



A rainfall trend analysis for the assessment of climate change in Friuli-Venezia Giulia (north-eastern Italy)

Tommaso Caloiero¹ · Ilaria Cianni² · Roberto Gaudio²

Received: 23 September 2022 / Accepted: 13 February 2023 / Published online: 18 March 2023
© Springer Nature Switzerland AG 2023

Abstract

Climate change is expected to impact on rainfall variability and lead to a substantial modification in rainfall amounts. In this study, the spatiotemporal variability of rainfall in Friuli-Venezia Giulia (north-eastern Italy) has been evaluated by means of 67 monthly series for the period 1940–2011. In particular, in order to analyse possible trends in rainfall series, two non-parametric tests for trend detection have been used. Moreover, the monthly rainfall distribution throughout the year was also investigated by means of the precipitation concentration index (PCI). In addition, a correlation analysis has been performed between seasonal rainfall and four of the most important teleconnection indices, i.e. the Western Mediterranean Oscillation Index (WeMOI), the Oceanic Niño Index (ONI), the North Atlantic Oscillation Index (NAOI) and the Arctic Oscillation Index (AOI). The results evidenced a reduction in rainfall amount, mainly detected in the spring and the summer months, and a positive trend in the PCI. The latter indicates a tendency towards a more seasonal rainfall distribution in the Friuli-Venezia Giulia region throughout the year. Finally, the WeMO was identified as the most relevant teleconnection over all of Friuli-Venezia Giulia in the different seasons.

Keywords Rainfall · Trend analysis · Non-parametric test · Friuli-Venezia Giulia

Introduction

Climate change is affecting all regions worldwide. Globally, polar ice shields are melting and the sea is rising. Moreover, some regions are facing more common extreme weather events and rainfall, while others are experiencing more extreme heatwaves and droughts, causing changes in mean renewable water supplies (IPCC 2013). Many studies have shown that rainfall has already increased with twentieth-century warming driven by anthropogenic forcing (Zhang et al. 2013), and a further increase during the twenty-first century is visible (Toreti et al. 2013; Pendergrass and Hartmann 2014). Although more extreme

rainfall events have been forecasted for many regions of the world, the increases in heavy rainfall may not always lead to an increase in the total amount of rain over a season or over the year. This is particularly evident in some areas, such as the Mediterranean region, which has been identified as one of the most responsive regions to climate change (IPCC 2013). In fact, climate change has been severely impacting the Mediterranean basin, and thus numerous studies on the spatial and temporal evolution of several hydrological variables—with particular attention been paid to rainfall—have been performed in this region. In particular, when considering the western side of the Mediterranean basin, the results of these studies evidenced a general rainfall reduction at different timescales from monthly to annual (Caloiero et al. 2018). Owing to its shape (it spreads over more than 10° of latitude from north to south), its position in the middle of the western Mediterranean and its mountainous nature, Italy can be considered particularly important, from a climatological point of view, among the different countries in the Mediterranean basin (Chiaravalloti et al. 2022). As regards the Italian territory, due to the lack of a national database, several rainfall trend studies have been performed at a regional

Responsible Editor: Mohamed Ksibi.

✉ Tommaso Caloiero
tommaso.caloiero@isafom.cnr.it

¹ Institute for Agriculture and Forest Systems in the Mediterranean (CNR-ISAFOM), National Research Council of Italy, Via Cavour 4/6, 87036 Rende, CS, Italy

² Department of Civil Engineering, University of Calabria, Rende, CS, Italy

or at a slightly larger scale (Chiaravalloti et al. 2022). The results of these studies showed a decrease in annual rainfall, especially in the southern (Liuzzo et al. 2016; Montaldo and Sarigu 2017; Caloiero et al. 2019) and in the central (Gentilucci et al. 2019; Scorzini and Leopardi 2019) regions of the country, while the decreasing tendencies in the annual values were only rarely found to be significant in its northern part (Todeschini 2012). In this area, and especially in the Alpine regions, quantifying past and future rainfall changes due to climate change is paramount. In fact, in these regions, rainfall is one of the most important climate variables, as it is related to water supply and energy production through dams. Moreover, it plays a crucial role in droughts and floods (Blanchet et al. 2021). Under the effects of climate change, the Alpine regions are undergoing fast and highly perceptible evolutions which are attracting the growing attention of people, scientists and managers (Einhorn et al. 2015). Nonetheless, in these areas, rainfall amounts have not changed much, but more droughts and less snow cover are predicted for the future (Gobiet et al. 2014). Therefore, it could be interesting to detect the rainfall heterogeneity at a monthly scale within a year. In this context, Oliver (1980) proposed the precipitation concentration index (PCI), which can provide useful information on the way annual rainfall totals are distributed across months. This index, which was later adopted by De Luis et al. (2011), has been recently applied in several analyses performed in the Mediterranean region and in different parts of the world, and it has allowed interesting scientific insights into the temporal variability and distribution of their rainfall regimes to be gained (e.g. Bartolini et al. 2017; Caloiero et al. 2019; Zhang et al. 2019; Tolika 2019; Bhattacharyya and Sreekesh 2022).

At a large scale, the Euro-Mediterranean rainfall variability is often related to the so-called teleconnection patterns, which have been widely described in the literature since the last century (Wallace and Gutzler 1981; Barnston and Livezey 1987; Rogers 1990). In fact, these patterns reflect large-scale changes in atmospheric waves and impact on several variables such as temperature, rainfall, storm tracks, jet stream location and intensity over vast areas (Hurrell and Deser 2009; Woollings et al. 2010; Bader et al. 2011).

In this context, the aim of this paper was to perform an analysis of rainfall values in a specific region of north-eastern Italy, Friuli-Venezia Giulia, which is characterized by a mountainous northern part belonging to the Southern Alps and a southern side touched by the Adriatic Sea. Moreover, the Friuli-Venezia Giulia region lacks rainfall analyses at different timescales and at a regional scale. To achieve this aim, rainfall trends were first detected at annual, seasonal and monthly scales, and then the effects of climate change on the rainfall distribution throughout the year were analysed by means of the PCI. Finally, a correlation analysis was performed between

seasonal rainfall and teleconnection patterns to identify the most relevant one over the region in the different seasons.

Methodology

Theil–Sen estimator method

Generally, the Theil–Sen estimator is considered more powerful than linear regression methods in trend magnitude evaluation because it is not subject to the influence of extreme values (Lo Presti et al. 2010). Given x_1, x_2, \dots, x_n rainfall observations at times t_1, t_2, \dots, t_n (with $t_1 \leq t_2 \leq \dots \leq t_n$), for each N pairs of observations x_j and x_i taken at times t_j and t_i , the gradient Q_k can be calculated as (Sen 1968)

$$Q_k = \frac{x_j - x_i}{t_j - t_i} \quad \text{for } k = 1, \dots, N, \quad (1)$$

with $1 \leq i \leq j \leq n$ and $t_j > t_i$.

The estimate for the trend in the data series x_1, x_2, \dots, x_n can then be calculated as the median Q_{med} of the N values of Q_k ranked from the smallest to the largest:

$$Q_{\text{med}} = \begin{cases} Q_{[(N+1)/2]} & \text{if } N \text{ is odd} \\ \frac{Q_{[N/2]} + Q_{[(N+2)/2]}}{2} & \text{if } N \text{ is even} \end{cases} \quad (2)$$

The sign of Q_{med} reveals the trend behaviour, while its value indicates the magnitude of the trend.

Mann–Kendall method

The Mann–Kendall method (Mann 1945; Kendall 1962) is one of the most widely adopted methods for trend detection in hydro-climatic datasets. The method is the most popular of various techniques because of its non-parametric character, its robust to extreme values and its simplicity in implementation. In this method, a pairwise data comparison is first performed to estimate the test statistic S , considering the j th and k th data,

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k), \quad (3)$$

where n is the number of data points in the series and the sign function (sgn) is given by

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \quad (4)$$

The variance of S is estimated as

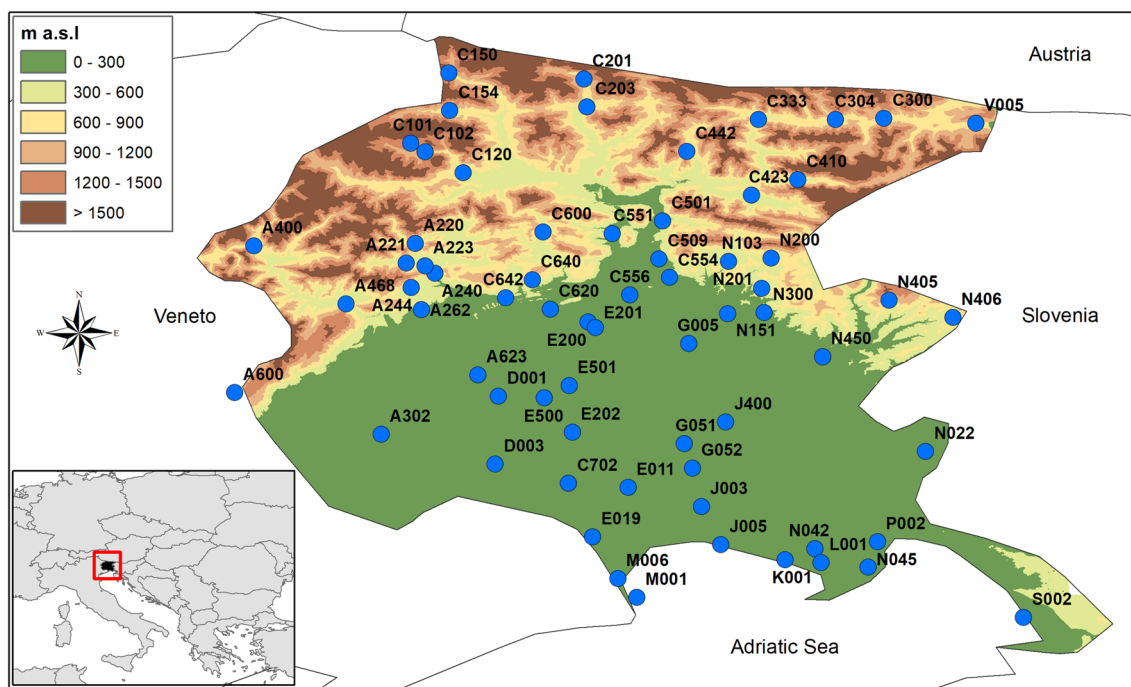


Fig. 1 Locations of the 67 selected rain gauges on a Digital elevation model (DEM)

$$\text{Var}(S) = \left[n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5) \right] / 18, \tag{5}$$

where t_i is the number of tied groups with extents ranging from i to m .

If n is larger than 10, the test statistic Z is computed as

$$Z_{\text{MK}} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{for } S < 0 \end{cases} \tag{6}$$

Positive and negative values of Z indicate increasing and decreasing trends, respectively. If the estimated value of $|Z|$ is $> Z_{\alpha/2}$, then the null hypothesis of no trend is rejected at the level of significance of α , for which 5% is commonly adopted.

Precipitation concentration index

The effects of climate change on the rainfall distribution throughout the year were analysed by means of the PCI (Oliver 1980), which can be evaluated as follows:

$$\text{PCI} = \frac{1}{N} \sum_{j=1}^N \text{PCI}_j, \tag{7}$$

where N is the number of years of observations and PCI_j is the PCI calculated for the j th year as

$$\text{PCI}_j = 100 \frac{\sum_{i=1}^{12} P_{ij}^2}{\left(\sum_{i=1}^{12} P_{ij} \right)^2}, \tag{8}$$

where P_{ij} is the rainfall amount in the i th month of the j th year.

PCI values lower than 10 indicate a uniform precipitation distribution; PCI values higher than 20 correspond to climates with substantial monthly precipitation variability; while PCI values between 10 and 20 represent seasonality in the precipitation distribution.

Teleconnections and correlation analysis

Rainfall from 1950 to 2011 was compared with four recurring patterns of atmospheric circulation that can be related to global climate variability on seasonal to interannual time-scales: the Western Mediterranean Oscillation (WeMO; Martin-Vide and Lopez-Bustins 2006), the North Atlantic Oscillation (NAO; e.g. Barnston and Livezey 1987), the El Niño/La Niña Southern Oscillation or ENSO (Bjerknes 1966) and the Arctic Oscillation (AO; Thompson and Wallace 1998).

In particular, a correlation analysis was performed between seasonal rainfall and the indices evaluated for the different teleconnection patterns. Data were retrieved

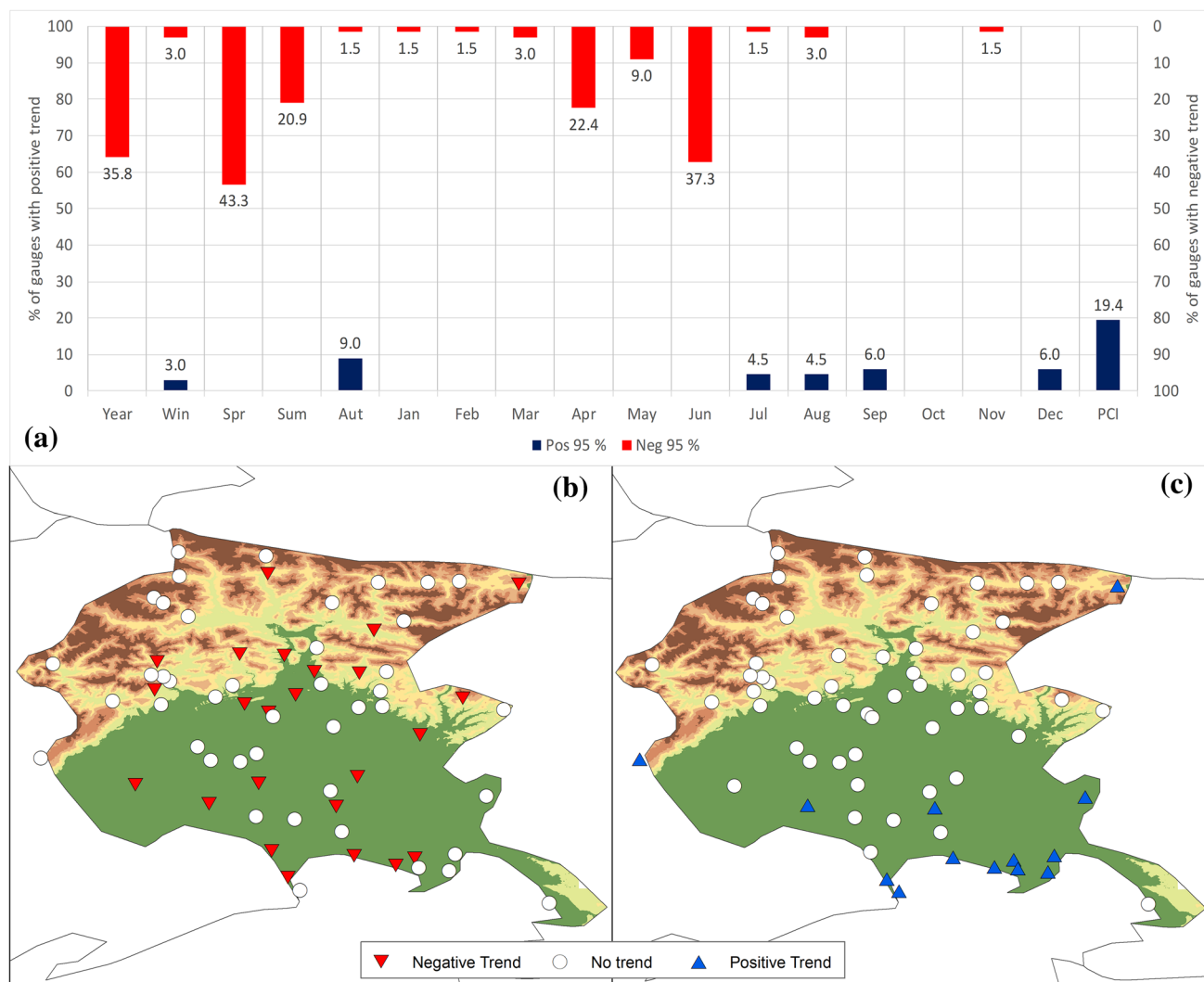


Fig. 2 Percentages of the rain gauges showing positive or negative trends (a), and spatial distributions of the results of the trend analysis for the annual rainfall (b) and the PCI values (c)

from the University of East Anglia’s Climate Research Unit (<https://crudata.uea.ac.uk/cru/data/moi/>) for the Western Mediterranean Oscillation Index (WeMOI) and from the United States National Weather Service’s (NWS) Climate Prediction Center (<https://www.cpc.ncep.noaa.gov>) for the Oceanic Niño Index (ONI, a measure of the El Niño Southern Oscillation, ENSO), the North Atlantic Oscillation Index (NAOI) and the Arctic Oscillation Index (AOI).

The connections between rainfall and these large-scale atmospheric patterns were investigated by means of Spearman’s rank correlation nonparametric test (Spearman 1904). Spearman’s rank correlation coefficient (ρ) is evaluated as

$$\rho = 1 - \frac{6 \sum D^2}{N(N^2 - 1)}, \quad (9)$$

where D is the difference between the ranks of corresponding values of the two variables, and N is the number of pairs of values.

Study area and data

The Friuli-Venezia Giulia region, the north-easternmost region of Italy, covers an area of about 8,000 km² and is the fifth smallest region of the country. It borders the Veneto region to the west, Austria to the north and Slovenia to the east. The south of the region faces the Adriatic Sea. Although Friuli-Venezia Giulia is a mountainous region (42.5% of the area in the north of the region), several plains characterize the central and coastal parts of the region (38.2%) while 19.3% is hilly, mostly to the south-east (Fig. 1). In fact, from

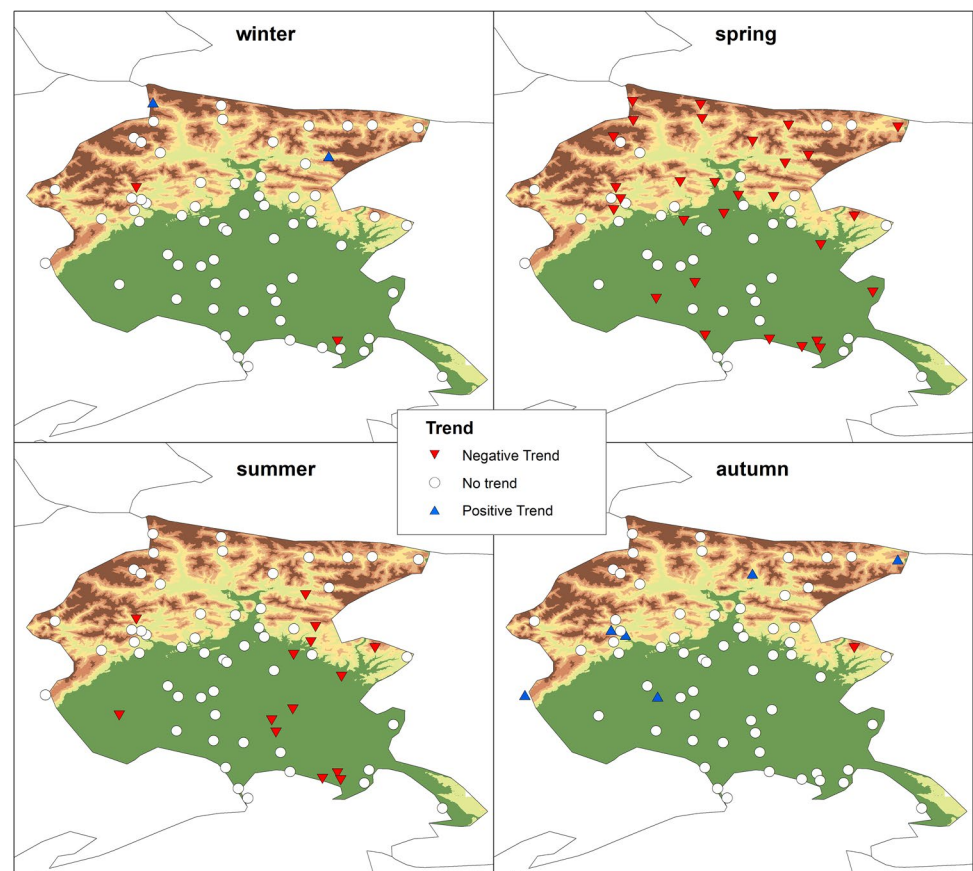
Table 1 Results of the trend analysis (mm/year) performed with the Theil–Sen estimator method

ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Autumn	Winter	Spring	Summer	PCI
A244													-4.62			-2.14		
C501																		
N042	-0.96							-1.79					-8.18		-4.14	-1.63	-2.54	0.05
V005				-1.43		-1.19		1.54					-6.93	4.10		-2.55		0.03
C101				-0.54												-0.97		
K001						-0.53							-3.54			-0.71	-0.70	0.01
C551													-7.46			-2.32		
A600									2.29					7.43				0.07
E500		-1.36				-1.59							-5.27			-2.27		
C600				-0.92												-4.35		
C442								3.18						7.23				
N045																		0.03
C300											-0.68							0.05
M001																		
A262																		
M006													-3.99					0.03
C203				-0.69									-3.37			-1.32		
L001				-1.09												-1.83	-2.94	0.07
E011						-0.47												
C154				-0.74												-1.14		
C702																		
G005												4.42						
E200													-3.07					
C120																		
N151						-2.69												-3.63
A400				-0.66			0.45											
C150				-0.76				0.29							0.88	-1.01		
J005													-2.41			-1.31		0.02
N406				-0.44		-0.47												
D001									0.86									
A623						-1.13												
C640																		
N200						-2.97												-6.34
S002																		
E202						-0.54							-2.46			-0.76		
A220				-3.49		-3.35							-19.56		-5.52	-7.08	-3.61	
A240									2.74					9.18				

Table 1 (continued)

ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Autumn	Winter	Spring	Summer	PCI
J400						-1.53							-7.59			-0.71	-2.99	0.01
N022						-0.47						0.55						
J003						-0.52												
C201			-0.69													-1.68		
C423			-0.91			-1.13							-6.94			-2.04	-1.44	
N103			-0.85			-0.97							-5.68			-2.49		
E501						-1.51												
E019						-0.46							-2.12			-0.68		
C102																		
N405			-0.87										-7.15	-2.89		-2.27	-1.69	
C410							0.52								1.71	-1.46		
G052						-0.65							-2.25				-0.82	0.01
N201						-0.93											-1.64	
P002																		
A223					-1.26												-2.03	0.02
A468																		
N300												0.75						
E201							2.15											
N450					-0.65	-0.62							-2.95			-1.48	-1.11	
C554						-3.35												
A221								3.09						9.45				
C333																-1.00		
D003						-0.46							-4.71			-1.18		0.01
C620				-0.55	-0.68	-0.60							-4.01			-1.80		
C642						-1.09	-0.68											
C304			-0.55															
G051						-1.74											-3.47	
C509													-3.97			-1.49		
A302						-1.05							-6.44				-1.91	
C556					-0.76	-0.77							-4.92			-1.88		

Fig. 3 Spatial distribution of the results of the trend analysis for seasonal rainfall



a morphological point of view, the region can be subdivided into four main areas: the mountainous area in the north, with the highest peaks exceeding 2700 m a.s.l.; the hilly area situated to the south of the mountains and along the central section of the border with Slovenia; the central plains, characterized by poor, arid and permeable soil; and the coastal area, which can be further subdivided into a western and an eastern side. According to the Köppen classification (Köppen 1936), the study area presents three different climates: Cfa (humid subtropical climate), Cfb (oceanic climate) and Dfb (warm humid continental climate).

The database used in this study consists of 67 monthly series for the period 1940–2011, with an average density of 1 station per 118 km² in the study area (Fig. 1). These data were collected, checked for quality (i.e. inhomogeneities) and freely distributed online by the Friuli-Venezia Giulia Region until 2011. The rainfall series presented missing data. In this study, in order to perform a reliable analysis, only stations with at least 30 years of observations were considered.

Results and discussion

In this section, the results of the trend analyses performed at annual, seasonal and monthly scales are presented and discussed. In particular, Fig. 2a shows the percentages of the rain gauges in which significant trends, either positive or negative, were detected at a significance level equal to 95%. As regards the annual rainfall, a marked negative tendency is evident. In fact, in 35.8% of the rain gauges, a negative trend was identified, while the remaining 64.2% showed no significant trends. This negative trend is spatially distributed throughout the entire region, from the mountains through the plains to the coastal parts of the region (Fig. 2b), but the highest reduction (more than 10 mm/year) was identified in the mountainous area in the north, at station A220 (Table 1).

At the seasonal scale, only four rain gauges showed significant trends in winter (Fig. 2a); these were equally divided between positive (two out of 67 rain gauges, equal to about 3%) and negative values. Owing to the low number of significant trends, the spatial behaviour of the trend results could not be identified. In any case, the rain gauges

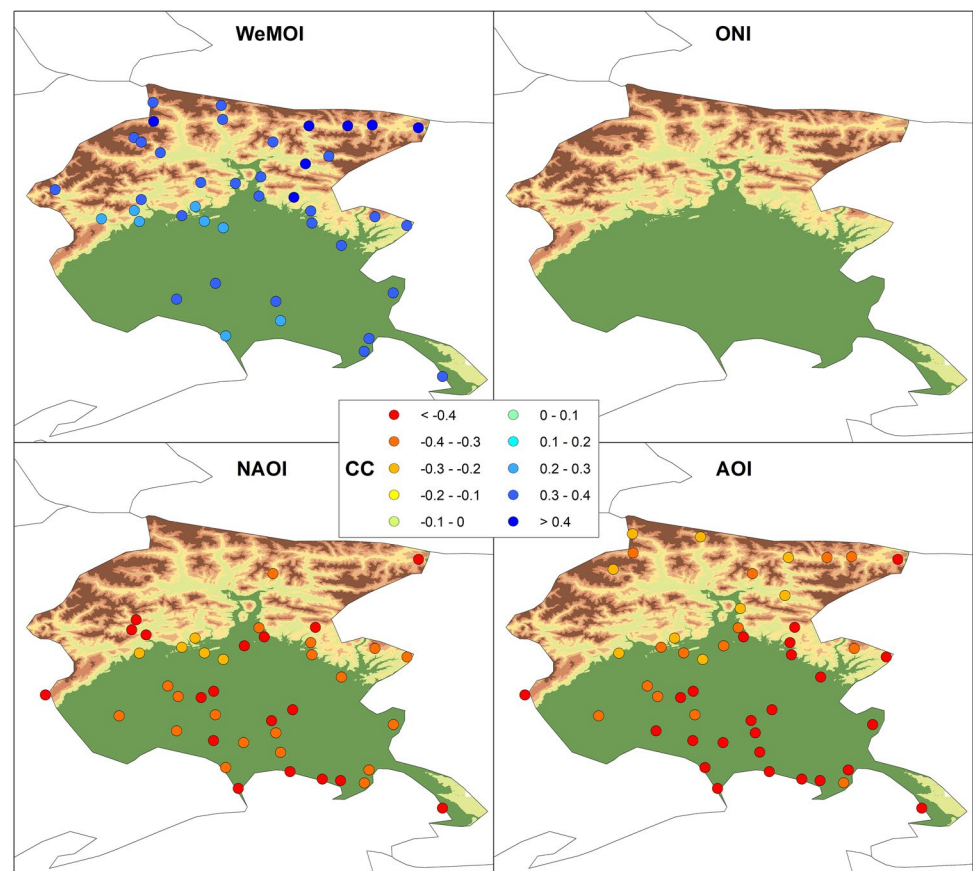


Fig. 4 Spatial distribution of the results of the trend analysis for monthly rainfall

showed positive trends in the northern part of the region (Fig. 3), with a maximum increase of 1.71 mm/year, while the central and southern areas showed negative trends, with a reduction of about 5 mm/year (Table 1). Differently from winter, spring is characterized by a marked reduction in the rainfall values. In fact, this trend behaviour was detected in 43.3% of the rain gauges, whereas there were no positive

trends at all (Fig. 2a). As regards the spatial distribution of these trend results, the mountainous and the coastal areas seem to be more affected than the central plains by a rainfall reduction (Fig. 3). In particular, the highest reduction was identified in the mountainous area in the north, in the stations A220 (about 7 mm/year), C442 (4.35 mm/year) and V005 (−2.55 mm/year) (Table 1). A similar trend behaviour

Fig. 5 Maps of Spearman's rank correlation coefficients between winter rainfall and the climatic indices

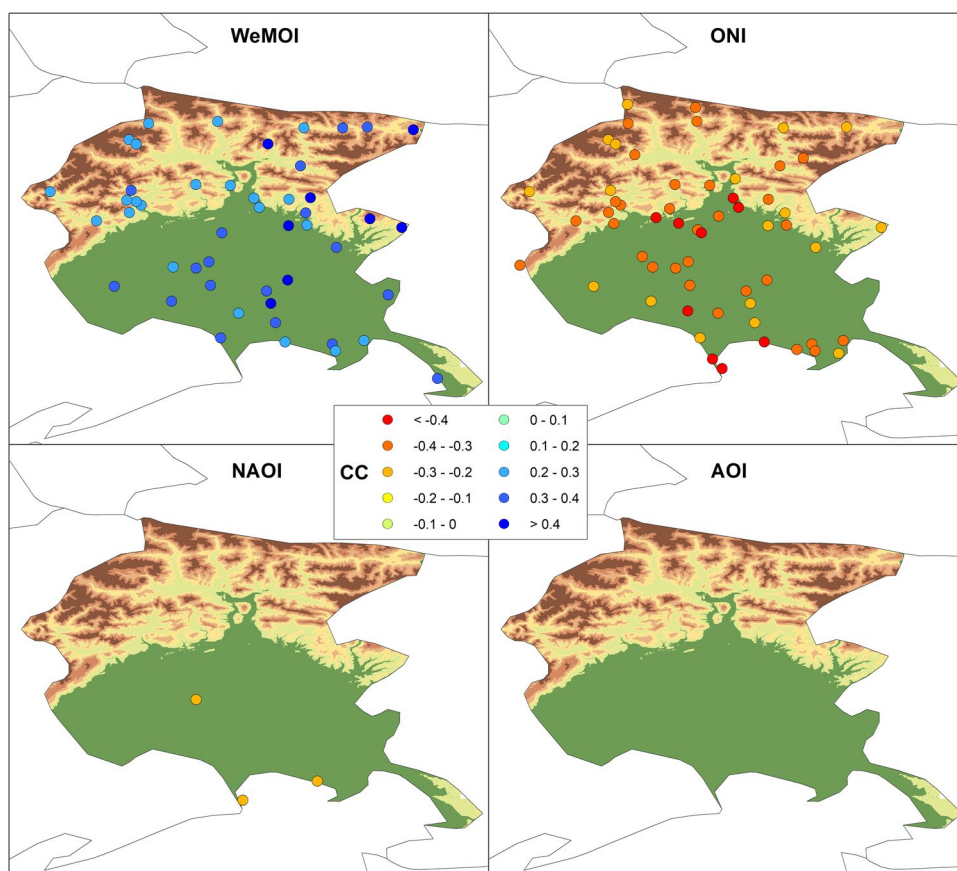


to that in spring was identified for summer, but with a lower percentage of significant trends. In fact, in summer, about 20% of the rain gauges showed negative trend values, while no significant trends were detected in the remaining rain gauges (Fig. 2a). Even though similar trend behaviours characterize spring and summer, the spatial distribution of the rain gauges showing significant trends is totally different; they were mainly from the eastern side of the region and, especially, the central plains and the coastal areas (Fig. 3). Further confirming this behaviour, the highest negative tendencies were detected in the central-western area of the region, with reductions of 6.34 mm/year and 3.63 mm/year seen for the rain gauges N200 and N151, respectively (Table 1). Finally, in autumn, the opposite trend behaviour was detected, with 9% and 1.5% of the stations showing a positive and a negative trend, respectively (Fig. 2a). The spatial distribution of these trends evidenced opposite results compared to those for summer, with a significant increase in the rainfall values mainly on the western side of Friuli-Venezia Giulia (Fig. 3). In fact, on this side of the region, the highest trend magnitudes were detected, reaching values of higher than 9 mm/year in the rain gauges A221 and A240 (Table 1).

This seasonal trend behaviour was confirmed at the monthly scale. In particular, in the spring months (i.e.

March, April and May), only negative trends were detected, with relevant results in April when 22.4% of the rain gauges evidenced a rainfall decrease (Fig. 2a). In March and May, the percentage of rain gauges showing negative trends was lower than in April, being equal to 3% and 9%, respectively (Fig. 2a). The spatial distribution of the trend results reflects the seasonal ones, with the mountainous and the coastal areas appearing to be more affected by a rainfall reduction than the central plains, especially in April and in May (Fig. 4). In fact, the highest reductions were identified in the rain gauge A220 in March (3.49 mm/year) and April (3.45 mm/year) and in gauge A223 in May (1.26 mm/year), both of which are within the mountainous area (Table 1). Among the summer months (i.e. June, July and August), only June showed a marked negative trend (37.3% of the series), while both positive (4.5% for both) and negative (1.5% and 3%, respectively) values were identified in July and August (Fig. 2a). Due to the low number of significant trends in July and August, the spatial behaviour of the trend results can only be identified for June, when the negative trends occurred in the central plains and the coastal areas of the region (Fig. 4), with a maximum reduction of 3.35 mm/year seen in rain gauge C554 (Table 1). In autumn (i.e. September, October and November), the positive trend evidenced at the seasonal scale is influenced by the results

Fig. 6 Maps of Spearman's rank correlation coefficients between spring rainfall and the climatic indices



for September, when this behaviour was identified in 6% of the rain gauges (Fig. 2a), which were mainly located on the western side of the region (Fig. 4), where an increase of 3 mm/year was evaluated for rain gauge A221 (Table 1). Finally, in the winter months (i.e. December, January and February), only a very low percentage of the rain gauges showed significant trends (Figs. 2a and 4), which were of a low magnitude (Table 1).

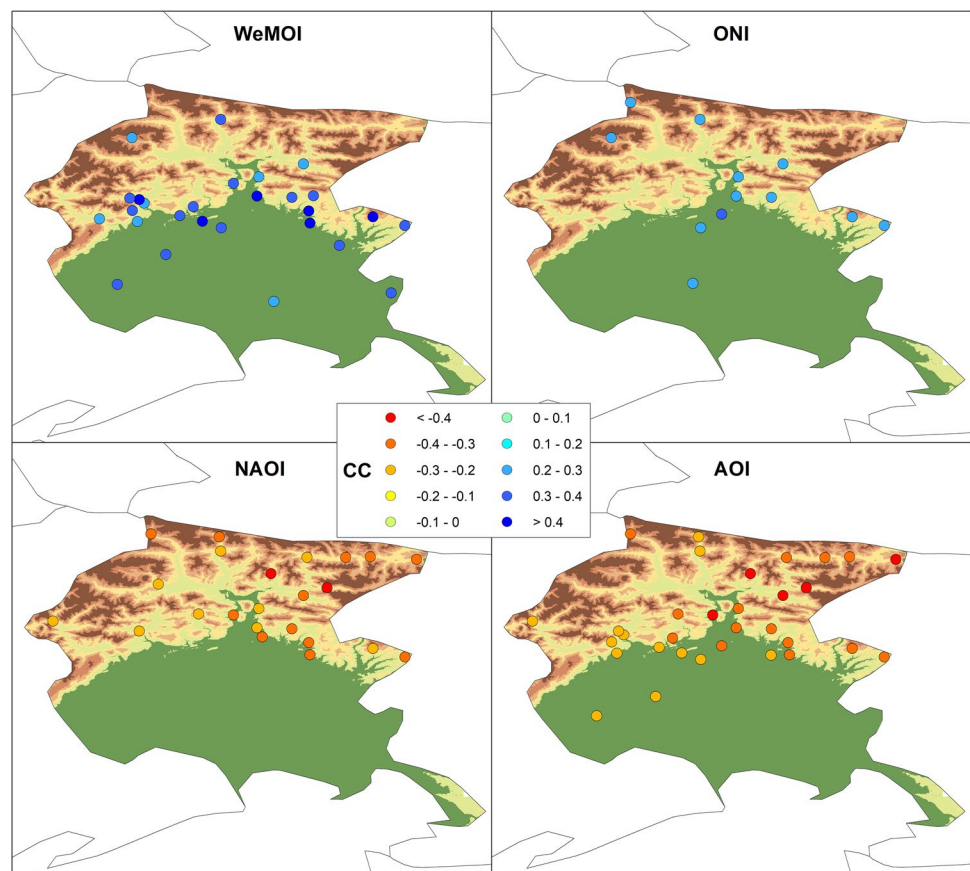
Besides the trend analysis, the effects of climate change on the rainfall distribution throughout the year were analysed by means of the PCI, which, based on the rain gauges within the Friuli-Venezia Giulia region, is characterized by values ranging from 11.35 to 14.3 and shows seasonality in the precipitation distribution. Results of the trend analysis performed on the annual values of the PCI evidenced a positive trend in almost 20% of the stations, thus indicating a tendency towards a more seasonal rainfall distribution in the Friuli-Venezia Giulia region throughout the year. In fact, given the maximum increase in the PCI value of 0.07 per year, which was evaluated for rain gauges A600 and L001 (Table 1), the results of the trend analysis only evidenced a tendency toward a less uniform distribution of rainfall during the year without any further changes because the PCI threshold of 20, corresponding to climates with substantial monthly precipitation variability, cannot be reached in the

next few years. Moreover, this trend behaviour only characterizes some of the stations situated in the southern part of the region, with the exception of one station in the easternmost part (Fig. 2c).

The results of this work confirm past studies which evidenced a reduction in annual rainfall in Italy, especially in the southern regions of the country and in some regions of Central Italy such as Abruzzo and Marche (Scorzini and Leopardi 2019; Gentilucci et al. 2019), but which significantly differ from these studies in their seasonal trends. On the contrary, this study confirms the seasonal trend behaviour detected in southwestern Europe by several authors (e.g. Caloiero et al. 2018). The trend behaviour identified in Friuli-Venezia Giulia could be due to the different factors affecting its climate. In fact, the Alpine system protects the region from the direct impact of the northerly winds. Moreover, the opening toward the Po Valley influences the general circulation of air masses in the west–east direction, along which the low pressure moves, bringing thunderstorms and hailstorms, especially in the summer. Finally, being open to the Adriatic Sea, the territory also receives sirocco winds, bringing heavy rainfalls with them.

The results of the correlation analysis performed between seasonal rainfall and the indices evaluated for the different teleconnection patterns allowed us to identify the most

Fig. 7 Maps of Spearman's rank correlation coefficients between summer rainfall and the climatic indices

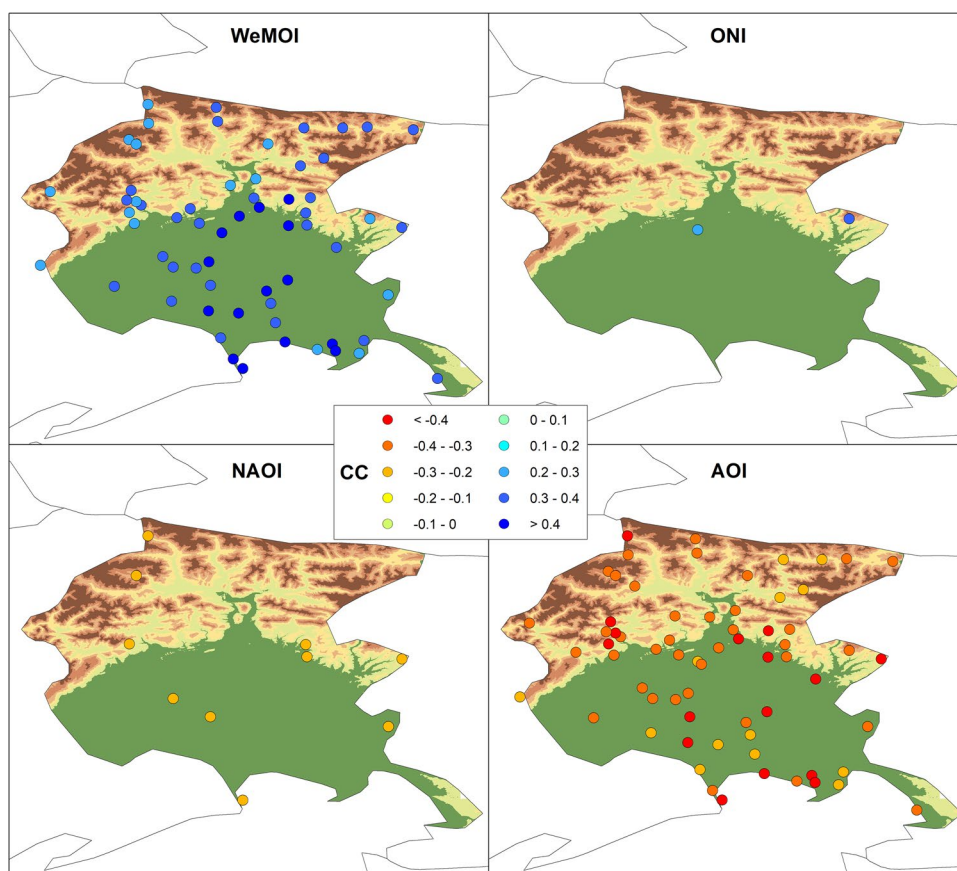


relevant one over Friuli-Venezia Giulia in the different seasons. In particular, Fig. 5 shows the significant correlations between the indices and the winter rainfall. No significant correlations were identified for the ONI, a positive correlation was identified for the WeMOI in 42 out of 67 series, and negative correlations were detected for the NAOI and the AOI in 42 and 48 series, respectively. The highest coefficient of correlation (CC) in terms of the absolute value is 0.69, corresponding to a negative correlation with the NAOI. However, high CC values were also detected for the WeMOI (about 0.5) and for the AOI (−0.61). Differently from winter, in spring, the highest number of series showing a significant correlation were identified for the ONI (Fig. 6), with 58 out of 67 series presenting negative CC values and a maximum (absolute value) of 0.53. A marked significant correlation was also detected for the WeMOI (52 series were positively correlated and the maximum CC was 0.49), while the NAOI and the AOI evidenced a very low number of correlations (only three out of 67 series) and a total lack of correlation, respectively. As regards the summer (Fig. 7), significant positive correlations were detected between rainfall and the WeMOI (in 32 out of 67 series) and the ONI (in 12 out of 67 series), with CC values higher than 0.5 and 0.3, respectively. At the same time, negative correlations characterized NAOI and AOI, with the highest CCs in absolute value equal to

0.52 for the NAOI (significant correlations in 23 out of 67 series) and 0.61 for the AOI (significant correlations in 32 out of 67 series). Similar results to those in summer were detected in autumn (Fig. 8), although there were even more marked correlations for the WeMOI and the AOI, with 63 and 66 out of the 67 rainfall series showing significant positive (a maximum CC of 0.59) and negative (a maximum CC of 0.46 in absolute value) correlations, respectively. Only a few rainfall series were found to be correlated with the ONI (2) and the NAOI (10), and with low CC values of 0.32 and −0.27, respectively.

As a result of the correlation analysis, the WeMO can be considered the most relevant teleconnection over all Friuli-Venezia Giulia in the different seasons. In fact, the WeMO is only defined within the synoptic framework of the western Mediterranean basin and its vicinity. Furthermore, the WeMOI is evaluated by considering the difference between the standardized atmospheric pressure recorded at two points: Padua in northern Italy and Cádiz in Spain (Martin-Vide and Lopez-Bustins 2006). These points fall within the Po plain, an area with a relatively high barometric variability, and the Gulf of Cádiz, which is often subject to the influence of the Azores anticyclone. As a consequence, positive WeMOI values indicate an anticyclone in the Gulf of Cádiz area and a low-pressure area by the Ligurian Sea,

Fig. 8 Maps of Spearman's rank correlation coefficients between autumn rainfall and the climatic indices



whereas negative WeMOI values refer to a low in the Gulf of Cádiz and an anticyclone in Central Europe (Martin-Vide and Lopez-Bustins 2006).

Conclusions

This spatiotemporal analysis of the regional precipitation climate regime in the mountainous Alpine regions of northern Italy, one of the major mountainous areas in Europe, could be particularly interesting in many fields of the applied sciences. The rainfall in these regions contributes to the freshwater and hydropower within and beyond the area. Moreover, it enables transportation on rivers and shapes the distribution and diversity of ecosystems. In order to get a better understanding the rainfall variability in northern Italy, in this paper, 67 rainfall series for the Friuli-Venezia Giulia region have been analysed. In particular, a trend analysis has been performed using two non-parametric tests, and the effect of climate change on the rainfall distribution throughout the year has been analysed by means of the PCI. The following main results were obtained:

(1) A negative trend in the annual rainfall especially in the central and southern areas of the region

- (2) The mountainous and the coastal areas of the region seem to be more affected by a rainfall reduction in spring than the central plains
- (3) A negative trend in the summer rainfall was mainly identified in the eastern side of the region and, especially, in the central plains and the coastal areas
- (4) The opposite trend behaviour was detected in autumn
- (5) The seasonal trend behaviour was confirmed at the monthly scale
- (6) Results of the trend analysis performed on the annual values of the PCI evidenced a positive trend, thus indicating a tendency towards a more seasonal rainfall distribution
- (7) The WeMOI was identified as the most relevant teleconnection over all Friuli-Venezia Giulia in the different seasons.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

References

- Bader J, Mesquita MDS, Hodges KI, Keenlyside N, Østerhus S, Miles M (2011) A review on Northern Hemisphere sea-ice, storminess and the North Atlantic Oscillation: observations and projected changes. *Atmos Res* 101:809–834
- Barnston AG, Livezey RE (1987) Classifications, seasonality, and persistence of low-frequency atmospheric circulation patterns. *Mon Weather Rev* 115:1083–1126
- Bartolini G, Grifoni D, Magno R, Torrigiani T, Gozzini B (2017) Changes in the temporal distribution of precipitation in a Mediterranean area (Tuscany, Italy) 1955–2013. *Int J Climatol* 37:1366–1374
- Bhattacharyya S, Sreekesh S (2022) Assessments of multiple gridded-rainfall datasets for characterizing the precipitation concentration index and its trends in India. *Int J Climatol* 42:3147–3172
- Bjerknes J (1966) A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus* 18:820–829
- Blanchet J, Blanc A, Creutin JD (2021) Explaining recent trends in extreme precipitation in the Southwestern Alps by changes in atmospheric influences. *Weather Clim Extrem* 33:100356
- Caloiero T, Caloiero P, Frustaci F (2018) Long-term precipitation trend analysis in Europe and in the Mediterranean basin. *Water Environ J* 32:433–445
- Caloiero T, Coscarelli R, Gaudio R, Leonardo GP (2019) Precipitation trend and concentration in the Sardinia region. *Theor Appl Climatol* 137:297–307
- Chiaravalloti F, Caloiero T, Coscarelli R (2022) The long-term ERA5 data series for trend analysis of rainfall in Italy. *Hydrology* 9:18
- de Luis M, Gonzalez-Hidalgo JC, Brunetti M, Longares LA (2011) Precipitation concentration changes in Spain 1946–2005. *Nat Hazards Earth Syst Sci* 11:1259–1265
- Einhorn B, Eckert N, Chaix C, Ravanel L, Deline P, Gardent M, Boudières V, Richard D, Vengeon JM, Giraud G, Schoeneich P (2015) Climate change and natural hazards in the Alps. *Rev Geogr Alp* 103:2
- Gentilucci M, Barbieri M, Lee HS, Zardi D (2019) Analysis of rainfall trends and extreme precipitation in the middle Adriatic side, Marche region (Central Italy). *Water* 11:1948
- Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, Stoffel M (2014) 21st century climate change in the European Alps: a review. *Sci Total Environ* 493:1138–1151
- Hurrell JW, Deser C (2009) North Atlantic climate variability: the role of the North Atlantic oscillation. *J Mar Syst* 78:28–41
- IPCC (2013) Summary for policymakers. Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
- Kendall MG (1962) Rank correlation methods. Hafner, New York
- Köppen W (1936) Das geographische System der Klimate. In: Köppen W, Geiger R (eds) *Handbuch der Klimatologie Bd. 1: Teil C*. Bornträger, Berlin
- Liuzzo L, Bono E, Sammartano V, Freni G (2016) Analysis of spatial and temporal rainfall trends in Sicily during the 1921–2012 period. *Theor Appl Climatol* 126:113–129
- Lo Presti R, Barca E, Passarella G (2010) A methodology for treating missing data applied to daily rainfall data in the Candelaro River Basin (Italy). *Environ Monit Assess* 160:1–22
- Mann HB (1945) Nonparametric tests against trend. *Econometrica* 13:245–259
- Martin-Vide J, Lopez-Bustins JA (2006) The Western Mediterranean Oscillation and rainfall in the Iberian peninsula. *Int J Climatol* 26:1455–1475
- Montaldo N, Sarigu A (2017) Potential links between the North Atlantic Oscillation and decreasing precipitation and runoff on a Mediterranean area. *J Hydrol* 553:419–437
- Oliver JE (1980) Monthly precipitation distribution: a comparative index. *Prof Geogr* 32:300–309
- Pendergrass AG, Hartmann DL (2014) Changes in the distribution of rain frequency and intensity in response to global warming. *J Clim* 27:8372–8383
- Rogers JC (1990) Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated wave cyclone frequencies. *J Clim* 3:1364–1379
- Scorzini AR, Leopardi M (2019) Precipitation and temperature trends over central Italy (Abruzzo Region): 1951–2012. *Theor Appl Climatol* 135:959–977
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc* 63:1379–1389
- Spearman C (1904) The proof and measurement of association between two things. *Am J Psychol* 15:72–101
- Thompson DWJ, Wallace JM (1998) The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys Res Lett* 25:1297–1300
- Todeschini S (2012) Trends in long daily rainfall series of Lombardia (northern Italy) affecting urban stormwater control. *Int J Climatol* 32:900–919
- Tolika K (2019) On the analysis of the temporal precipitation distribution over Greece using the Precipitation Concentration Index (PCI): annual, seasonal, monthly analysis and association with the atmospheric circulation. *Theor Appl Climatol* 137:2303–2319
- Toreti A, Naveau P, Zampieri M, Schindler A, Scoccimarro E, Xoplaki E, Dijkstra HA, Gualdi S, Luterbacher J (2013) Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. *Geophys Res Lett* 40:4887–4892
- Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon Weather Rev* 109:784–812
- Woollings T, Hannachi A, Hoskins B (2010) Variability of the North Atlantic eddy-driven jet stream. *Q J R Meteorol Soc* 136:856–868
- Zhang X, Wan H, Zwiers FW, Hegerl GC, Min SK (2013) Attributing intensification of precipitation extremes to human influence. *Geophys Res Lett* 40:5252–5257
- Zhang K, Yao Y, Qian X, Wang J (2019) Various characteristics of precipitation concentration index and its cause analysis in China between 1960 and 2016. *Int J Climatol* 39:4648–4658

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.