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RESEARCH

Spatiotemporal investigation of meteorological drought variability over northern Algeria and its relationship with different atmospheric circulation patterns

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Abstract

This study examines the spatial and temporal variations of meteorological drought over northern Algeria based on the Standardized Precipitation Index (SPI) and Principal Component Analysis (PCA) with Varimax Rotation. It also evaluates the relationship between different atmospheric circulation indices and drought variability at seasonal and annual time scales. The atmospheric circulation indices considered in this assessment are the Southern Oscillation Index (SOI), the North Atlantic Oscillation (NAO) Index, the Westerly Index (WI), the two Mediterranean Oscillation Indices (MOI1) (MOI2), the Western Mediterranean Oscillation Index (WeMOI), the North Sea Caspian Pattern (NCP) Index, the Trans Polar Index (TPI), and the Eastern Mediterranean Pattern (EMP) Index. The obtained results indicate that drought varies widely over the study area, as four Rotated Principal Components (RPCs) were retained for the Varimax Rotation, which divided the study area into four drought sub-regions: the central and eastern coastal regions represented by RPC1, the western regions represented by RPC2, the eastern regions represented by RPC3, and the west-central southern regions represented by RPC4. Drought variability on seasonal basis was successfully associated with different atmospheric circulation indices, mainly with EMP at the eastern part of the study area, which gathers the sub-regions represented by RPC1 and RPC3, and with SOI, NAO, WI, MOI1, and MOI2 in the western part, which gathers the sub-regions represented by RPC2 and RPC4. Drought inter-annual variability was better explained by EMP in RPC1 sub-region, by SOI in RPC2 sub-region, by NCP in RPC3 sub-region, and by MOI1 in RPC4 sub-region. Another important outcome revealed by this study is the prevalence of a general increasing trend in drought conditions over the study area, with more statistically significant trends in the western regions. Overall, this study has resulted in a better understanding of the mechanisms responsible for drought variability over northern Algeria, constituting valuable material for enhancing drought forecasting and water resource planning.

1 Introduction

Drought is among the most significant global natural hazards caused by lack of precipitation over a certain period. It is a highly variable and recurrent phenomenon which can lead to numerous environmental and socioeconomic disasters, such as decrease of water levels and stream flows, agricultural damages, increased wildfire hazards, emergence of diseases and epidemics, and conflicts and wars (Vicente-Serrano et al. 2012; Muiruri 2018; Khoshoei et al. 2019). Giving consideration to its process of occurrence and its effects on different sectors, Wilhite and Glantz (1985) classified drought into four main categories: (1) meteorological

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drought, (2) hydrological drought, (3) agricultural drought, and (4) socioeconomic drought.

The Standardized Precipitation Index (SPI) developed by McKee et al. (1993) is currently the most popular drought index due to its simplicity (as it requires only precipitation data) and its applicability for different timescales. Besides, the SPI has proven its effectiveness in assessing and quantifying meteorological droughts in many countries around the world, e.g., in Kuwait (Almedeij 2014), in Italy (Buttafuoco et al. 2015), in Morocco (Ouatiki et al. 2019), and in Turkey (Komuscu 1999). Furthermore, the SPI can be employed in analyzing other types of drought. For instance, Gumus and Algin (2017) provided a reliable relationship between meteorological and hydrological drought events for the Seyhan−Ceyhan Basins in Turkey based on the use of SPI along with the stream flow drought index (SDI) at different time scales. Meliho et al. (2020) successfully identified the relationship between meteorological drought and agricultural drought in the Tensift Watershed in Morocco by comparing SPI characteristics at different time scales with the volume of water allocated to the major crops. In this context, Mishra and Singh (2010) suggested that the use of SPI values calculated at short time scales (3 to 6 months) are appropriate to describe agricultural droughts, while larger time scales, such as 12 or 24 months, are more appropriate to describe hydrological droughts.

Algeria, as a part of the western Mediterranean Basin, is particularly vulnerable to drought hazard (Habibi et al. 2018). It is situated between mid-latitudes and a tropical zone, in which atmospheric dynamic interacts with a contrasting topography and generates a high spatiotemporal variability of rainfall (Zerouali et al. 2021a). In fact, Algeria ranks among the poorest countries in terms of water potential despite the huge efforts allocated by the national authorities of the water sector since its independence in 1962 (Roudi-Fahimi et al. 2002; Hamiche et al. 2015). Currently, freshwater availability is estimated at only 600 m^3/capita/year (Sahnoune et al. 2013), whereas the threshold for water scarcity is 1000 m^3/capita/year according to the (Bucknall 2007). Drought effects are mainly felt in the northern part of Algeria that comprises the main renewable water resources, and not in the Saharan southern part, which contains enormous amounts of fossil ground waters (Drouiche et al. 2012; Derdous et al. 2020).

Indeed, in northern Algeria, rainfall is a predominant factor that significantly affects agricultural yields. Insufficient rainfall directly leads to agricultural drought, resulting in a substantial decline in harvests, primarily cereals, which account for 97% of the arable land, covering an area of 2.7 million hectares (Chourghal et al. 2016; Habibi and Meddi 2021). Cereals occupy a strategic position within Algeria's food system and national economy (Chaib 2022). The lack of rain during 2021 has led to a decline in local cereal production by around 38% (3.5 million metric tons), while cereal imports increased by 25% (8.1 million metric tons) compared to the previous year (Tanchum 2021; FAO 2022). Therefore, understanding drought mechanisms in northern Algeria is critical as a first step for establishing suitable strategies to mitigate its adverse agricultural and socioeconomic implications. Lately, a large number of studies were carried out aiming at characterizing past drought events over northern Algeria. Taibi and Souag (2011) reported that the northwestern and central highland regions witnessed severe droughts during the 1970s and 1980s. Khezazna et al. (2017) revealed significant inter-annual fluctuation of annual rainfall across the Seybouse Basin (northwestern Algeria), which resulted in a long drought cycle between 1970 and 2000, followed by a wet cycle, which has started since 2001. Likewise, Derdous et al. (2021b) identified important interannual variability of rainfall across the Cheliff Basin (northwestern Algeria) which is organized in a long wet cycle (1938–1976) followed by a long drought cycle (1977–2008) with a rainfall deficit of about 20%.

Several other studies attempted to identify the probable climatic causes of these recent droughts (Meddi et al. 2014; Zeroual et al. 2017; Taibi et al. 2017; Hallouz et al. 2020). They showed that the observed droughts were part of a regional behavior, which occurred throughout the Mediterranean Basin. Previous research has linked rainfall variability over the Mediterranean basin with several atmospheric circulation patterns, such as the Mediterranean oscillation (MOI) (Conte et al. 1989; Palutikof 2003), the North Atlantic Oscillation (NAO) (Maheras et al. 1999), the North Sea-Caspian Pattern (NCP) (Kutiel and Benaroch 2002), the Western Mediterranean Oscillation (WeMOI) (Martin-Vide and Lopez-Bustins 2006), the Eastern Mediterranean Pattern (EMP) (Hatzaki et al. 2007), the Trans Polar Pattern (TPI) (Onyutha and Willems 2015), the southern oscillation (SOI) (Duzenli et al. 2018), and the Westerly winds (WI) (Casas-Gómez et al. 2020). Among these atmospheric circulation patterns NAO, MOI, and SOI were identified as the main driving atmospheric patterns influencing rainfall variability in northwestern Algeria (Zeroual et al. 2017; Taibi et al. 2017). On the other hand, rainfall/drought variability in northeastern Algeria was not linked to any of the recognized atmospheric circulation patterns (Taibi et al. 2017; Derdous et al. 2020). The identification of relationships between drought variability and atmospheric circulation patterns is a necessary material for drought forecasting using physical models, which relay on the oceanic–atmospheric interaction, for predicting the trends of climatic parameters (Philandras et al. 2011). This is of great importance for establishing efficient water resources planning and management at the regional level. This emphasizes the critical need to further explore drought spatiotemporal variability in northern Algeria and its main driving patterns.

The main objectives of this study are (1) to characterize meteorological droughts that occurred between 1948 and 2005 over northern Algeria by means of SPI at seasonal and annual time scales, (2) to identify drought sub-regions using Principal Component Analysis, (3) to assess the long-term temporal trend of droughts at each sub-region, and (4) to investigate the potential relationships between drought variability and large-scale atmospheric circulation patterns.

2 Data and methodology

2.1 Study area and data

Northern Algeria, which occupies an area of 227,740 km^2, is located between the latitudes 32°37′ N and 37°00′ N and the longitudes 8°42′ E and 2°12′ W. It is bounded to the north of the Mediterranean Sea, to the west of Morocco, to the east of Tunisia, and to the south of the Sahara Desert (Fig. 1). Northern Algeria depicts high spatial diversity of climate varying from humid conditions in the northeast to arid conditions in the southwest following the same spatial pattern of rainfall amounts (Derdous et al. 2020; Derdous et al. 2021a).

Monthly rainfall data, registered during the period 1948–2005, were collected from the national agency for hydraulic resources (ANRH). A total number of 118 rainfall stations, spread over the whole study area (see Fig. 1), were considered.

The atmospheric circulation indices (see Table 1) employed in this study comprise the following: (1) the Southern Oscillation Index (SOI) calculated by Ropelewski and Jones (1987), (2) the North Atlantic Oscillation (NOA) presented by Hurrell (1995), (3) the Westerly Index (WI) developed by Cornes et al. (2013), (4) the first version of the Mediterranean Oscillation Index (MOI1) developed by Conte et al. (1989), (5) the second (MOI2) developed by Palutikof (2003), (6) the Western Mediterranean Oscillation Index (WeMOI) calculated by Martin-Vide and Lopez-Bustins (2006), (7) the North Sea Caspian Pattern Index (NCP) by Kutiel and Benaroch (2002), and (8) the Trans Polar Index (TPI) developed by Pittock (1980); the above-mentioned atmospheric indices are available on the website of the Climatic Research Unit, University of Anglia (https://www.uea.ac.uk/groups-and-centres/climatic-research-unit), and (9) the Eastern Mediterranean Pattern (EMP) Index that was developed by Hatzaki et al. (2007), which was calculated for the 1948–2005 period based on the climate data store (CDS) available on the website https://cds.climate.copernicus.eu/.

2.2 Methodology

The statistical analyses have been conducted in the framework of this study in four steps:

First, the calculation of SPI at seasonal (SPI-3) and annual (SPI-12) time scales was carried out using the two-parameter gamma distribution. This latter is widely accepted as the most suitable method for SPI calculation across northern Algeria (Merabti et al. 2018a; Achour et al. 2020a; Achite et al. 2021; Merabti et al. 2023). Additionally, it is recommended by the World Meteorological Organization (Kebaili Bargaoui and Jemai 2022). The cumulative probability extracted from the gamma distribution for each of the datasets is used to calculate the respective standard normal distribution quantile of any data point, resulting in the SPI (Merabti et al. 2023).

Second, Principal Component Analysis (PCA) was applied to SPI-3 and SPI-12 time series for the considered rainfall stations in order to identify drought homogeneous regions. PCA is a multivariate technique that reduces the dimensionality in a dataset and forms a new set of orthogonal

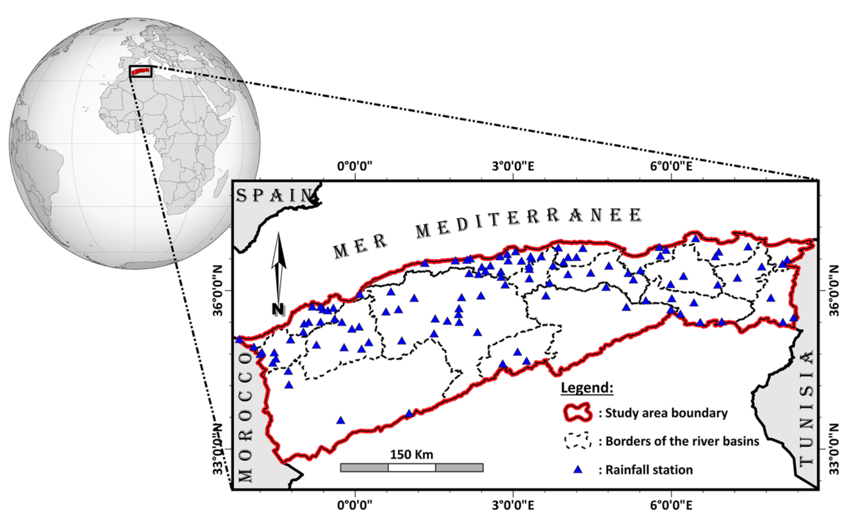

Fig. 1 Geographical location of the study area and the considered rainfall stations

Table 1 Names and description of atmospheric circulation patterns

Abbreviation	Index description	References
SOI	The Southern Oscillation Index is defined as the temporal evolution of the normalized difference sea-level pressure between Tahiti and Darwin Poles.	Ropelewski and Jones (1987)
NAO	The North Atlantic Oscillation index is defined as the normalized sea-level pressure difference, as derived from Gibraltar to Southwest Iceland.	Hurrell (1995)
WI	The Westerly Index based on Paris to London normalized sea-level pressure difference.	Cornes et al. (2013)
MOI1	The first version of the Mediterranean Oscillation Index based on Algiers (3.1°E, 36.4°N) to Cairo (31.4°E, 30.1°N) normalized difference sea-level pressure.	Conte et al. (1989)
MOI2	The second version of the Mediterranean Oscillation Index based on Gibraltar's Northern Frontier (5.3°W, 36.1°N) and Lod Airport (34.5°E, 32.0°N) normalized difference sea-level pressure.	Palutikof (2003)
WeMOI	The Western Mediterranean Oscillation Index is based on the calculation of the surface pressure difference between San Fernando, Spain (6.2°W, 36.5°N) and Padua, Italy (11.9°E, 45.4°N).	Martin-Vide and Lopez-Bustins (2006)
NCP	The North Sea Caspian Pattern Index is defined as the normalized geopotential height difference at 500 hPa level between the average of the North Sea region (0°, 55°N and 10°E, 55°N) and the North Caspian Region (50°E, 45°N and 60°E, 45°N).	Kutiel and Benaroch (2002)
TPI	The Trans Polar Index based on Hobart to Stanley normalized difference sea-level pressure.	Pittock (1980)
EMP	The Eastern Mediterranean Pattern index is defined as the normalized geopotential height difference at 500 hPa level between the north-eastern Atlantic (25°W, 52.5°N) and the eastern Mediterranean (22.5°E, 32.5°N) poles.	Hatzaki et al. (2007)

variables, which represent linear combinations of the original variables (Jolliffe 2002; Abdi and Williams 2010; Demšar et al. 2013). The coefficients of the linear combinations are called loadings and they represent the weights of the original variables in the Principal Components (Serrano et al. 1999). In order to get more localized spatial patterns of drought variability, the Varimax Rotation was applied to the loadings. Varimax Rotation is widely accepted as being the most accurate orthogonal rotation method and has been widely employed in drought studies (Serrano et al. 1999; Martins et al. 2012; Merabti et al. 2018b). The decision on the number of principal components to be retained for rotation was established, at a significance level of 5%, based on three statistical tests namely the North's rule of thumb (North et al. 1982), Cattell's scree test (Cattell 1966; Cattell and Vogelmann 1977) and bootstrapping techniques (Peres-Neto et al. 2005).

In the third step, the temporal trends of the SPI-3 and SPI-12 time series identified in each drought sub-region by the rotated principal components are analyzed using the non-parametric Mann-Kendall (MK) test at a significance level of 5% (Mann 1945; Kendall 1948).

Finally, the detection of monotonic that links between the atmospheric circulation indices and the principal component scores retained for SPI-3 and SPI-12 was carried out using the Pearson correlation test. The test was employed at three different significance levels: 1%, 5%, and 10% in order to categorize the varying degrees of influence that different atmospheric circulation patterns exert on drought variability.

3 Results and discussion

3.1 Spatiotemporal variability of drought

Based on the results of the North rule of thumb, Scree plot and the Bootstrap tests, four principal components were retained for Varimax Rotation considering the contribution of each principal component to explain the variability of meteorological drought across northern Algeria. Table 2 summarizes the explained variance of the un-rotated and the rotated components.

The spatial variability of the rotated principal component loadings over northern Algeria, RPC1, RPC2, RPC3 and RPC4 for SPI-3 and SPI-12, are shown in Fig. 2.

Table 2 Explained variance of the un-rotated and Varimax rotated factors of the SPI-3 and SPI-12

Factor	3 months (SPI-3)		12 months (SPI-12)	
	Un-rotated (%)	Rotated (%)	Un-rotated (%)	Rotated (%)
PC-1	46.39	23.17	41.64	24.25
PC-2	09.85	21.01	12.41	20.55
PC-3	04.69	12.35	05.37	10.96
PC-4	03.28	07.69	4.70	08.37
Cumulative	64.22	64.22	64.13	64.13

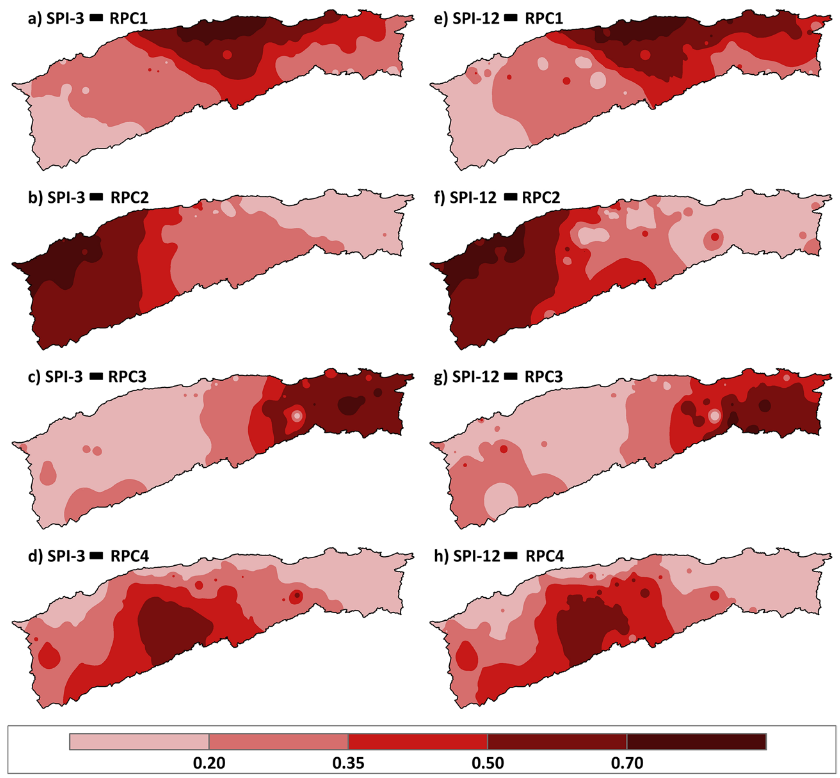

Fig. 2 Varimax rotated loadings relative to the SPI-3 and SPI-12- for the period 1948–2005

The spatial variability of the first component (RPC1) loadings' depicts the highest values in the central and the eastern coastal regions. The second component (RPC2) loadings show that the highest values occur over the western regions. The highest loadings of the third component (RPC3) occur over the eastern regions of northern Algeria. The fourth component (RPC4) concerns mainly the west-south central regions. These outcomes suggest that the study area is composed of four drought sub-regions, with different drought variability and characteristics.

Compared to the climate classification of northern Algeria according to the De Martonne aridity index (Derdous et al. 2020), the drought sub-region represented by the first component (RPC1) relatively coincides with the regions under Humid, Semi-humid and Mediterranean climatic conditions. The fourth component (RPC4) relatively relates to the arid regions of northern Algeria. The remaining two components (RPC2 and RPC3) are mainly found in semi-arid regions but each of them has different geographic and topographic conditions. Specifically, these two drought sub-regions show a contrasting topography, which is higher in the east than in the west, besides the eastern regions are in closer proximity to the Atlantic Ocean.

Figure 3 displays the temporal evolution of the four components scores obtained from the analysis. The results of MK test at a significance level of 5%, reveals the presence of a significant trend (P-value < 0.05) in the evolution of SPI-3 scores of the principal component (RPC1), which represents the central and eastern coastal regions. On the contrary, at the annual time scale (SPI-12), no significant negative trend was detected by the MK test (P-value > 0.05). Besides, the seasonal time scale (SPI-3) plot reveals the occurrence of significant drought events (seasons) during the 1960s. While, according to the annual time scale (SPI-12) plot, the most severe drought events (years) are observed in the decades of the 1990s and 2000s. This can be explained by the changes in rainfall seasonality over Africa (Dunning et al. 2018), related to the observed changes in rainfall amounts in the transition seasons or months at the beginning and the end of the wet season. More specifically, Merniz et al. (2019) revealed that the north-eastern Algerian coasts witnessed significant increasing rainfall trends during the months of July and September while significant decreasing trends during the months of February and March were registered, implying a seasonal delay with likely significant agro-ecological implications.

Regarding the second rotated component (RPC2), representing the western part, significant negative trends (P-value < 0.05) according to MK test were found at both seasonal and annual time scales. For SPI-3 and SPI-12, the most significant drought events were observed after 1980. This is in agreement with several previous studies conducted in northwestern Algeria, including Hamlaoui-Moulai et al. (2013); Hallouz et al. (2020); Achour et al. (2020b); Derdous et al. (2021b) among others. These studies identified a general decreasing trend of annual rainfall amounts in the

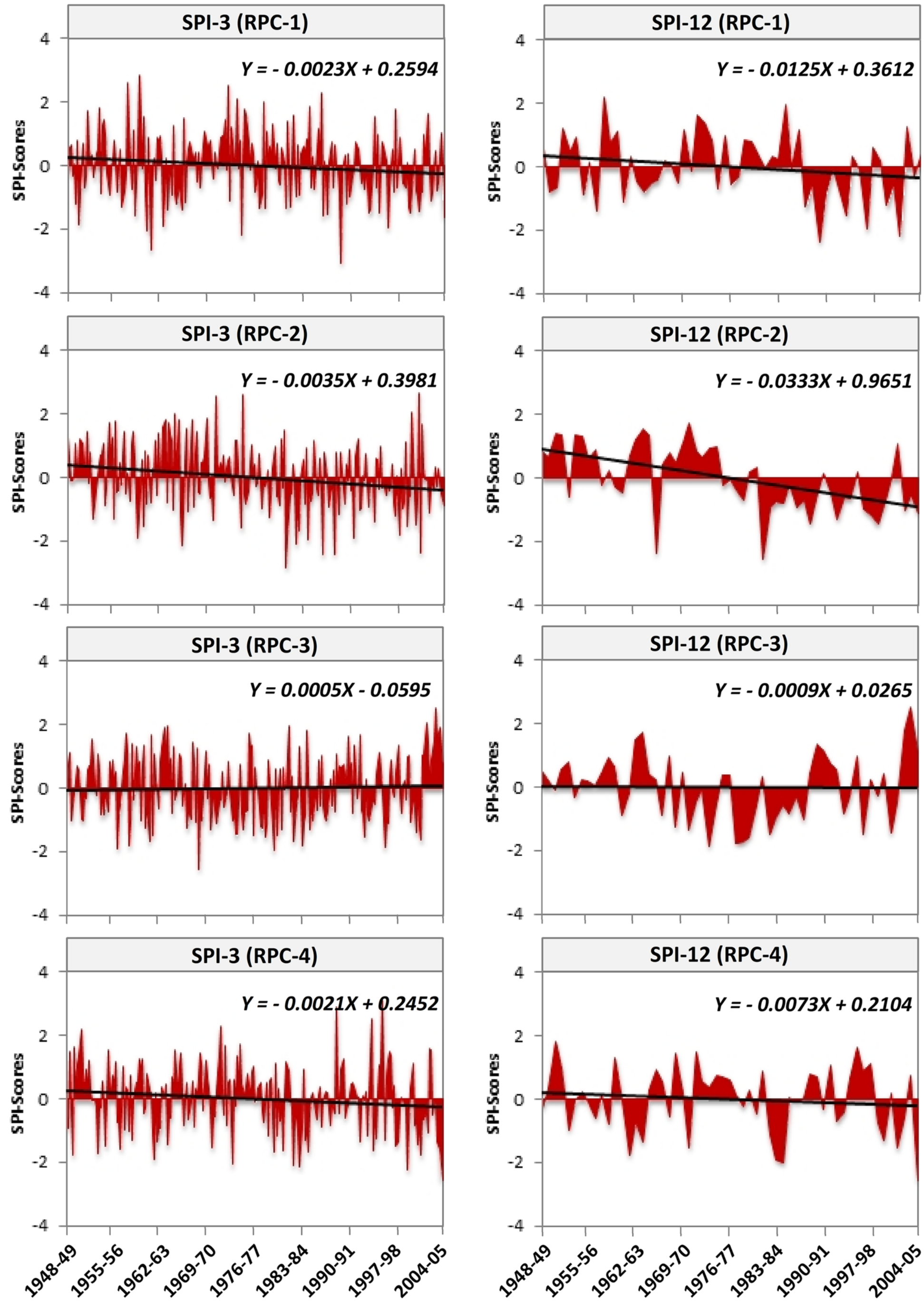

Fig. 3 Time variability of the rotated PC scores of the SPI-3 and SPI-12 for the period 1948–2005 (corresponding to the loadings presented in Fig. 2)

last decades accompanied by abrupt downward shifts of stationarity occurring in the middle of the 1980s.

The third rotated component (RPC3) plot, representing the eastern part of northern Algeria, reveals contrasting SPI trends between 1948 and 2005 with a negative SPI-12 trend and a positive SPI-3 trend. However, these trends were statistically not significant according to the MK test (P-value > 0.05). These results are in good agreement with those of Mrad et al. (2018) which revealed that there was no significant trend in the inter-annual rainfall evolution in northeastern Algeria between 1969 and 2012. The contrasting trends are probably related to the occurrence of significant drought events during the late 1950s and 1960s in SPI-3 time series and not in SPI-12 series. This can be related to the changes in rainfall seasonality, evidently this change was more obvious in RPC1 plots.

The last plot RPC4 that was related to the arid regions of northern Algeria revealed almost similar characteristics to RPC2, which represents to the eastern regions of the study area. However, in these regions the evolution of SPI-12 showed non-significant negative trend according to MK test (P-value >0.05), while SPI-3 gave significant negative trend (P-value < 0.05)

Despite the important differences in drought patterns among drought sub-regions, the general decrease in SPI values is the main feature that characterizes drought variability in northern Algeria during the (1948–2005) period. Negative trends in SPI are indicative of the increase in drought conditions (Vicente-Serrano and López-Moreno 2006). It should be noted that these findings are in good agreement with those of previous research, which identified negative trends in drought indices time series (Merabti et al. 2018a; Achour et al. 2020a; Zerouali et al. 2021b) and in rainfall amounts (Derdous et al. 2021a; Hamlaoui-Moulai et al. 2013) across northern Algeria. These findings hold significant implications since trends in drought conditions are valuable indicators for developing an early warning system to prepare for potential drought conditions. However, it is important to note that it may not be a sufficient material for water resource planning, as it has the potential to generate false alarms, which may lead to unnecessary resource allocation and costs (Rad et al. 2017).

3.2 Relationship between drought and the atmospheric circulation indices

The relationship between the atmospheric circulation indices and SPI-3 and SPI-12 time series was assessed by the Pearson correlation test. The spatial variability of the obtained Pearson correlation coefficients is illustrated in Fig. 4. Upon visual inspection, it is obvious that the study area's response to the different atmospheric patterns at both seasonal and annual time scales shows large spatial contrasts among the four drought sub-regions identified by RPC1, RPC2, RPC3, and RPC4. For a better assessment, the correlations between the scores of each principal component and the concurrent series of the considered atmospheric circulation indices were investigated. The results are illustrated in Table 3.

As depicted in Table 3, the most significant correlations between SPI time series and these indices were observed in the western regions of the study area (RPC2 and RPC4) particularly in winter and spring.

For instance in the RPC2 sub-region, several significant relationships were observed between spring drought variability and various indices; The SOI emerged as the main driver of SPI in spring, with a significant positive correlation at the 99% confidence level. Additionally, spring drought variability exhibited negative correlations with NAO, WI, and both MOI indices, although these correlations were statistically less robust as they were achieved at the 90% confidence level. Likewise, winter drought variability showed significant negative correlations with NAO and MOI1 at the 99% confidence level and negative relationships with WI and MOI2, achieved at the 95% confidence level. In the RPC4 sub-region, winter drought variability exhibited significant

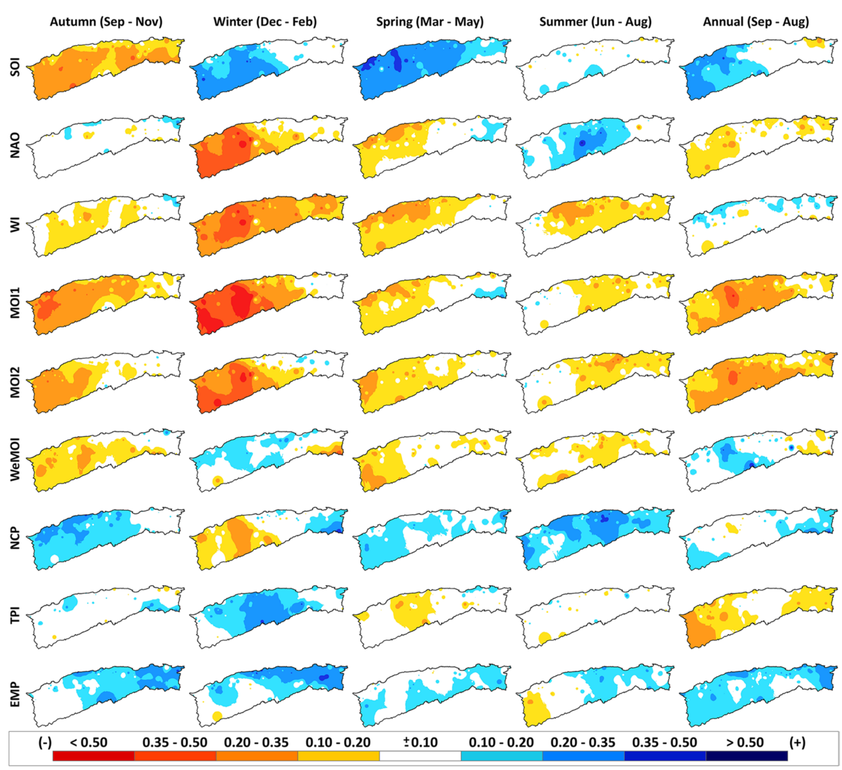

Fig. 4 Spatial distribution of Pearson's correlation coefficients between SPI and atmospheric circulation indices at seasonal and annual time scales

Table 3 Correlations between the SPI series of RPC1, RPC2, RPC3, and RPC4 and the atmospheric circulation indices at seasonal and annual time scales

Factors	Time scales	SOI	NAO	WI	MOI1	MOI2	WeMOI	NCP	TPI	EMP
RPC1	Autumn	0.11	0.06	0.21	0.07	0.13	0.14	0.11	−0.21	0.03
	Winter	0.01	0.07	−0.21	−0.05	0.10	0.16	0.08	0.18	0.32**
	Spring	0.20	−0.20	−0.24*	−0.22	−0.08	0.08	0.003	−0.09	−0.11
	Summer	−0.01	0.15	−0.20	−0.18	−0.19	−0.04	0.24*	−0.06	0.29**
	Annual	−0.07	−0.10	0.13	−0.20	−0.10	−0.02	−0.02	0.01	0.22*
RPC2	Autumn	0.14	0.15	−0.02	−0.07	−0.11	−0.05	0.35***	0.17	0.06
	Winter	0.19	−0.36***	−0.28**	−0.45***	−0.32**	0.10	−0.19	0.07	0.08
	Spring	0.36***	−0.25*	−0.24*	−0.23*	−0.25*	−0.21	0.09	−0.04	0.07
	Summer	0.04	−0.03	0.12	0.13	0.11	−0.10	0.08	−0.01	−0.18
	Annual	0.38***	−0.08	0.14	−0.12	−0.13	0.16	0.03	−0.29**	0.19
RPC3	Autumn	−0.06	0.19	0.14	0.14	0.26*	0.34**	−0.23*	−0.12	−0.08
	Winter	−0.07	−0.004	−0.09	0.15	0.11	−0.21	0.22*	−0.01	0.22*
	Spring	0.02	0.29**	0.16	0.23*	0.03	−0.17	0.11	0.17	0.20
	Summer	−0.04	−0.05	−0.07	−0.06	−0.14	−0.004	0.09	−0.01	0.06
	Annual	−0.09	−0.04	−0.04	0.03	−0.14	−0.19	0.25*	−0.15	0.04
RPC4	Autumn	0.02	0.02	0.04	0.03	0.11	0.19	0.01	−0.01	−0.05
	Winter	0.30**	−0.33**	−0.22*	−0.48***	−0.45***	0.05	−0.23*	0.26*	−0.24*
	Spring	0.07	0.04	−0.04	0.08	−0.01	0.03	0.13	−0.31**	0.16
	Summer	0.04	0.30**	−0.29**	−0.13	−0.09	−0.02	0.20	−0.02	−0.05
	Annual	0.01	−0.06	−0.25*	−0.36***	−0.33**	0.16	−0.07	0.08	−0.12

*Significant correlation at the 90% confidence level; **Significant correlation at the 95% confidence level; ***Significant correlation at the 99% confidence level

negative relationships with MOI1 and MOI2 at the 99% confidence level and with SOI and NAO achieved at the 95% confidence level.

At an annual time scale, the results reconfirmed the SOI as the main driver of drought variability in northeastern Algeria (mainly represented with RPC2) since a statistically significant positive correlation at the 99% confidence level was observed, consistent with the findings reported by several authors (Zeroual et al. 2017; Taibi et al. 2017; Meddi et al. 2010). In the RPC4 drought sub-region, the correlation results indicated that MOI1 was the main driver of annual drought variability, demonstrating a significant positive correlation at the 99% confidence level.

Several studies have reported that atmospheric circulation patterns associated with the westerly flow such as NAO and SOI have a significant influence on precipitation patterns in northwest Africa (Jemai et al. 2017; Zeroual et al. 2017; Hakam et al. 2022). Generally, when surface temperatures of the tropical South Pacific and the North Atlantic are above normal, the western Mediterranean experiences prolonged anticyclonic conditions that impede cloud development and lead to a decline in precipitation (Meddi et al. 2010).

Nevertheless, the contrasting topography of northern Algeria, which is higher in the east, may modify these influences spatially. In fact, the lack of significant correlations of drought variability in the eastern regions (represented with RPC1 and RPC3) and the majority of indices representing atmospheric patterns linked with the westerly flow is likely attributable to the sheltering effect exerted by the mountain chains situated within the central regions of northern Algeria. Previously, several authors have revealed that the atmospheric influence on precipitation in northern Algeria is highly affected by topography (Taibi et al. 2017; Zerouali et al. 2021b; Derdous et al. 2021b).

With that being noted, this study revealed that drought variability in northeastern Algeria seems to be more likely influenced by atmospheric patterns with predominantly North-South direction. In the RPC1 sub-region, significant positive correlations at the 95% confidence level were observed between EMP and SPI in winter and summer. The relationship between annual SPI and EMP also showed a positive relationship, although their correlation achieved statistical significance at the 90% confidence level. These outcomes explain to a large extent drought events that occurred during the 1960s (Fig. 3) as they were concomitant with the negative phase of EMP, which occurred between 1957 and 1964, and caused a decline in rainfall during winter and summer. The negative phase of EMP is characterized by an increased southwesterly anomaly flow toward the central Mediterranean and strong westerly winds prevailing over the middle Atlantic (Türkeş and Erlat 2018). Previously, Hatzaki et al. (2009) linked the negative phase of EMP with precipitation decrease over the eastern Mediterranean. In the RPC-3 sub-region, some positive relationships were observed between indices and SPI in different seasons, but the most significant were with NAO in spring and with WeMOI in autumn, at the 95% confidence level. At an annual time scale, only the NCP has succeed in explaining a part of the drought variability over the eastern regions demonstrating a significant positive correlation with SPI at the 90% confidence level.

These findings are of great importance for the establishment of drought mitigation strategies in a region that is increasingly vulnerable to drought. According to the latest IPCC report (Ali et al. 2022), the Mediterranean basin represents one of the most important "hot spots" in the context of global warming, with recent trends toward drier climatic conditions being associated to alterations in atmospheric circulation patterns. This underscores the urgent need to further investigate the mechanisms of the changing feature of droughts in northern Algeria. In this regard, the relationships between various atmospheric circulation indices and SPI time series identified in this study emerge as a reliable material for drought forecasting over northern Algeria.

4 Conclusion

This study intended to investigate the spatiotemporal variability of meteorological droughts over northern Algeria during the period (1948–2005) using the Standardized Precipitation Index (SPI) and to identify possible relationships between drought variability and different atmospheric circulation patterns. Spatial and temporal patterns of SPI at seasonal and annual time scales were identified using Principal Component Analysis (PCA) with Varimax Rotation.

The rotated PCA divided the study area into four drought sub-regions, each with different drought variability patterns; the first component (RPC1) represents the central and the eastern coastal regions, the second component (RPC2) is associated with the western part of northern Algeria, The third component (RPC3) represents the eastern part, and the last component (RPC4) was associated with the arid regions located in the central-west southern part of the study area.

The temporal drought variability in RPC1 and RPC3 sub-regions emphasized the occurrence of changes in rainfall seasonality in northeastern Algeria, which were more pronounced in the RPC1 sub-region. This study also revealed that these changes are mainly related to the EMP negative phase, as EMP exhibited significant influence on winter drought in RPC1 and RPC3 sub-regions and on summer drought in the RPC1 sub-region. At an annual time scale, drought variability showed significant correlation with EMP in the RPC1 sub-region and with NCP in the RPC3 sub-region. It is worth noting that through this study, drought variability in northeastern Algeria has been for the first time linked with two recognized atmospheric circulation patterns, which are EMP and NCP. In the western part represented by RPC2, various indices have shown significant correlations with drought variability particularly with SOI, NAO, MOI1, and NCP at a seasonal time scale and with SOI at an annual time scale. In the arid regions represented by RPC4, drought variability at a seasonal time scale significantly correlated with MOI1, MOI2, TPI, NAO, and WI. MOI1 explained most of the inter-annual drought variability in those regions.

Generally, this study successfully identified drought sub-regions over northern Algeria and the main atmospheric drivers of drought variability in each sub-region, which will contribute to improving drought forecasting and water resource planning. This is highly required for enhancing resilience against severe drought events, particularly in northwestern Algeria, which is experiencing significant increasing trends in drought conditions.

Author contribution All authors contributed to the study conception and design. Data collection and analysis were performed by HB and MH. All the figures were prepared by SET. The first draft of the manuscript was written by OD, and HA commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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