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Assessment of Drought Characteristics under Changing Climatic Conditions using SPI and SPEI Indices in Semi-Arid Environment of Southeastern Niger

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In the sahelian zone where 80% of the populations rely on rainfed-agricultural activities for their livelihood, drought episodes had significant socio-economics and ecological impacts. In recent decades, there has been an increase in the intensity, frequency and severity of drought occurrence mainly attributed to climate change. Thus, the main objectives of this study were: i) to understand drought multi-scale patterns and trend; ii) to assess drought duration, frequency and temporal extent over Mainé-soroa and Diffa located in the lake chad basin. To achieve these objectives standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI) at 1, 3, 6, 9, 12 and 24-month timescales were employed for the stations of Mainé-soroa and Diffa. Stations' monthly rainfall, air minimum and maximum temperature spanning 1950-2009

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and 1988-2017 respectively for Mainé-soroa and Diffa were used for the analysis. The Mann–kendall trend test was performed and revealed negative SPEI and SPI trends in the station of Mainé-soroa. Results indicate a significant negative SPI-12 and SPI-24 trend (p-value < 0.05), while no trend was detected in the rest of the time-scale series. The absolute value of declining trend was gradually increasing when SPEI was calculated with more lagged months. Meanwhile, at the Diffa station both SPEI and SPI showed positive trends. The pettitt's t-test on the SPEI series indicated particularly 1968 as the change point detected for three time scales including spei-9, SPEI-12, and SPEI-24. Drought frequency generally increased in Mainé-soroa over the period of 1950–2009. SPEI appear to be the most powerful tool of monitoring drought in semi-arid environment in the context of climate change. To build resilience to drought and cope with its effects in the area we stress the importance of the establishment of early risk identification and advices framework at local level such study should be extended to lake chad basin.

Keywords: Drought; climate change and variability; SPI; SPEI; Lake Chad.

1. INTRODUCTION

The African Sahel is a semi-arid strip of land that stretches from the Atlantic coast (Senegal and Mauritania) to the Red Sea coast of Sudan and Eritrea [1] and separating the Sahara in the north from the tropical savannas in the south [2]. It covers an area of about 3,053 103 km and has about 60 million inhabitants [3].

The Sahel zone is belong the most drought-prone areas in the world and has long experienced a series of historic droughts where the most prominent began at the end of the 1960s and ended in the mid-1980s [4]. Drought is considered as any reduction of average precipitation in the long-term period. Drought is an insidious scourge that results from a decrease of precipitation from the long-term average and levels considered as normal impacting severely human livelihood [5].

Wilhite and Glantz [6] distinguished four main types of droughts according to how the effects were noticed: (i) meteorological, due to the scarcity of rainfall; (ii) hydrological, detected by low streamflow; (iii) agricultural, when soil water is not sufficient to maintain a crop; and (iv) socioeconomic when it affects the normal functioning of society. In this study we dealt with the meteorological drought. These types of drought can be characterized in multiple ways [7,8] and differ according to their intensity, duration and spatial coverage [9,10,11].

Although a consensus on the causes of the Sahelian droughts has not been achieved [12,13], several studies reported that droughts in sahelian region are mainly caused by sea surface temperature changes [14,15], vegetation and land degradation [2], dust feedbacks [16,17] and human-induced climate change [18,19]. Furthermore, weather extreme events such as flood and drought are pronounced and exacerbated by human-induced climate change [20]. It has shown that drought and its severe consequences and extensive damages are likely to happen in the future especially in the western Sahel region that will experience the strongest drying, with a significant increase in the maximum length of dry spells [20].

In the Sahelian zone where 80% of the populations rely on agricultural activities for their livelihood, droughts have socio-economics and ecological impacts. In fact, over the past six decades drought episodes in this area have gradually become more prolonged and frequent causing low agricultural productivity [21], shortage of food and water resources placing the population at the mercy of food crisis [22,23,24], livestock decimation [23], substantial ecological losses and adverse socioeconomic impacts, hence affecting ecosystem services and rural livelihood. Drought, desertification and scarcity of natural resources have led to heightened conflicts between crop farmers and cattle herders, [25].

The region of Diffa is located in Lake Chad basin. The Lake Chad is experiencing a shrinking attributed to drought and climate change [26]. The climate change impacts are exacerbated by the growing concern on terrorism-related violence in the region. Combating climate change, desertification and effects of drought is vital to communities living in this area who are mostly depending on rainfed-agriculture for ensuring their food security.

To characterize droughts by determining their onset, extent, and end, and identifying their duration, severity and spatial variability [27, 28] several methodologies were developed, however, the one using drought indices is prevalent [29]. Indeed, in the past decades, scientists have developed several drought indices associated with specific time-scales for drought quantification, monitoring, and analysis [30, 31, 32, 33] (Du Pisani et al. 1998) [7,8]. These indices correspond to different types of drought, including meteorological, agricultural, and hydrological drought and their pros and cons have been extensively discussed [34, 30, 35, 36, 37]. To increase societal resilience to disasters, especially drought in the context of climate change observing long term rainfall and temperature data would be of great importance for managing drought, agroecosystems, thus developing long-term adaptation strategies. Thus the objective of this study is to assess the drought intensity by combining Standardized Precipitation Evapotranspiration index (SPEI) [10] and Standardized Precipitation index (SPI) [38] in Diffa and Mainé Soroa. Both indices are valuable tools for supporting decision-makers in mitigating drought impacts on various related-water sectors.

2. MATERIALS AND METHODS

2.1 Study Area

The study area is located in southeastern Niger and covers two urban communes of the region of Diffa including Maïné Soroa and Diffa (Fig. 1). It falls within the Sahelian ecological zone in South-Eastern Niger. The natural vegetation is dominated by shrubs and dense grasslands with scattered trees. The area is drained by the Komadugu Yobe which flow into the Lake Chad. It is characterized by a semi-arid climate, severe drought and high rainfall variability with a long dry season from 8 to 9 months (October-June) and a short rainy season 3 to 4 month (June to September) [39]. The mean annual rainfall is of 322.2 mm and 313.8 respectively for Mainé Soroa and Diffa. The average maximum temperature spanning 1950-2009 is of 36.67 ° C in Maine Soroa and an annual average minimum temperature of 20.43 ° C. While in Diffa mean annual maximum and minimum temperatures are of 36.9 °C and 20.8 °C respectively over the period 1988-2017.

In Mainé Soroa, the average wind speed observed at 10 m from ground is of 2 m / s. It is higher in the dry season (between 2.4 and 4 m / s) than in the rainy season (between 1.5 and 3.6 m / s). In the dry season, the maximum relative humidity varies between 17% and 64%, while the minimum value varies between 6% and 24%. In the rainy season, the maximum relative humidity varies between 32% and 99%, while the minimum value varies between 15% and 64%.

Agriculture, livestock, fishing, crafts and trade are the main sources of income for the populations mostly composed of Kanuri, Fulani, Hausa, and Arabs. The impact of climatic hazards (recurrent droughts and flood) on agricultural production systems, which remain rudimentary, generates chronic food insecurity [25].

2.2 Climate Data Analysis

2.2.1 Climate data acquisition and processing

We collected climate data from the National Meteorological Direction of the Niger Republic for two stations Mainé Soroa and Diffa (Fig. 1). Stations' monthly rainfall, air minimum and maximum temperature spanning 1950-2009 and 1988-2017 respectively for Mainé Soroa and Diffa were used for the analysis. Climate indices were calculated based on these data. Monthly precipitation and temperature datasets were checked for homogeneity and trends.

2.2.2 Computation of climate indices

More than 100 drought indices were proposed in the literature, but in this study we choose Standardized Precipitation Evapotranspiration Index (SPEI) and Standardized Precipitation Index SPI to assess drought intensity in the study area.

The Standardized Precipitation Index, SPI was developed by McKee et al. [38], and recommended by the World Meteorological Organization. It is an index used to quantify the precipitation deficit and its impacts on the availability of various water supplies for any time scale. SPI is widely used for drought monitoring by drought planners and monitors because it is less complicated and only rainfall data are needed for its computation. For McKee et al. [38], SPI defines the intensity of drought episodes according to the value of the index provided in Table 1. They also defined the criteria for a drought event for any time scale. Drought occurs when the index continuously shows a negative value of -1.0 or less and ends when the index becomes positive. Furthermore, to classify the intensity of drought event, the magnitude of negative SPI values was used such that the larger the negative SPI values are, the more serious the event would be. For example, negative SPI values greater than 2 are often classified as extremely dry conditions. Merits and cons of this index have been deeply discussed [30]. For instance an advantage in using SPI is that only rainfall data are needed for its computation and SPI can also be compared across regions of different climatic zones.

SPI was computed based on the two parameter gamma distribution function which is then transformed into a normal distribution so that the mean SPI is zero [38,40].

The SPI is expressed mathematically following the formula provided by McKee et al., [38]:

Equation 1

$$SPI = \frac{(Pi - Pm)}{S}$$

Where Pi is the precipitation of the month or year i, Pm: the average rainfall of the series on the considered time scale; S: the standard deviation of the series on the considered time scale.

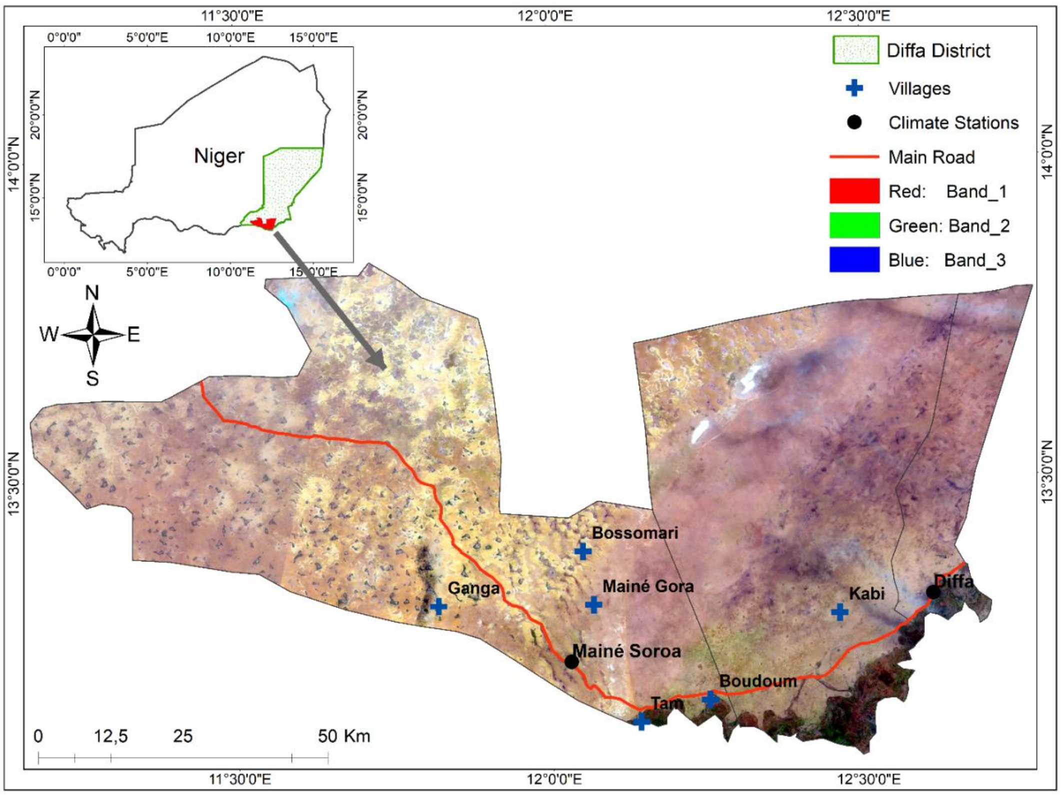

Fig. 1. Location map of the study area

Table 1. The seven categories of climatic conditions according to the Standardised Precipitation Index (SPI) and the Standardised Precipitation Evapotranspiration Index (SPEI) values

SPI and SPEI	Category	Cumulative Probability %
≥2.00	Extremely wet	2.3
1.50 to 1.99	Very wet	4.4
1.00 to 1.49	Moderately wet	9.2
-099 to 0.99	Near normal	68.2
-1.49 to -1.00	Moderately dry	9.2
-1.99 to -1.50	Severely dry	4.4
≤ -2.00	Extremely dry	2.3

SPI did not take into account the importance of other variables such as temperature and potential evapotranspiration (PET) that are considered as stationary and droughts are controlled by the temporal variability in precipitation. Since SPI could not identify the pattern of increase in the duration and magnitude of droughts resultant from higher temperatures, some authors have developed new drought indices in the last decade such as Standardized Precipitation Evapotranspiration Index (SPEI). SPEI was developed by Vicente-Serrano et al. [10] to overcome the shortcomings of SPI in addressing the consequences of climate change on drought behaviour. SPEI added a temperature component to capture a simplified water balance [10,41]. It was used for detecting and monitoring the e□ects of global warming on drought events [10]. It can detect the temporal variety of drought events more than SPI [42].

Since SPI and SPEI can be computed at di□erent time scales, we selected variable times scales 1, 3, 6, 9, 12 and 24 for estimating these indices that were defined for monthly data. Both SPI and SPEI were computed using SPEI package in R statistical software developed and provided by Begueria and Vicente-Serrano [10].

SPI was computed based on the two parameter gamma distribution function which is then transformed into a normal distribution so that the mean SPI is zero [38,40].

SPEI was computed by calculating the climatic water balance at different time scales that is the di□erence between monthly precipitation (P) and potential evapotranspiration (PET) data. With a value for PET, the difference between the precipitation (P) and PET for the month i is calculated:

Equation 2

$$D_i = P_i - PET_i$$

Monthly PET was computed following the method of Hargreaves [43]. According to this method PET is calculated by using data on minimum and maximum air temperature and extra-terrestrial radiation.

The probability distribution function of *D* according to the Log-logistic distribution is then given by:

Equation 3 $$F(x) = \left[1 + \left(\frac{\alpha}{x-y}\right)^{\beta}\right]^{-1}$$

With F(x) the SPEI can easily be obtained as the standardized values of F(x). For example, following the classical approximation of Abramowitz and Stegun (1965):

$$\text{SPEI} = W - \frac{C_0+C_1W+C_2W^2}{1+d_1W+d_2W^2+d_3W^3}$$

Where

Equation 4 $$W = \sqrt{-2\ln(P)}$$

For P ≤ 0.5, P being the probability of exceeding a determined D value, P=1-F(x). If P>0.5, P is replaced by 1−P and the sign of the resultant SPEI is reversed. The constants are: C0=2.515517, C1=0.802853, C2=0.010328, d1=1.432788, d2=0.189269, d3=0.001308.

The average value of the SPEI is 0, and the standard deviation is 1. The SPEI is a standardized variable, and it can therefore be compared with other SPEI values over time and space.

In order to understand long-term data trends, the Mann-Kendall statistical test was used. The magnitude of the trends was detected by calculating the slope of the line. The t point of change in the SPEI data was detected by the Pettitt t test (Kundzewicz and Robson, 2000).

Drought characteristics including drought event duration and frequency were determined using SPEI and SPI data at 6 and 12-month time-scales.

In this study we determined the duration of the drought event at each station for each year. Drought event is defined as a period in which the SPI or SPEI is continuously negative and when their value reaches ≤ −1 [38]. The duration is expressed in number of months in drought conditions. The duration (m) of a drought event equals the number of months between its start (included) and end month (not included) [44].

Drought frequency (Fs) which is defined as the number of drought events occurred was calculated. It is used to assess the drought liability [45]. The formula is provided as fallow:

Equation 5 $$F_s = \frac{n_s}{N_S} X\ 100$$

where *ns* is number of drought events, *Ns* is total number of years for the study period, and *s* is a station.

3. RESULTS AND DISCUSSION

3.1 Drought Multi-Scale Patterns and Trend

To identify drought sequences in the study area, the SPI and the SPEI were analyzed for the stations of Mainé Soroa and Diffa. The Mann–Kendall trend test was performed. During years 1950–2009, drying climate tendencies are observed in both the SPI and SPEI series at interannual scales (Fig. 2) at the station of Mainé-Soroa. Furthermore, our results show a significant negative SPEI-9, 12 and 24 trend (P-value < 0.05) (Fig. 2 and Table 2). While no significant trend was detected in the rest of the time-scale series. Meanwhile, at the Diffa station both SPEI and SPI showed positive trends but, all these positive trends are not significant. The findings show that abrupt changes were detected in the SPEI and SPI data series at different times-scale as indicated by table 2. The results showed that the droughts were frequently occurred after 2005 (Fig. 2). Results indicate that the most severe drought was recorded in the year of 1985 with SPEI value reaching −1.5 (Fig. 2). This severe drought has already been reported by several studies in West Africa (Sighomnou, 2004; Goula et al., 2005; Soro et al., 2014), and particularly in Sahel [46,47, 48].

Before 1970, Mainé-Soroa was mainly characterized by moderate to severe humidity conditions (eg. July 1953 with 2, 29 on the 12-month time scale, Fig. 3). However, droughts have really started since 1970 and are mild to moderate, although cases of severe to extreme droughts appear in certain months on different time scales. Results show that trends in the SPEI series are generally consistent with those in the SPI series.

The findings show that abrupt changes were detected in the SPEI and SPI data series at different times-scale as indicated by Table 2. The Pettitt's t-test on the series indicated particularly 1968 as the change point detected for three time scales including SPEI-9, SPEI-12, and SPEI-24. From these years of rupture values SPEI on different time scales have fallen sharply.

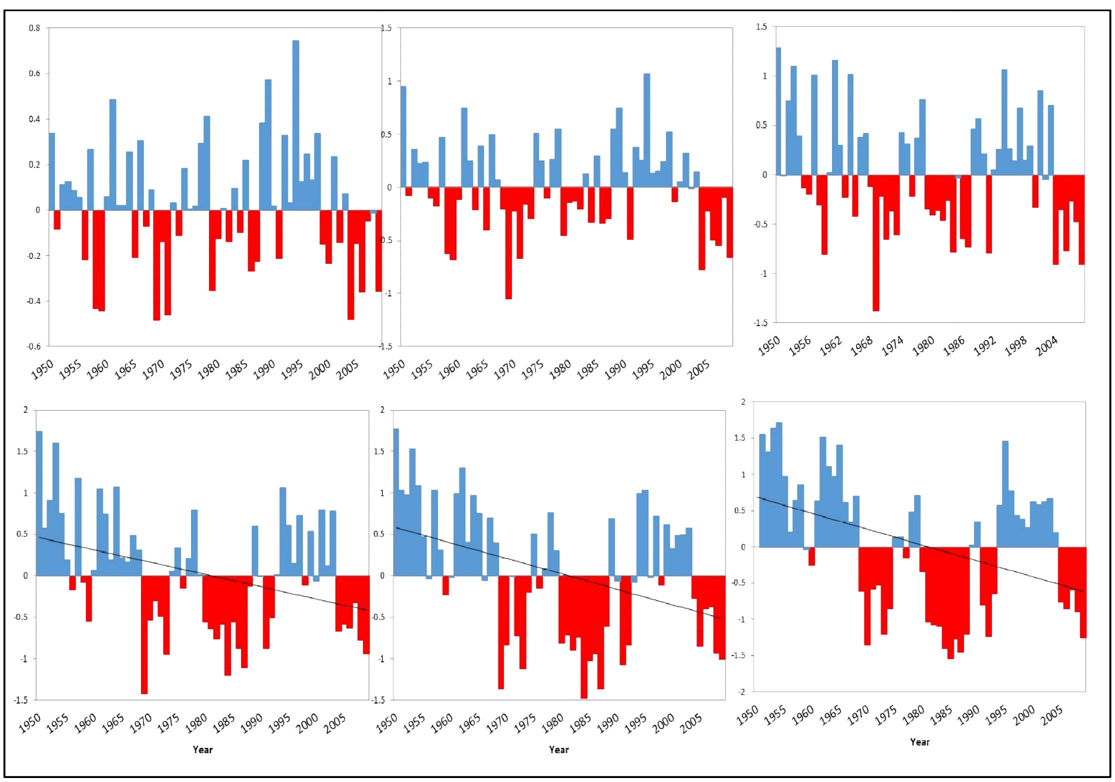

Fig. 2. Temporal evolution of SPEI values at time-scales 1, 3, 6, 9, 12 and 24 month from 1950 to 2009 in Mainé-Soroa

Table 2. Trend and change point of SPEI series on 1, 3, 6, 12 and 24 month time-scales from 1950 to 2009 on Mainé-Soroa (NT= No Trend; De= Decreasing)

	Mann Kendall test and Sen's slope				**Test t of Pettitt**			
SPEI-Time-scales	P-value	Tau	Sen's slope	Trend	P-value	Change year	Mean before change	Mean After change
SPEI-1	0.38	-0.07	-0.002	NT	0.24	-	-	-
SPEI-3	0.39	-0.07	-0.003	NT	0.37	-	-	-
SPEI-6	0.17	-0.16	-0.09	NT	0.12	-	-	-
SPEI-9	0.004	-0.25	-0.01	De	0.001	1968	0.56	-0.21
SPEI-12	0.001	-0.28	-0.02	De	0.0004	1968	0.72	-0.27
SPEI-24	0.001	-0.28	-0.02	De	< 0.0001	1968	0.89	-0.34

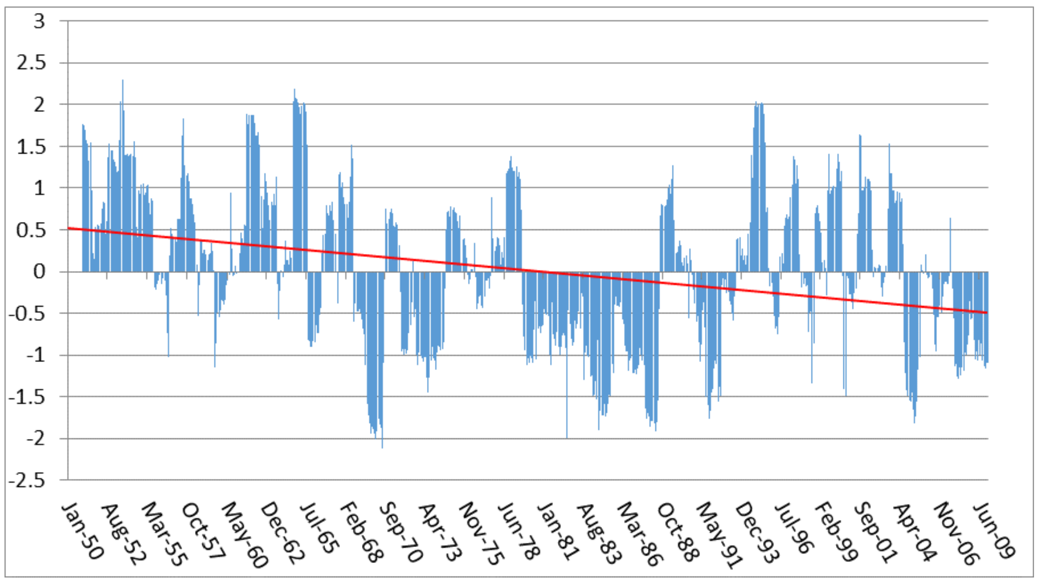

Fig. 3. Variation of the standardized precipitation evapotranspiration index over 12 months (SPEI-12) during the period studied (1950–2009) in Mainé-Soroa

3.2 Difference between SPEI and SPI

The difference in terms of temporal evolution of SPI with SPEI at 12- and 24-month lags were shown in Fig. 4. It indicated that the SPEI was gradually lower than SPI and the difference was increasing in recent decade. Especially in 2009, the difference even reached up to −0.6 for SPI-SPEI 12 and −0.7 for SPI and SPEI-24. This difference was likely related to the reported increase of temperature in the study area where warm spell duration, warm day-, and warm night frequencies exhibit statistically significant positive trends [39]. The mean temperature in the Sahelian region was observed to increase remarkably by 0.78°C between 1985 and 2015 [48]. It has been argued that the increase of temperature enhanced the PET in the region [49, 50] leading to higher water deficit and therefore lowered the value of SPEI (Xing et al., 2015). This fact is likely due to the global warming reported by IPCC [20]. Global warming would likely intensify the water cycle (Yeh and Wu, 2018), that impact the availability of water resources and increase the frequency and intensity of droughts (Huntington, 2006). Several studies showed a significant warming trend in the Lake Chad basin and Sahel [51, and 52].

3.2.1 Drought duration and temporal extent

Results revealed that during years 1950–1979, average drought duration identified by both SPI-6 and SPI-12 were 1.7 and 4.8 months respectively, while 3 and 4.7 months were recorded by SPEI-6 and SPEI-12 in this order (Table 2). However, the highest average drought duration was identified during years 1980–2009 by SPEI-12 with 5.2 months. Thus our findings indicated that average duration of the drought increases with increasing times-scale (Table 2). Furthermore, the maximum drought duration (12 months) was recorded during years 1980–2009 by SPI-12 (Table 2), suggesting that drought duration identified by the SPI is generally consistent with that by the SPEI. Meanwhile at the station of Diffa the maximum drought duration was 9 months and the highest average drought duration 5.2 months was identified by SPI-12 during the study period (1988-2017) (Fig. 5). It appears that the average drought duration vary from 5.2 to 2.3 months (Fig. 5). Similar study conducted by Bouly et al., (2020) in Senegal revealed that the number of dry months did not exceed 2 before 1968, but has increased considerably, especially in recent years when all the months of a year can be dry such the period spanning 2002 and 2014 as showed by SPEI_24. Their findings indicated that the average number of dry months reached 5.9 for SPEI_3 and 6 for SPEI_1 and the maximum number even went up to 9 months for SPEI_1, 10 months for SPEI_6, 11 months for SPEI_12 and 12 for SPEI_24. Furthermore, Burke et al., [53] findings indicated the worldwide expansion of the area subjected to extreme drought from 1% to 30% in the 21st century. While Blunden et al., [54] reported that the number of severe drought events and drought duration are likely to increase.

The maximum drought frequency calculated from the SPI and SPEI is up to 56% identified by SPEI-6 during 1980-2009 for the station of Mainé-Soroa (Table 2). Drought frequency calculated during years 1980–2009 compared to the period of 1950–1979 increased from 46.6% to 56.6% as revealed by SPEI-6. Drought frequency generally increased in Mainé-Soroa over the period of 1950–2009 (Table 2). In addition, during 1988-2017 period drought frequency at the station of Diffa is up to 46.6% identified by SPEI-6 (Fig. 6). This increasing drought frequency trend have been reported by several studies [44] (Bouly et al., 2020). Over the Mediterranean Region, the Sahel, and the Congo River basin, the increase of drought frequency and severity is due to both precipitation decrease

Table 3. Drought events duration and frequency from SPI/SPEI data at 6-month and 12 scales for different periods in the Station of Mainé-Soroa

	1950-1979				1980-2009			
Drought indicators	SPEI-6	SPEI-12	Spi-6	Spi-12	SPEI-6	SPEI-12	Spi-6	Spi-12
Maximum Drought duration	10	11	6	7	7	11	7	12
Minimum drought duration	1	1	1	1	1	1	1	1
Average drought duration	3	4.7	1.7	4.8	3.3	5.2	3	5.1
Drought frequency	46.6	16.6	16.6	13.3	56.6	53.3	40	46.6

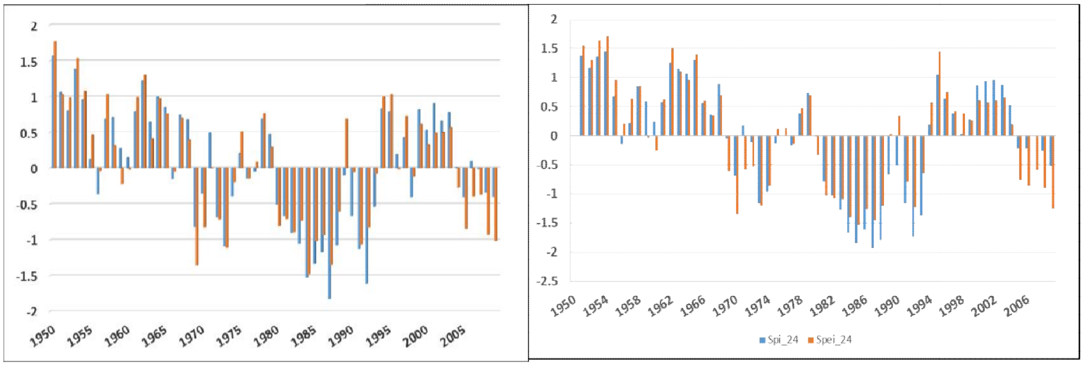

Fig. 4. Difference between SPEI and SPI at 12 and 24-month time-scales from 1950 to 2099 on Mainé-Soroa

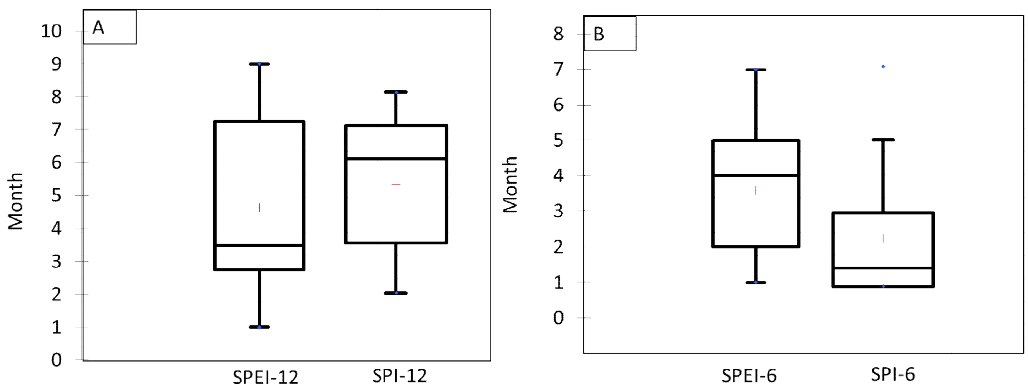

Fig. 5. Drought events duration from SPI/SPEI data at 6-month (A) and 12 scales (B) for different periods in the Station of Diffa

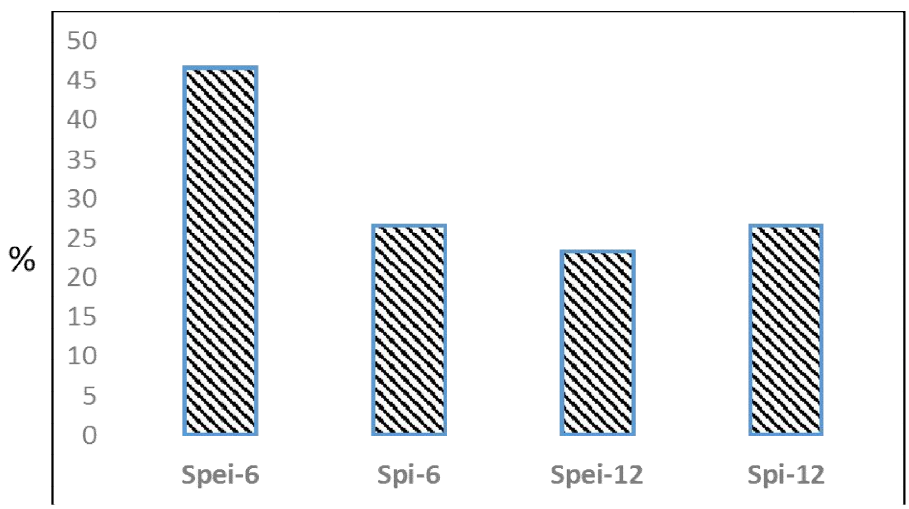

Fig. 6. Drought events frequency from SPI/SPEI data at 6-month and 12 scales for different periods in the Station of Diffa

and hotter climate conditions [44]. Sahel region experienced a drought of unprecedented severity that caused the most serious crop failure observed from 1960 to the 1980s [55,56].

4. CONCLUSION

This study investigates drought characteristics using the SPI and SPEI indices in Mainé-Soroa and Diffa. SPI and SPEI calculated by precipitation and temperature data were used to provide a comprehensive analysis of the drought characteristics in the study area. This research tracked the multi-scale patterns, the trend, the frequency and the duration of the drought. This study revealed explicitly a drying trend of Mainé-Soroa detected by SPEI series with different time scales. The findings indicated that the mean SPEI values at five time scales (1-, 3-, 6-, 9-, 12-, and 24-month) decreased from 1950 to 2009. The absolute value of declining trend was gradually increasing when SPEI was calculated with more lagged months. Studying of temporal evolution of averaged SPI and SPEI showed an increasing in drought frequency and duration. The Pettitt's t-test on the SPEI series indicated particularly 1968 as the change point detected for three time scales including SPEI-9, SPEI-12, and SPEI-24. Drought frequency generally increased in Mainé-Soroa over the period of 1950–2009.

The results demonstrated the SPEI advantage over SPI due to its capability in identifying and exploring the role of evapotranspiration and temperature variability in drought characteristics and thus the ability of SPEI in detecting drier conditions than the SPI. To build resilience to drought and cope with its effects in the area we stress the importance of the establishment of early risk identification and advices framework at local level.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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