthly data points out that the first WMO period exhibits a number of rain gauges with significant trend greater than the second period. February has shown a peculiar behavior: the percentage of stations with a significant trend is almost the same in both 1921–2000 and 1931–1960 periods, while in the 1961–1990 period is roughly zero. The presence of these anomalies suggests to carry out further studies and investigations on the rainfall gauging systems evolution even if the rainfall data have been released after a homogeneity check using standard normal homogeneity test (Alexandersson, 1986).

Table 2
Number of stations with significant trends in the periods 1921–2000, 1931–1960 and 1961–1990 for $\alpha = 0.05$

$a = 0.05$	1921–2000	1931–1960	1961–1990
Annual	155	36	44
Moving average	230	193	227
January	103	3	18
February	85	71	1
March	59	1	1
April	11	22	1
May	3	21	2
June	39	18	20
July	8	5	9
August	26	1	6
September	16	5	12
October	1	46	17
November	52	3	22
December	57	37	23
Winter	170	65	51
Spring	48	15	6
Summer	0	9	37
Autumn	14	18	8

4. Conclusions

The aim of this work was to study rainfall trend in Sicily and its spatial distribution. The application was led using monthly data, recorded or reconstructed from 247 rain gauge station during the period 1921–2000. These stations are quite regularly distributed over the island. Available data were aggregated to obtain seasonal and annual dataset, so the trend analysis was carried out for each historical series.

The results have shown that positive trends are very infrequent and have been found only for few stations and in summer months. Significant negative trends are instead much more common mainly in annual and winter data. A great number of stations with a statistically significant negative trend are located in the western and south-western part of the island. Anyway, no trend for every temporal scale is quite frequent.

Rainfall temporal distribution during the year has been studied by PCI because it is general opinion that decreasing in annual rainfall involves a greater concentration of rainfall in time. Instead a general steady situation was detected and furthermore few stations has shown negative trend.

To create a common scientific discussion field for Mediterranean climatologic researches, analysis on two WMO periods was carried out. The results disagree with those ones obtained for the 1921–2000 period because in the latter case significant negative trend are much less frequent. The presence of these anomalies suggests to carry out further studies and investigations. At the annual scale, a negative regional trend was detected using two different procedures and this fact consolidates the presence of a negative rainfall trend in Sicily in the last 80 years.

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