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Spatial distribution and trend analysis of extreme rainfall time series in Apulia region (Italy)

Abstract: Roseto R., Dellino P., Schena P., Capolongo D., *Spatial distribution and trend analysis of extreme rainfall time series in Apulia region (Italy).* (IT ISSN 0391-9838, 2023). Extreme rainfall events have been extensively studied at different spatial scales over the Mediterranean and Italian territory. Different interactions between atmospheric disturbances and morphological features have been found, mainly depending on precipitation duration and geo-graphical position. While climate change is shown to be responsible for the increase of frequency and intensity of extreme rainfall, the analysis of temporal trends at the national scale does not show significant variations and calls for more detailed studies. The main purposes of this study were both to investigate how the main geographical features of Apulia region controlled the spatial distribution of the extreme precipitations of short duration and to carry on a time-series analysis. The parameters of the Depth-Duration-Frequency (DDF) curves were correlated to elevation, latitude, longitude, distance from the sea and aspect by means of both Simple Linear Regression and Multiple Linear Regression. A wide range of duration were considered, spanning from 1 hour to 5 days. The Mann-Kendall non-parametric test was used as to demonstrate the significance of trend analysis. Multiple Linear Regression shows to overperform the Simple Linear Regression results, revealing that elevation has the strongest correlation with the DDF parameters, followed by longitude and distance from the sea. A slight increase of the sub-daily precipitation and a decrease of the multi-daily precipitation results from trend analysis, whereas no significant differences emerged during the climate normal 1991-2020. A set of maps are also presented as to point out the occurrence of local anomalies related either to the spatial variation of the DDF parameters and to the temporal trend direction. The outcomes of this study reveal the growing importance of this type of analysis, as well as the differences resulting from performing Simple and Multiple Linear Regression over time series related to a wide range of rainfall duration.

Key words: Rainfall, Extreme rainfall analysis, Time-series analysis, Statistical analysis, Apulia region, Climate change.

Riassunto: Roseto R., Dellino P., Schena P., Capolongo D., *Distribuzione spaziale e analisi dei trend delle serie temporali di precipitazioni estreme nella regione Puglia (Italia).* (IT ISSN 0391-9838, 2023). Gli eventi pluviometrici estremi sono stati ampiamente studiati a diverse scale spaziali sia nell'area mediterranea che in territorio italiano. Sono state evidenziate diverse interazioni tra le perturbazioni atmosferiche e le caratteristiche morfologiche, che dipendono principalmente dalla durata delle precipitazioni e dalla posizione geografica. Mentre il cambiamento climatico si dimostra responsabile dell'aumento della frequenza e dell'intensità delle precipitazioni estreme, l'analisi dei trend temporali a scala nazionale non mostra variazioni significative e richiede studi più dettagliati. Gli obiettivi principali di questo studio sono stati indagare come le principali caratteristiche geografiche della regione Puglia controllino la distribuzione spaziale delle precipitazioni estreme di breve durata e di effettuare un'analisi delle tendenze delle serie temporali. I parametri delle curve di probabilità pluviometrica (DDF) sono stati correlati all'altitudine, alla latitudine, alla longitudine, alla distanza dal mare e all'esposizione mediante Regressione Lineare Semplice e Regressione Lineare Multipla. È stata considerata un'ampia gamma di durate, da 1 ora a 5 giorni. Il test non parametrico di Mann-Kendall è stato utilizzato per dimostrare la significatività dell'analisi delle tendenze. I risultati della regressione lineare multipla mostrano che l'altitudine ha la correlazione più forte con i parametri DDF, seguita dalla longitudine e dalla distanza dal mare. Dall'analisi dei trend si evidenzia un leggero aumento delle precipitazioni a scala oraria e una diminuzione di quelle a scala giornaliera, mentre non sono emerse differenze significative durante la norma climatica 1991-2020. Vengono inoltre presentate una serie di mappe per evidenziare la presenza di anomalie locali legate sia alla variazione spaziale dei parametri DDF sia alla direzione dei trend delle serie temporali. I risultati di questo studio rivelano la crescente importanza di questo tipo di analisi, nonché le differenze derivanti dall'esecuzione di Regressioni Lineari Semplici e Multiple su serie temporali relative a un ampio intervallo di durata delle precipitazioni.

Termini chiave: Precipitazioni, Analisi delle precipitazioni estreme, Analisi delle serie temporali, Analisi statistica, Regione Puglia, Cambiamenti climatici.

INTRODUCTION

In recent decades, the Mediterranean region has experienced a surge in extreme climate events, such as heavy rainfall and droughts, which have significantly impacted the region's

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socio-economic well-being (Piccarreta *et al.*, 2013). According to the European Environment Agency, in Europe during the period 1980-2020 the economic losses from weather and climate-related events amounted to EUR 450-520 billion (in 2020 euros) and fatalities during the same period amounted to between 85.000 and 145.000 (https://www.eea.europa.eu/publications/economic-losses-and-fatalities-from/economic-losses-and-fatalities-from, last accessed Jun 10th, 2024). A report by the Italian Institute for Environmental Protection and Research (ISPRA) states that Italy's complex terrain and orography make it particularly susceptible to landslides and floods (Trigila *et al.*, 2018). It is widely believed that climate change is increasing the frequency and intensity of such extreme rainfall events (IPCC, 2019; Yin *et al.*, 2018), although their effects are not uniformly distributed (Tabari *et al.*, 2019). Numerous studies have explored the connection between the spatial distribution and intensity of extreme rainfall events, along with their trends and other geographical and morphological factors in Italy. However, a key challenge in this research is the limited availability of rainfall statistics due to the difficulties in constructing high-quality, large-scale time-series datasets (Mazzoglio *et al.*, 2020, Pelosi *et al.*, 2022). The analysis of extreme events trends over the Italian territory resulted in not statistically significant variations (Brunetti *et al.*, 2004). A study focusing on Southern Italy revealed how, for most durations, the extreme precipitation trends were not statistically significant (Avino *et al.*, 2024). Moreover, increasing trends were often observed for shorter durations at specific locations, but these trends typically diminished or vanished for longer-duration rainfall events (Avino *et al.*, 2024). A notable finding was the dependence of short-duration extreme precipitations on orography, particularly the "reverse orographic effect", which is the decrease of maximum annual precipitation with elevation (Avanzi *et al.*, 2015).

An high-quality dataset called I2-RED (Italian Rainfall Extreme Dataset) (Mazzoglio *et al.*, 2020), confirmed the presence of the reverse orographic effect and highlighted the spatial persistence of extreme rainfall in coastal areas, possibly due to the intricate interplay between orography and the sea. Additional research has focused on smaller regions within Italy, with varying results. For instance, regarding the rainfall-orography relationship, a significant decrease in maximum annual short-duration precipitation with elevation in the Alpine region was observed (Allamano *et al.*, 2009), while no significant changes were found in heavy rainfall trends in the Umbria region over the last 50-70 years (Cifrodelli *et al.*, 2015). A regional frequency analysis of extreme rainfall in Sicily allowed to provide a detailed analysis of characteristics of these events and showed an increasing trend in their intensity (Forestieri *et al.*, 2017). These findings emphasize the importance of a multiscale approach to provide a more accurate understanding of localized trends, as the outcomes of national-scale trend analyses do not reveal significant changes (Libertino *et al.*, 2018; Mazzoglio *et al.*, 2022b).

As for the Apulia region, researchers have reported both a decrease in mean annual precipitation and an increase in the intensity of maximum 5-day precipitation (Boenzi *et al.*, 2007; Cherubini *et al.*, 2007). The Apulia region can be subdivided into two domains based on precipitation type, with stratiform precipitation dominant in the north and convective precipitation more frequent in the south (Cotecchia, 2014).

The aim of this study is to relate extreme precipitation of different durations to the region's main geographical factors by means of both Simple Linear Regression (SLR) and Multiple Linear Regression (MLR). A trend analysis on the extreme precipitation hourly and daily time series is also performed as to investigate how climate change affected the frequency and intensity of these phenomena in recent decades.

STUDY AREA

The dataset of hourly and daily extreme rainfall time series, from which 90 pluviometric stations were selected for this study, extends throughout the entire Apulia region and the upstream area of Ofanto river, which includes also small areas belonging to the Campania and Basilicata regions. The area extends in a NW-SE direction for around 350 km, spanning different geomorphological domains (fig. 1a).

In the northern area three different geomorphological domains can be distinguished: the mountains of Subappennino Dauno, the Tavoliere plain and the Gargano promontory. The Subappennino Dauno, where the highest elevation of the region is reached (M. Cornacchia, 1152 m), borders the Apulia territory with the Campania region. The Tavoliere plain extends from the Subapennino Dauno to the Manfredonia Gulf and the Gargano promontory, a mountain massif that sticks out into the Adriatic Sea. The middle section is dominated by the Altopiano delle Murge, an inland plateau that gently slopes till the Adriatic coast and extends in Southeast direction to the Taranto-Brindisi line. The southern area, the Salento Peninsula, divides the Adriatic from the Ionian Sea. It is mostly flat, except for the presence of low altitude reliefs named Serre.

Due to the predominant presence of karstic rocks, which characterize all the domains, going from the Gargano promontory to the Serre Salentine (except for the Subapennino Dauno area), there are neither major rivers nor a well-developed river network in the entire regional territory, despite the presence of a complex groundwater reservoirs system (Parise, 2003). The major river is the Ofanto river, which is approximately 170 km long (De Santis *et al.*, 2018). It springs in the Campania region and crosses the Apulia region for around 50 km before flowing into the sea, near Barletta. The upstream area of the Ofanto catchment

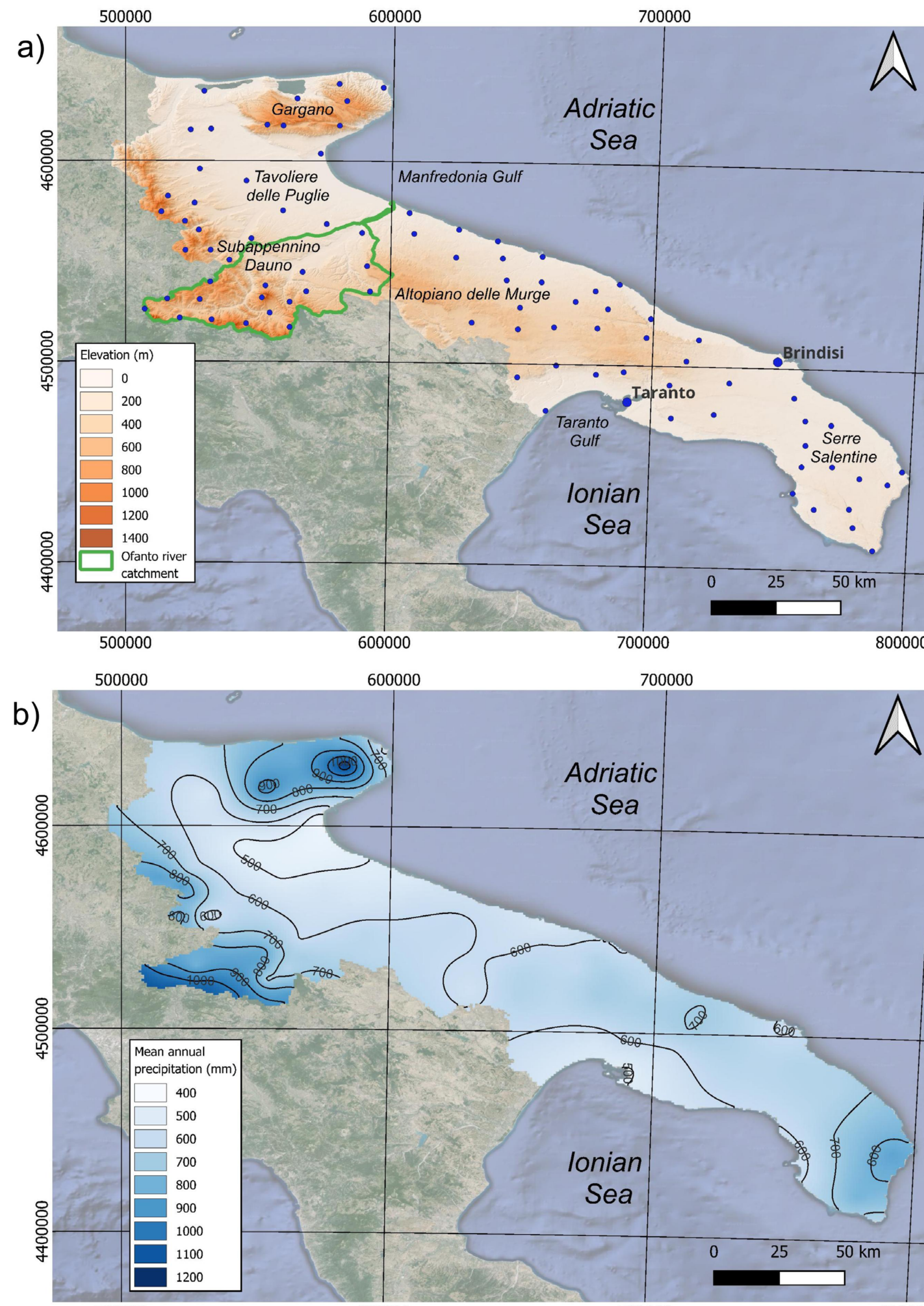


Figure 1 - Elevation map and spatial distribution of the rainfall gauge stations over the study area (Background from Google Satellite) (a). Mean annual precipitation (1931-2020) over the study area (Background from Google Satellite) (b).

outside the Apulia region is entirely mountainous, belonging to the Apennine chain domain, and reaches a maximum altitude of 1435 m. The mountainous areas cover 1.5% of the entire region, while hills and plains cover 45.2% and 53.3%, respectively (Gioia *et al.*, 2021). Other smaller rivers include the Fortore, which forms the northern border with the Molise region, and the Candelaro, Carapelle, and Cervaro in the Tavoliere area, as well as the Lato river, which flows into the Ionian Sea.

The climate of the Apulia region is typically Mediterranean, characterized by hot and dry summers and warm winters. The average annual temperature is around 15-16 °C, and the peak of precipitation occurs in the autumn. The mean annual precipitation for the period 1930-2020 is 685 mm (fig. 1b), ranging from the lowest values in the Tavoliere plain (~450 mm) to the greatest values in the Subappennino Dauno and Gargano areas (~1100 mm), with strong interannual differences (Cotecchia, 2014). The

Apulia climate can be defined as Cs in the Köppen classification (Marsico *et al.*, 2007). Rainfall affecting the northern and central areas of the region is mostly related to Adriatic atmospheric disturbances from the north and the Balkan area, while the southern area is predominantly affected by disturbances from the south (Cotecchia, 2014).

MATERIALS AND METHODS

The pluviometric data analyzed in this paper were downloaded from the Apulia Civil Protection regional center platform (https://protezionecivile.puglia.it/annali-idrologici-parte-i-dati-storici, last accessed May 29th, 2024). Ninety gauge stations were selected for the length and consistency of their time series. Hourly time series are available, in different gauges, starting from 1930 to 1960, while daily time series start range from 1921 to 1950; both end in 2020 (table 1). As we can see in fig. 1, the gauge stations are uniformly distributed over the regional territory. The average length of the hourly time series is 59 years, while for the daily time series it is 73 years. The percentage of gaps of the hourly and daily time series ranges from 0% to 18% and from the 4% to 23%, respectively.

Geographical factors and Depth-Duration-Frequency curves

The geographical factors taken into account for depicting the relationship between the spatial distribution of the extreme rainfall events and the geographical and morphological characteristics of the study area are elevation, latitude, longitude, distance from the sea and aspect. Starting from the maximum measurement for each year during consecutive hours of rain (1, 3, 6, 12, and 24 for hourly time series) and consecutive days of rain (1, 2, 3, 4, and 5 for daily time series), the 50th and 95th percentiles were calculated for each time slot and station. Two Depth-Duration-Frequency (DDF) curves were obtained, one for the 50th percentile and one for the 95th percentile. They are expressed in the form of a power-law (eq. 1):

$$h = ax^n \tag{1}$$

where h is the rainfall value expressed in millimeters during the time x, and a and n are the parameters of the power-law function. This equation is the most commonly used in order to relate the maximum annual precipitation and duration (Allamano *et al.*, 2009). The parameter a is approximately the rainfall value corresponding to 1 hour (or 1 day for the daily time series), while the parameter n is a measure of the difference between the 24-hour and the 1-hour values (or 5-day – 1-day for the daily time series). Both parameters a and n were related to the aforementioned geographical and morphological factors to find any correlation. Moreover, a spatial interpolation of the DDF parameters was carried on (by using an Inverse Distance weighted method, with 1 km grid cell size), producing a and n maps.

We use Tinitaly DTM to extract the morphometric parameters, which was developed by the National Institute of Geophysics and Volcanology. The spatial resolution of this DTM is 10 meters, and the dataset is freely available from the INGV website (http://tinitaly.pi.ingv.it/, last accessed May 29th, 2024). A value of elevation and slope direction (aspect) was assigned to each pluviometric station. Elevation ranges from 2 meters above sea level for the Manfredonia gauge station to 920 m a.s.l. for the Pescopagano gauge station. Moreover, using a GIS software (QGIS in this case), the corresponding values of latitude, longitude and shortest distance to the sea were extracted.

Simple and Multiple Linear Regression

Linear regression is a statistical technique used to analyze the relationship between a dependent variable and one (simple linear regression) or more (multiple linear regression) independent variables. The mathematical expression of this model is reported in equation 2

$$y = c + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \dots + \beta_k x_k \tag{2}$$

where c is the constant or intercept of the regression equation, β (i = 1, 2, ..., k) is the regression coefficient for the independent variable x (i = 1, 2, ..., k) and y is the dependent variable. For the simple linear regression only one independent variable is considered, so the equation becomes (eq. 3)

$$y = c + \beta_1 x_1 \tag{3}$$

Linear Regression and Multilinear regression analysis was carried on by considering the geographical factors taken as separately and together, respectively. R^2, p-values, and t-values are reported, for the first four factors, for each correlation for demonstrating the correlation power and significance. When the number of independent variables increases, the accuracy of the model may increase, but it may also lead to overfitting, which reduces the generalizability of the model to new data. The Adjusted R^2 coefficient is a modification of the R^2 coefficient that penalizes the addition of new variables to the model that do not contribute significantly to its predictive power. A larger difference between the Multiple R^2 and the Adjusted R^2 indicates that the model is overfitting the data. A small difference between the two coefficients suggests that the model is performing well and is not overfitting the data (Swain *et al.*, 2017).

For the aspect factor a comparison among the mean of the DDF parameters related to the gauge stations falling in the four different quadrants were carried out.

Table 1 - List of the gauge stations, their elevation, mean annual precipitation, period covered by time series.

	Elevation (m)	Name	Mean Annual Precipitation (mm)	Observation period (hourly time series)	Hourly time serie length (years)	Observation period (daily time series)	Daily time serie length (years)
1	153	Adelfia	612	1961-2020	56	1922-2020	78
2	458	Altamura	570	1952-2020	62	1921-2020	75
3	890	Andretta	804	1937-2020	47	1922-2020	65
4	162	Andria	578	1959-2020	52	1921-2020	78
5	435	Ascoli Satriano	624	1929-2020	63	1951-2020	66
6	490	Atella	685	1956-2020	47	1923-2019	74
7	34	Bari Osservatorio	536	1932-2020	80	1921-2020	77
8	30	Barletta	517	1959-2020	58	1921-2020	83
9	590	Biccari	761	1952-2020	55	1924-2020	72
10	900	Bisaccia	829	1959-2020	48	1932-2020	68
11	30	Bisceglie	573	1961-2020	51	1930-2020	74
12	126	Bitonto	583	1958-2020	51	1925-2020	76
13	780	Bosco Umbra	1177	1928-2020	70	1927-2020	73
14	596	Bovino	795	1929-2020	76	1921-2020	82
15	22	Brindisi	588	1936-2020	73	1921-2020	79
16	167	Cagnano Varano	825	1950-2020	66	1927-2020	77
17	116	Canosa di Puglia	541	1952-2020	62	1924-2020	80
18	380	Cassano Murge	652	1929-2020	68	1929-2020	68
19	300	Castellana Grotte	681	1961-2020	51	1924-2020	72
20	236	Castellaneta	590	1962-2020	58	1921-2020	84
21	312	Ceglie Messapica	702	1962-2020	42	1923-2020	66
22	134	Cerignola	554	1932-2020	79	1923-2020	83
23	212	Conversano	654	1968-2020	45	1921-2020	76
24	34	Copertino	639	1961-2020	52	1923-2020	75
25	265	Crispiano	609	1958-2020	48	1929-2020	68
26	809	Faeto	861	1941-2020	45	1958-2020	48
27	118	Fasano	629	1937-2020	58	1922-2020	73
28	94	Foggia Osservatorio	475	1934-2020	77	1921-2020	82
29	73	Galatina	706	1959-2020	56	1923-2020	77
30	31	Gallipoli	562	1934-2020	73	1921-2020	75
31	254	Ginosa	592	1932-2020	76	1922-2020	78
32	15	Ginosa Marina	530	1928-2020	63	1923-2020	75
33	377	Gioia Del Colle	629	1961-2020	51	1921-2020	75
34	22	Giovinazzo	572	1960-2020	56	1923-2020	79
35	165	Grottaglie	586	1958-2020	53	1927-2020	70
36	202	Grumo Appula	585	1928-2020	64	1921-2020	67
37	769	Lagopesole	880	1929-2020	70	1923-2020	72
38	114	Latiano	656	1958-2020	56	1930-2020	71
39	328	Lavello	595	1951-2020	59	1921-2020	74
40	51	Lecce	657	1930-2020	75	1921-2020	78
41	17	Lesina	637	1938-2020	74	1929-2020	79
42	71	Lizzano	562	1957-2020	51	1921-2020	75
43	397	Locorotondo	683	1964-2020	51	1921-2020	83
44	224	Lucera	574	1938-2020	66	1921-2020	80
45	102	Maglie	768	1935-2020	68	1921-2020	68

Table 1 - *(Continues)*

	Elevation (m)	Name	Mean Annual Precipitation (mm)	Observation period (hourly time series)	Hourly time serie length (years)	Observation period (daily time series)	Daily time serie length (years)
46	79	Manduria	623	1962-2020	47	1929-2020	69
47	2	Manfredonia	448	1932-2020	65	1921-2020	77
48	113	Massafra	541	1958-2020	55	1921-2020	74
49	569	Melfi	830	1939-2020	75	1922-2020	79
50	103	Minervino di Lecce	850	1949-2020	65	1930-2020	73
51	502	Minervino Murge	634	1960-2020	51	1921-2020	72
52	808	Monte Sant'Angelo	764	1933-2020	64	1921-2020	70
53	828	Monteleone di Puglia	823	1936-2020	64	1921-2019	78
54	350	Montemilone	589	1940-2020	54	1923-2020	70
55	713	Monticchio	845	1948-2020	56	1921-2020	65
56	54	Nardò	619	1957-2020	53	1923-2020	74
57	423	Noci	696	1929-2020	85	1921-2020	80
58	51	Novoli	653	1959-2020	58	1923-2020	79
59	863	Nusco	1083	1936-2020	62	1924-2020	70
60	689	Orsara di Puglia	874	1962-2020	48	1921-2020	69
61	84	Ortanova	492	1959-2020	47	1921-2020	65
62	115	Ostuni	704	1958-2020	60	1921-2020	82
63	27	Otranto	797	1934-2020	78	1921-2020	80
64	920	Pescopagano	1060	1964-2020	48	1921-2020	75
65	50	Polignano a Mare	595	1963-2020	56	1927-2020	78
66	105	Presicce	788	1954-2020	60	1921-2020	78
67	658	Ripacandida	652	1940-2020	64	1930-2020	69
68	679	Rocchetta Sant'Antonio	647	1961-2020	53	1924-2020	63
69	134	Ruffano	766	1943-2020	59	1924-2020	71
70	274	Ruvo di Puglia	616	1964-2020	44	1923-2020	74
71	902	San Fele	969	1941-2020	49	1928-2020	62
72	627	San Giovanni Rotondo	863	1932-2020	52	1925-2020	69
73	564	San Marco in Lamis	950	1928-2020	73	1921-2020	80
74	49	San Pietro Vernotico	657	1958-2020	51	1923-2020	83
75	99	San Severo	536	1932-2020	68	1928-2020	69
76	26	Santa Maria di Leuca	654	1942-2020	68	1921-2020	79
77	791	Sant'Agata di Puglia	564	1930-2020	54	1921-2020	64
78	886	Sant'Angelo dei Lombardi	917	1932-2020	54	1924-2020	69
79	503	Santeramo in Colle	657	1963-2020	47	1925-2020	73
80	726	Savignano Irpino	694	1932-2020	51	1921-2020	63
81	458	Spinazzola	633	1936-2020	61	1921-2020	71
82	27	Taranto	492	1935-2020	72	1921-2020	76
83	65	Taviano	630	1961-2020	55	1921-2020	79
84	762	Teora	1067	1938-2020	62	1921-2020	62
85	184	Torremaggiore	577	1940-2020	53	1921-2020	67
86	436	Troia	634	1930-2020	55	1921-2020	66
87	268	Turi	615	1960-2020	48	1927-2020	72
88	415	Venosa	686	1957-2020	49	1921-2020	63
89	450	Vico del Gargano	859	1967-2020	44	1921-2020	71
90	33	Vieste	588	1946-2020	59	1923-2018	78

First, elevation, distance from the sea, latitude and longitude were individually related to the four DDF parameters (50th and 95th percentile of both *a* and *n* parameters) by using SLR. To relate slope direction to the DDF parameters, four quadrants were defined: North (315°-45°), East (45°-135°), South (135°-225°), and West (225°-315°), and the mean of each parameter was calculated for each part. A MLR was performed, successively, as to characterize the relationship between the two variables of interest while considering the effect of other independent variables.

Trend analysis

For investigating the possible presence of temporal trends on the time series, a Mann-Kendall nonparametric test was performed, as described by Sneyers (1990), for each time interval, both for the hourly and the daily data. The Mann-Kendall non-parametric test is based on a null hypothesis (H0), which indicates that there is no trend, against the alternative hypothesis (Ha), which implies that there is a trend. If the p-value is lower than the significance thresholds of 0.05 and 0.01, the null hypothesis is rejected, and the trend can be defined as statistically significant. This test has been already used to detect trends in Italy and other Mediterranean areas (Piccarreta *et al.*, 2013; Brunetti *et al.*, 2002; Serrano *et al.*, 1999), thus it is possible to easily compare the outcomes. The tau statistic was used to show the results, with p-values indicating the significance at the 0.05 and 0.01 probability values. The tau statistic, or Kendall rank correlation coefficient, measures the monotony of the slope. It varies between -1 and 1; it is positive when the trend increases and negative when the trend decreases, while the lower the p-value, the more statistically significant is the trend.

A further comparison has been made between the mean rainfall values of each time interval along the entire time series and the mean rainfall values for the same time intervals during the climate normal 1991-2020 (WMO, 2017).

RESULTS AND DISCUSSION

Simple Linear Regression

In the case of SLR, it was possible to evaluate which of the geographical factors better explain the spatial distribution of the extreme rainfall events. The results of the SLR for the hourly time series are summarized in fig. 2. All the regression outputs are reported in table 2.

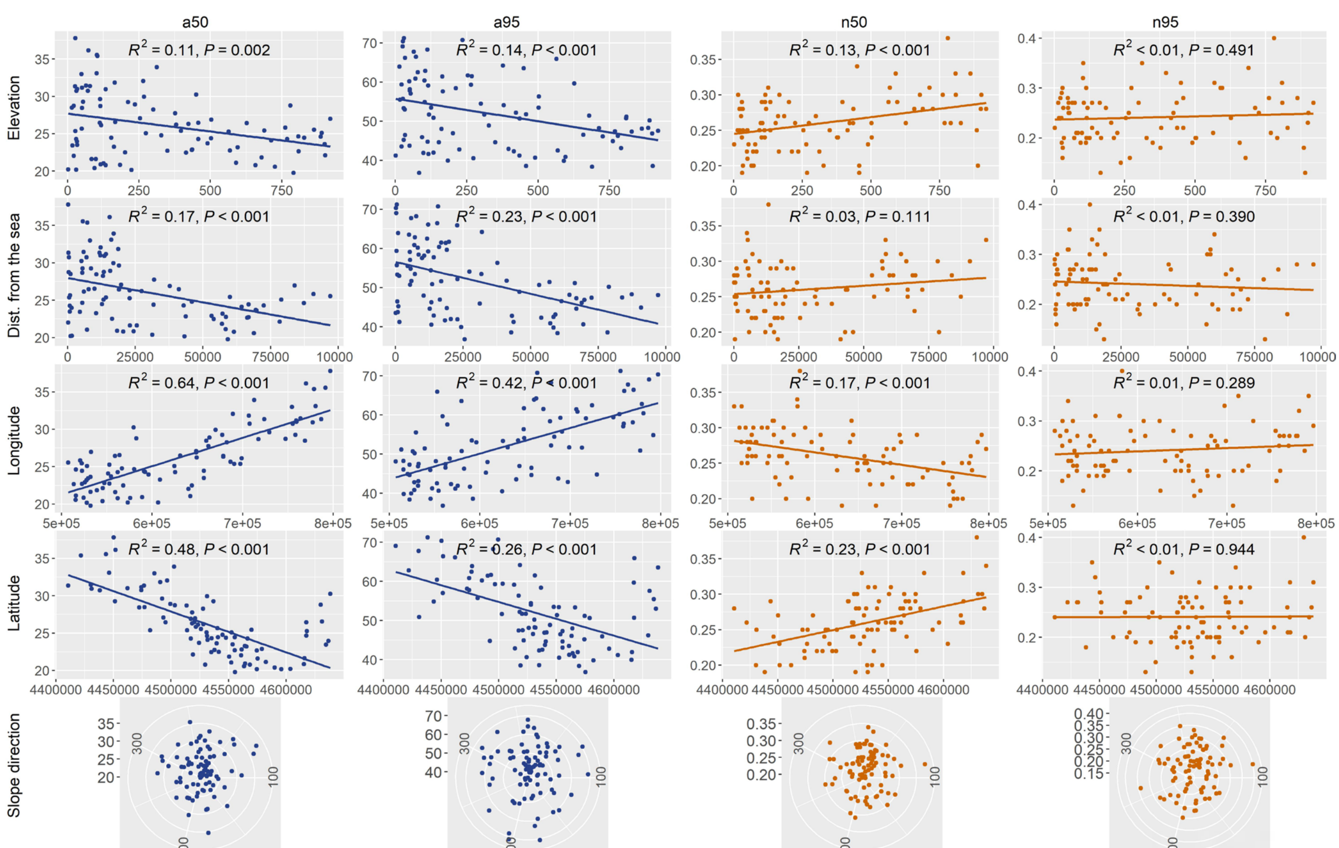


Figure 2 - Hourly time series Simple Linear Regression results.

Table 2 - Hourly time series DDF parameters SLR results. Significatively codes: (***) < 0.0001, (**) < 0.001, (*) < 0.01.

		a50	a95	n50	n95
	t-value	-3.26	-3.716	3.705	0.692
Elevation	p-value	0.00159(*)	0.000355(**)	0.000368(**)	0.491
	R^2	0.11	0.1356	0.135	0.005413
	t-value	-4.258	-5.151	1.611	-0.864
Distance from the sea	p-value	5.14E-05(***)	1.57E-06(***)	0.111	0.39
	R^2	0.1709	0.2317	0.02864	0.008413
	t-value	12.54	7.908	-4.32	1.066
Longitude	p-value	<2e-16(***)	7.15E-12(***)	4.08E-05(***)	0.289
	R^2	0.6412	0.4154	0.175	0.01275
	t-value	-9.043	-5.551	5.099	0.07
Latitude	p-value	3.34E-14(***)	2.97E-07(***)	1.94E-06(***)	0.944
	R^2	0.4817	0.2593	0.2281	5.59E-05

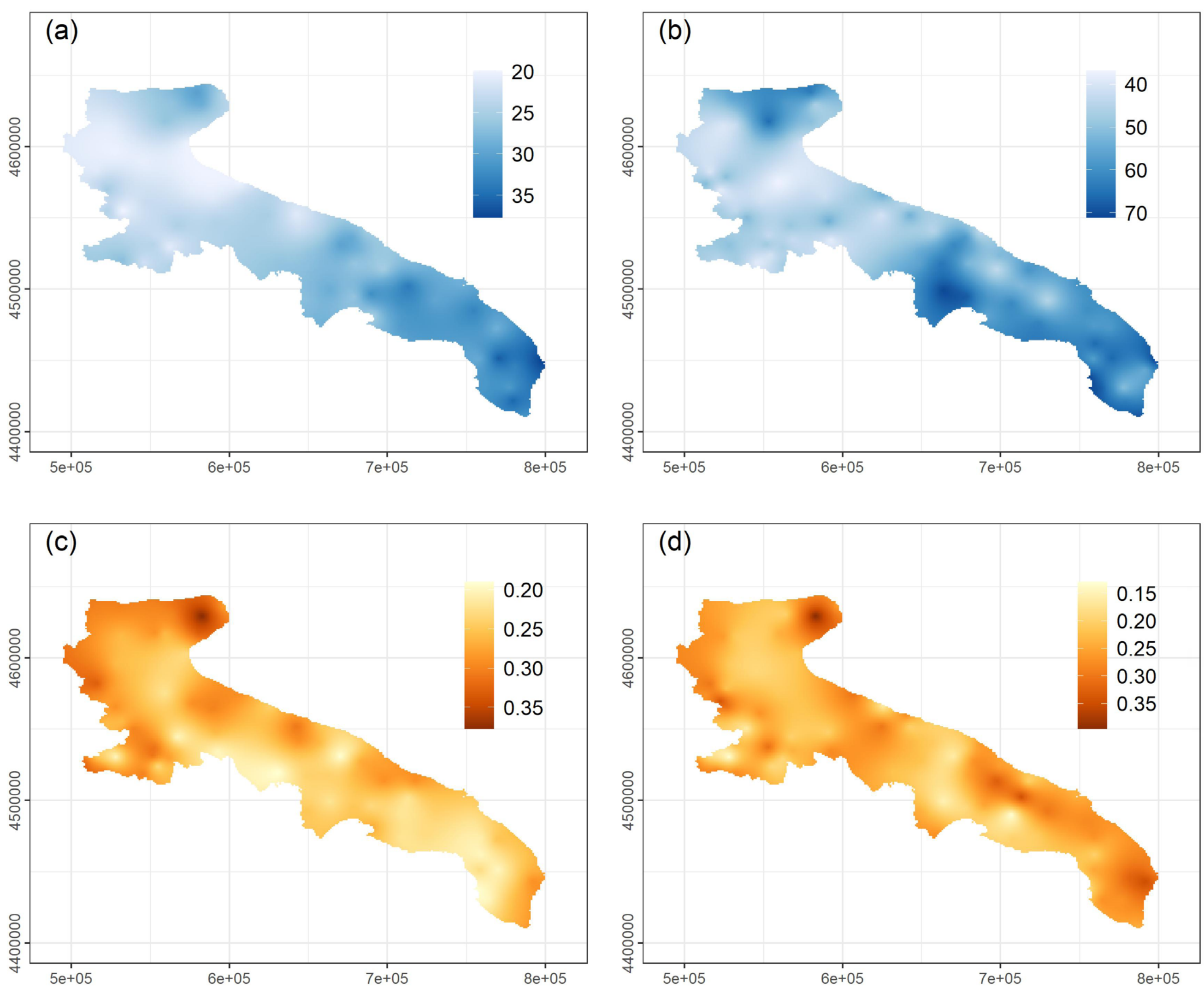


Figure 3 - Hourly time series of DDF parameters maps: a50 (a), a95 (b), n50 (c), n95 (d).

Regarding the hourly time series, the most statistically significant correlations were found between a50 and a95 and latitude and longitude, followed by a50 and a95 versus distance from the sea and elevation. This suggests that the DDF parameters a50 and a95 significantly increase moving Eastward and Southward, and slightly decrease with increasing elevation and distance from the sea. The n50 and n95 parameters generally showed weaker correlations with all the variables, except for latitude and longitude, which exhibited a moderate correlation with n50, but in the opposite direction to that of a50 and a95. There were no significant variations observed in the mean of the parameters across the four different slope directions.

The results of the spatial interpolation of the DDF parameters are shown in fig. 3. These maps provide a better visualization of the relationship between the geographical and geo-morphological factors and latitude and longitude (especially for the a50 and a95 parameters) and also allow for the detection of local anomalies such as higher values of a95, n50, and n95 in the Gargano area, and a95 in the Taranto area.

The Apulia region has the lowest elevation range among the Italian regions (1152 m), and even with the upstream area of the Ofanto catchment, the maximum elevation in the study area is only 1435 m. Additionally, the percentage of mountainous area is very low, so it could be expected that the reverse orographic effect observed in other Italian areas (Avanzi *et al.*, 2015; Mazzoglio *et al.*, 2020; Allamano *et al.*, 2009; Mazzoglio *et al.*, 2022a) would not be relevant. However, the particular orientation along the longitude and latitude dimensions, and the consequent influence of the sea and its related atmospheric disturbances, force the spatial distribution of extreme rainfall to be influenced by the orographic effect anyway. Due to the limited latitude and longitude range of the region, the latitude and longitude variation could also represent a factor in the exposure to the main atmospheric disturbances between the Southeastern area, which is mostly affected by convective precipitation (characterized by higher intensity and shorter duration), and the Northwestern area, where instead stratiform precipitation (lower intensity and longer duration) prevail, according to (Cotecchia, 2014). This interpretation leads us to consider the Murge area an orographic obstacle for the disturbances coming from the South.

Compared to the hourly time series, the daily time series DDF parameters generally show less significant correlations (fig. 4). n50 and n95 exhibit a slight increase with distance from the sea and elevation, while a50 and a95 increase with longitude and decrease with latitude. However, the overall weakness of these correlations, as indicated by the SLR coefficients (table 3), does not allow for further considerations. Similarly to the hourly time series, there is no significant relationship with the slope direction.

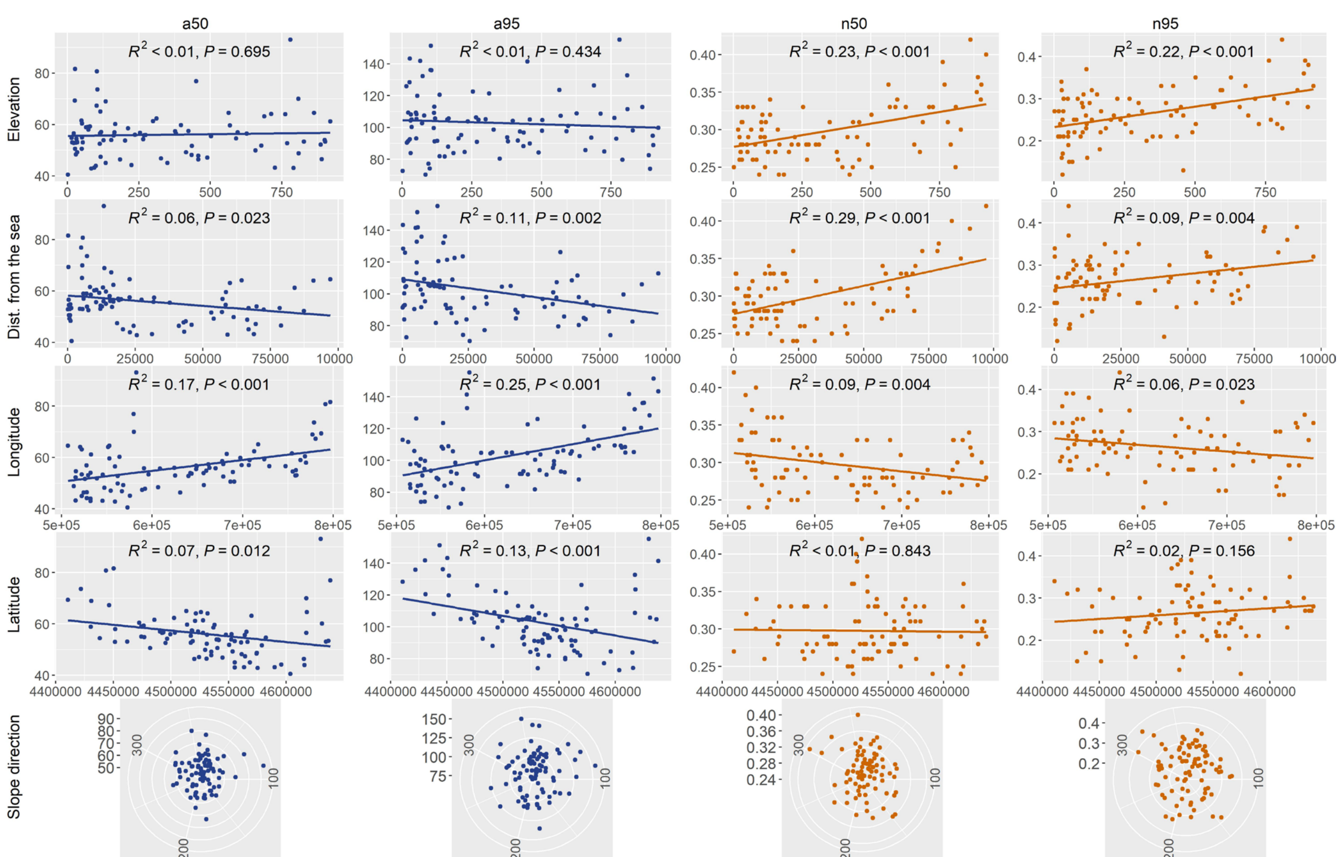


Figure 4 - Daily time series SLR results.

Table 3 - Daily time series DDF parameters SLR results. Significatively codes: (***) < 0.0001, (**) < 0.001, (*) < 0.01.

		a50	a95	n50	n95
	t-value	0.393	-0.786	5.154	4.949
Elevation	p-value	0.695	0.434	1.55E-06(***)	3.56E-06(***)
	R^2	0.001755	0.00698	0.2319	0.2177
	t-value	-2.311	-3.252	6.04	2.96
Distance from the sea	p-value	0.0232	0.00162(*)	3.60E-08(***)	0.00395(*)
	R^2	0.05722	0.1073	0.2931	0.0905
	t-value	4.251	5.389	-2.985	-2.312
Longitude	p-value	5.28E-05(***)	5.86E-07(***)	0.00367(*)	0.0231
	R^2	0.1704	0.2481	0.09194	0.05729
	t-value	-2.572	-3.661	-0.199	1.43
Latitude	p-value	0.01178	0.000428(**)	0.843	0.156
	R^2	0.06993	0.1322	0.0004503	0.0227

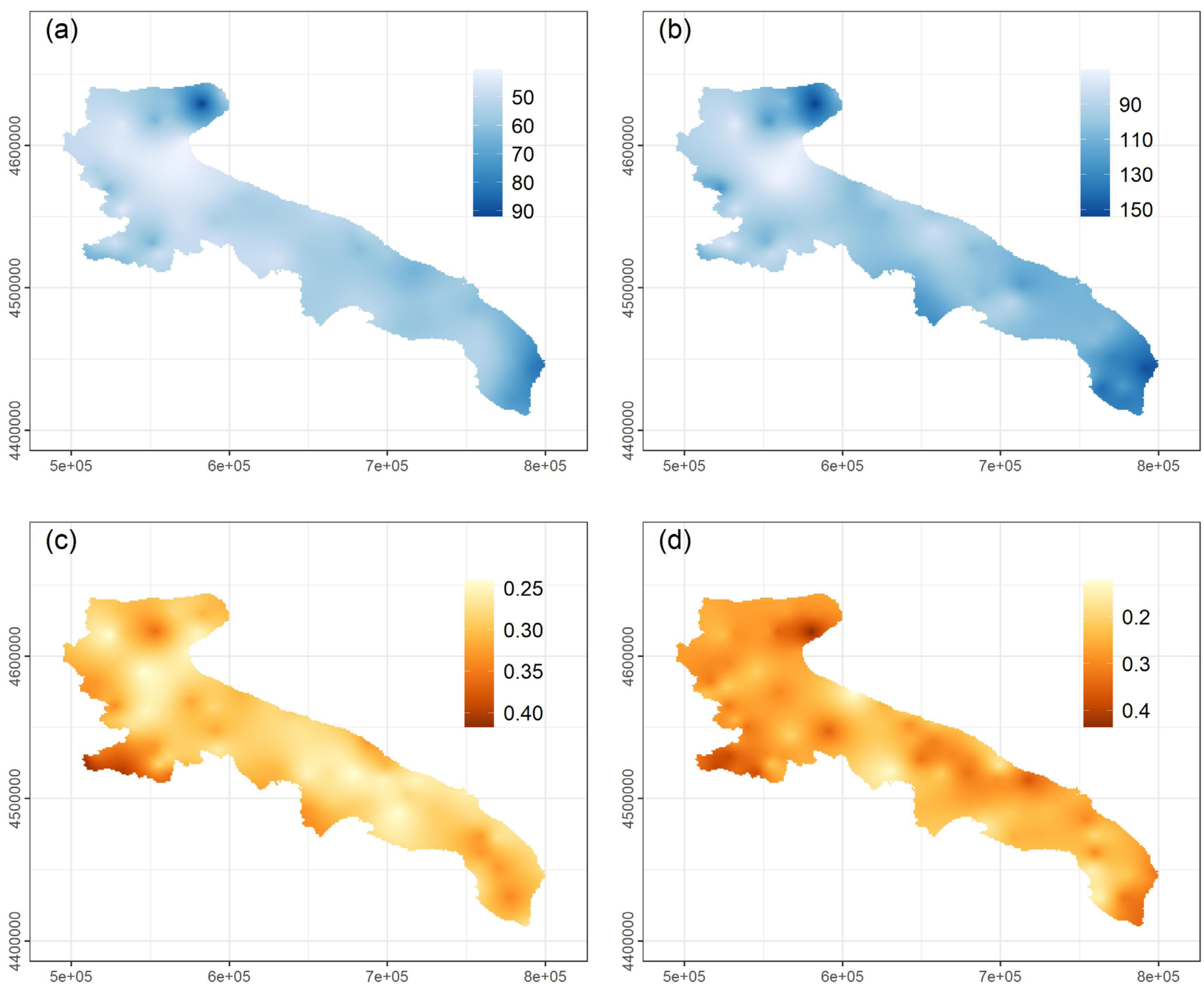


Figure 5 - Daily time series of DDF parameters maps: a50 (a), a95 (b), n50 (c), n95 (d).

The *a* and *n* maps related to the daily time series DDF parameters (fig. 5) highlight a strong positive anomaly of the a50 and a95 parameters in the Gargano area, and moderate anomalies of the n50 and n95 parameters in the Gargano and Subappennino Dauno area. The concentration of these anomalies in the Northern area at the daily timescale is consistent with the previous hypothesis of dividing the area into two parts, as stratiform precipitation of longer duration is predominant in this area.

Multiple Linear Regression

The results of the MLR are summarized in table 4 for the hourly time series and in table 5 for the daily time series. In the hourly data, elevation shows significant correlations with all four parameters, but, for a50 and a95 parameters, it is in the opposite direction compared to the SLR . The strongest relationship (in terms of p-values) is between the a50 parameter and longitude. Latitude and distance from the sea have the weakest relationship with the DDF parameters. Also for the daily data, the elevation is the most correlated variable, with higher statistical significance (except for the n50 parameter), while the other variables reveal much weaker relationships. Distance from the sea confirms to be inversely related to a50 and a95.

There are significant differences between the results of the SLR and the MLR. The SLR indicates that the a50 and a95 parameters have the most significant correlations with latitude and longitude. However, the MLR shows that the elevation variable has the strongest correlation with the same DDF parameters, but in the opposite direction respect to the SLR. In addition, except for the a50 parameter, longitude and latitude have weak correlations. Interestingly, the correlations with elevation are stronger for the daily time series parameters compared to the hourly time series ones. This suggests that the weak reverse orographic effect observed in the SLR becomes a direct orographic effect, which is more pronounced for the daily time series. Longitude remains an important variable after elevation, except for the a50 parameter where longitude is the most important.

The increased relevance of the elevation variable in the MLR (and with the change from sub-daily to multi-daily timescales) may be partially explained by the elevation gradient, which consistently decreases (except for the Gargano area) with longitude. This indicates that the elevation correlation found in the SLR was biased by the longitude variable, and this bias was corrected in the MLR. In light of these findings, the anomaly observed in the Gargano area for the a50 and a95 parameters in the daily time series could be explained by the combined influence of elevation and longitude, as well as the longer duration of stratiform precipitation in that area.

Table 4 - Hourly time series DDF parameters MLR results. Significatively codes: (***) < 0.0001, (**) < 0.001, (*) < 0.01.

		a50	a95	n50	n95
Elevation	p-value	0.004 (**)	0.013 (*)	0.001 (**)	0.02 (*)
	t-value	2.954	2.537	3.34	2.361
Distance from the sea	p-value	0.423	0.011(*)	0.114	0.957
	t-value	0.806	-2.609	-1.596	0.054
Longitude	p-value	9.15E-07 (***)	0.828	0.691	0.044 (*)
	t-value	5.296	0.218	-0.399	2.04
Latitude	p-value	0.367	0.064	0.336	0.092
	t-value	0.907	-1.871	0.967	1.7
Multiple R^2		0.72	0.47	0.32	0.13
Adjusted R^2		0.71	0.44	0.29	0.09

Table 5 - Daily time series DDF parameters MLR results. Significatively codes: (***) < 0.0001, (**) < 0.001, (*) < 0.01.

		a50	a95	n50	n95
Elevation	p-value	2.83E-08 (***)	6.03E-07 (***)	0.35	0.0002 (***)
	t-value	6.116	5.397	0.94	3.813
Distance from the sea	p-value	0.211	0.02 (*)	0.213	0.772
	t-value	-1.259	-2.37	1.254	-0.29
Longitude	p-value	0.001 (**)	0.084	0.845	0.368
	t-value	3.407	1.747	-0.196	0.905
Latitude	p-value	0.129	0.81	0.497	0.429
	t-value	1.532	-0.24	-0.682	0.794
Multiple R^2		0.47	0.45	0.31	0.25
Adjusted R^2		0.45	0.42	0.28	0.22

Trend analysis and tau maps

The results of the Mann-Kendall test performed on the hourly and daily time series are summarized in fig. 6. Regarding the hourly time series, the number of gauge stations with a positive trend is greater than the number of gauge stations with a negative trend (for the time intervals between 1h and 24h, the average ratio is 60/30), and the fraction of stations with a positive trend which show a significance level at 0.05 or more is around 10%. The stations with a negative trend which reveal a significance level at 0.05 or more are at a maximum of 2.

Spatial interpolation of the tau values was used to produce the tau maps, which make it easier to observe how the tau values vary spatially, similarly to the *a* and *n* maps. As for the hourly time series (fig. 7), gauge stations with a positive trend prevail. However, some local spots with negative trends stand out in the central and southern parts of the region, increasing slightly in intensity and dimension in correspondence to the 24 h time interval.

In contrast to the hourly time series, for the daily time series the number of gauge stations exhibiting a negative trend is much higher than the number of stations with a positive trend (for time intervals between 1 d and 5 d, the average ratio is 77/13) (fig. 8). The fraction of stations showing a negative trend with significance level at 0.05 ranges between 15% and 25%, whereas only one station shows a positive trend with significance level at 0.05. Furthermore, the ratio between the number of stations with negative trend and the number of stations with positive trend increases as the time interval increases, reaching 83/7 for the 5 d time interval. This difference in the fraction of stations with p-values under the 0.05 and 0.01 thresholds between the hourly and daily time series suggests that the daily time series trends are stronger than the hourly ones.

The tau maps of the daily time series (fig. 8) reveal that negative trends become stronger and more extensive as the time interval increases from 1 d to 5 d, with only a few small areas where positive trends persist (northern part of Gargano and Taranto area). Interestingly, these results contradict those of (Cherubini *et al.*, 2007), who found an increase in extreme precipitation in the Taranto area only for durations of less than 8 hours.

Comparison with climate normal 1991-2020

The comparison between the mean rainfall values for each time interval along the entire time series and the mean of the same values for the same time intervals during the climate normal 1991-2020 is presented in fig. 9. For the hourly time series, the number of stations where the mean of the climate normal 1991-2020 is greater than the mean of the entire time series is higher than the number of stations with the opposite result (for the time intervals between 1 h and 24 h, the average ratio is 60/30). In contrast, for the daily time series, the result is opposite, with the same ratio for the time intervals between 1 d and 5 d.

These results are consistent with the Mann-Kendall test results, indicating that a significant difference in extreme annual rainfall during the 1991-2020 period is not observed. However, a slight decrease is evident in the ratio between the number of stations where the mean of the entire time series is greater than the mean of the climate normal 1991-2020 compared to the ratio between the number of stations with a negative trend that is much greater than the number of stations with a positive trend (only for the daily time series). This suggests that for a few stations affected by the negative trend, the mean of extreme annual precipitation on a daily scale during the climate normal 1991-2020 is greater than the mean of the entire time series.

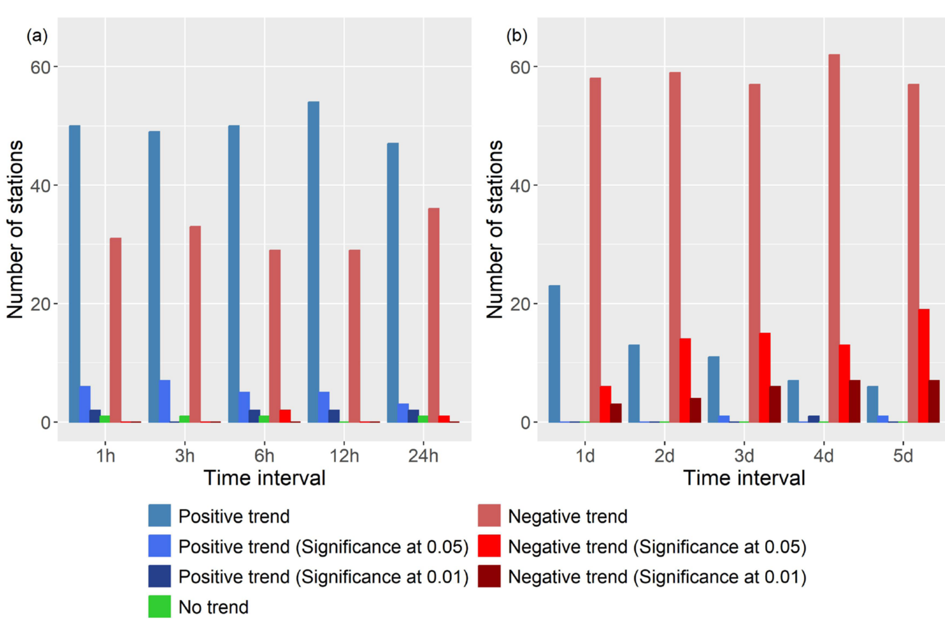
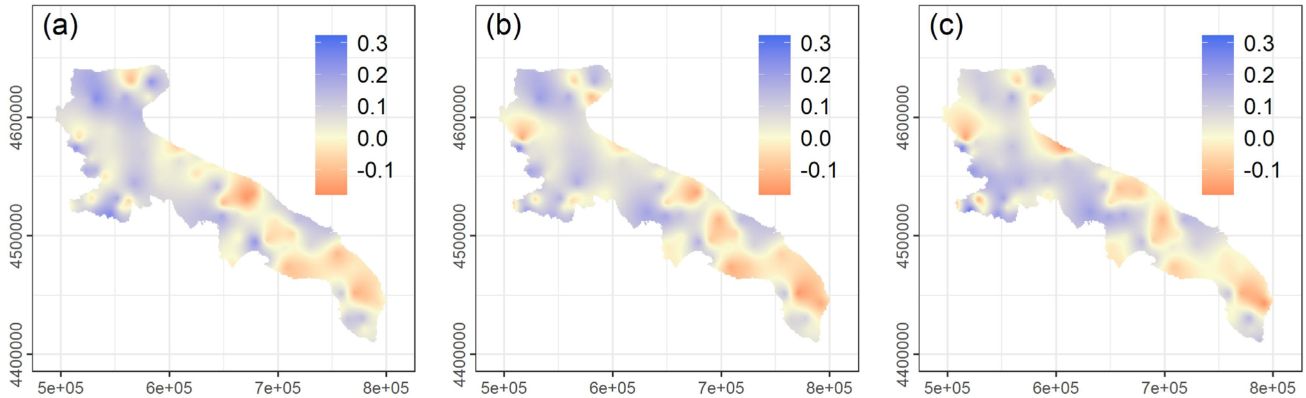


Figure 6 - Hourly (a) and daily (b) time series Mann-Kendall test results.



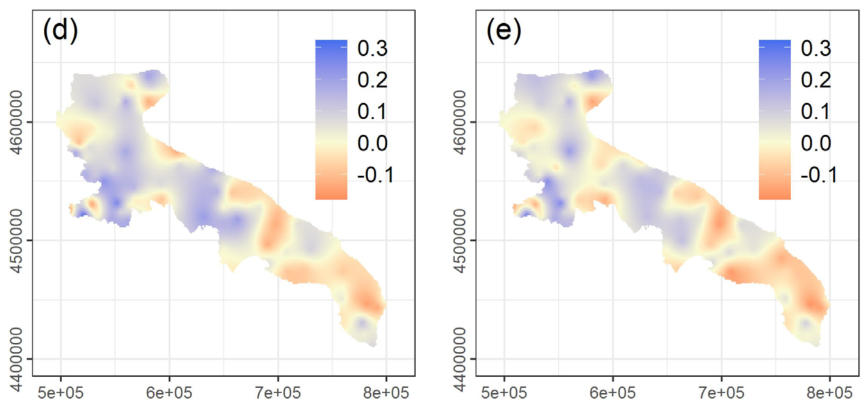
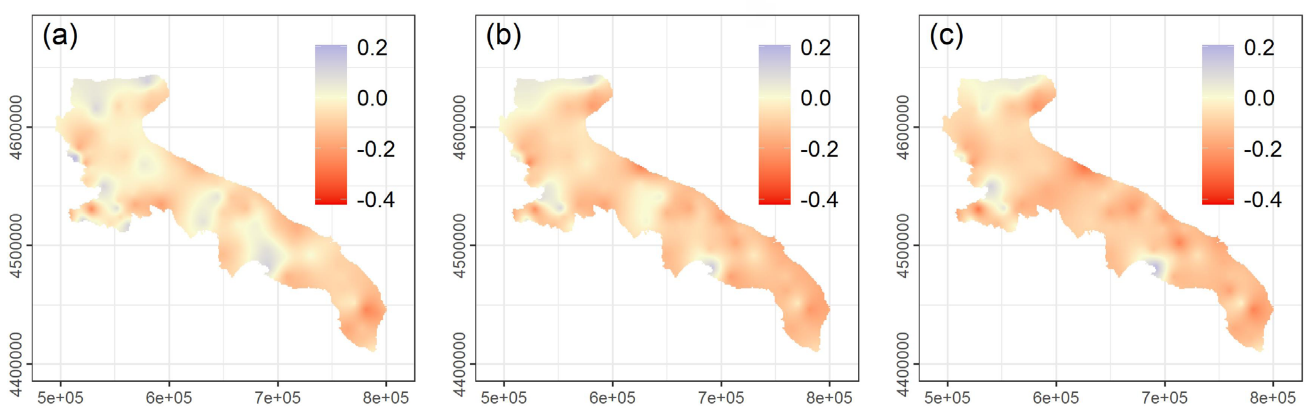


Figure 7 - Tau maps of hourly time series, 1 h (a), 3 h (b), 6 h (c), 12 h (d) and 24 h (e) time intervals.



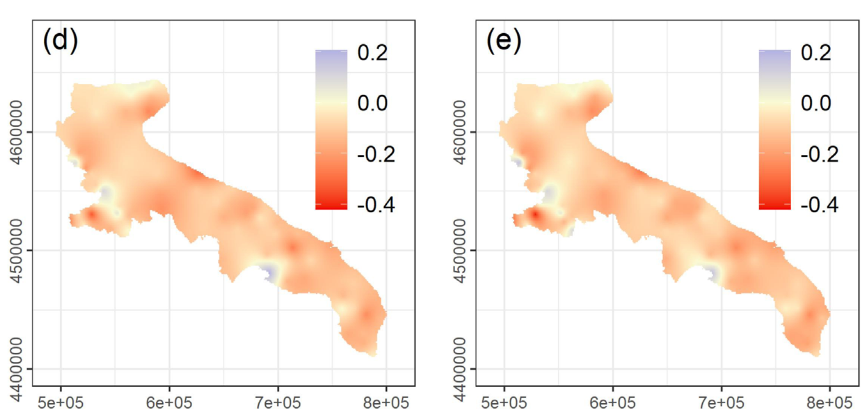


Figure 8 - Tau maps of daily time series, 1 d (a), 2 d (b), 3 d (c), 4 d (d) and 5 d (e) time intervals.

CONCLUSIONS

The dependence of extreme rainfall event distribution on geographical and morphological factors is an extensively investigated topic. Depending on the scale and features of the area, the relative importance of these variables can considerably vary. In this study, the maximum annual rainfall time series related to the period 1931-2020 were considered, and the corresponding DDF parameters were related to the geo-graphical and morphological features of the Apulia region. SLR indicated that the longitude and latitude variables are mainly correlated with the DDF parameters. However, MLR overturned this result, revealing that the elevation variable explains most of the variation in the DDF parameters (especially a50 and a95), and in the opposite direction. This difference suggests that, where the combination of geographical variables leads to biased SLR outcomes, MLR could represent a more solid and accurate methodology.

The trend analysis results reveal that extreme rainfall events at the hourly scale are generally slightly increasing, while they are decreasing at the daily scale. Comparing the mean rainfall values along the entire time series with the mean of the same values during the climate normal 1991-2020 does not show significantly different results from the trend analysis, except for a few stations affected by negative trends. During the climate normal 1991-2020, the mean of the extreme annual precipitation on a daily scale is greater than the mean of the entire time series at these stations. The difference that emerges by the comparison of our results to previous studies, reveal that a small-scale analysis based on different time intervals make it possible to emphasize some variations that in earlier research were not obvious. Different durations are linked to different atmospheric mechanisms that interact differently with the orography.

One intrinsic limitation of the approach we used is related to the type of time series available, as only one (the maximum) rainfall value per year for each time interval is reported. Moreover, the limited area extent of extreme rainfall of short duration, which may fall below the distance between the measuring stations, is another source of uncertainty in determining both the spatial distribution and temporal trends of extreme events. These issues raise the need to improve the density of the gauge station network, and the consistency and reliability of their records, as to minimize errors.

Some general considerations on the consequences of extreme rainfall events could be drawn from the present study. These events can lead to various ground effects, such as floods, flash floods, landslides, and sinkhole formation in karst areas. As the time of concentration of most hydrographic catchments is well below 24 hours, the increasing trend of extreme rainfall events at sub-daily time scales can increase the flood and flash flood hazard. Further investigations are required to link these results with the landslides hazard, which is influenced by a wider range of rainfall duration. In the Apulia region, which is dominated by karst environments, the interaction between groundwater and surface water is an additional complexity that could increase the negative effects of these harmful events.

The effects of extreme rainfall events are not only related to the magnitude of the natural phenomena, but also to the vulnerability of the territory, which is influenced by several factors such as land use, morphological setting, urbanization, population density, and preparedness levels. Detecting these factors and their variation over time at a useful scale for risk mitigation is often challenging. Therefore, a multidisciplinary approach that incorporates the latest available data and patterns, trends, and local anomalies is crucial for reducing the negative effects of such harmful events.

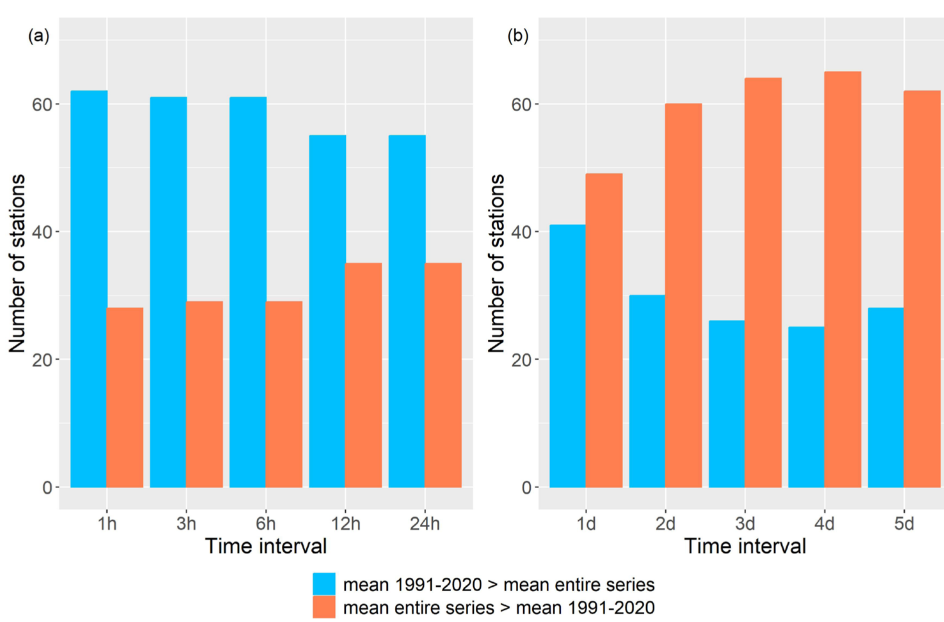


Figure 9 - Comparison between entire time series and the climate normal 1991-2020 results of hourly time series (a) and daily time series (b).

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