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Use of the Standardized Precipitation and Evapotranspiration Index (SPEI) from 1950 to 2018 to determine drought trends in the Senegalese territory

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ABSTRACT
The management of water resources in our states has become increasingly difficult in recent times because of the frequency and intensity of droughts. In the context of climate change, extreme weather and climate events such as floods and drought, which are increasingly occurring, have a negative impact on the socio-economic development of the Senegalese territory. In this study, the Standardized Precipitation and Evapotranspiration Index (SPEI) was applied to characterize drought conditions in Senegal between

1950 and 2018. The SPEI was calculated from precipitation and temperature data for different periods of time. accumulation. Based on the SPEI, multi-scale models, trend and spatio-temporal extent of drought were evaluated, respectively. The results explicitly show a tendency to dry out Senegalese territory. The average SPEI values at five time scales all decreased significantly. Some moderate and severe droughts were recorded after 2005 and have even been aggravated. In examining the spatio-temporal extent, the aggravating condition of the drought has been revealed. To study the performance of SPEI, a correlation analysis was performed between the SPEI and the standardized precipitation index (SPI). The results showed that SPI and SPEI correlations were approximate and that SPEI could better monitor soil moisture than SPI in months with a significant increase in temperature.

Keywords: standardized index, SPEI, SPI, trend, drought

1. INTRODUCTION

In the context of global warming, extreme weather and climate events such as floods and drought seem to occur more frequently. Drought, usually defined as a water deficit over a defined period of time (Törnros and Menzel, 2014), is one of the most costly and widespread natural disasters with negative impacts on agriculture, resources natural ecosystems and the activities of society (Du et al., 2013, Sahoo et al., 2015). Droughts are often divided into four categories according to the American Meteorological Society (Council 2004, Benitez and Domecq 2014): (1) Meteorological drought is defined as a lack of rainfall over a region during a given period. (2) Agricultural drought refers to a period characterized by a lack of moisture in the soil, resulting in reduced plant production and plant growth. (3) Hydrological drought occurs when surface and groundwater resources are insufficient; (4) Socio-economic drought is associated with an insufficient supply of water resources to meet the economic demand associated with the three types of drought mentioned above. Meteorological drought is accompanied by below-normal and above normal precipitation. It precedes and normally triggers other types of drought (Potop et al., 2014). Therefore, it is necessary to monitor meteorological drought in a timely manner and to establish early warning and risk management of water resources and agricultural production (Zhang and Jia 2013 ; Xing et al., 2015)..

To solve time scale problems, McKee et al. (1993) demonstrated the multi-scalar nature of droughts and developed the Standardized Precipitation Index (SPI) using a probabilistic precipitation approach. The SPI is calculated by fitting a probability density function to a given frequency distribution of historical precipitation, then the probabilities are transformed into a normalized normalized distribution with a mean of zero and a variance of one. The main advantages of the SPI include simplicity of calculation and its multi-scalar feature. The latter means that it can be analyzed at different time scales (for example, 1, 3, 6 months or more) depending on the users' need to monitor different types of drought, including meteorological, agricultural and hydrological droughts (McKee et al. 1993; Zhang and Jia, 2013; Törnros and Menzel, 2014). Nevertheless, the main criticism of the SPI is that its calculation is based solely on precipitation data and without taking into account the effect of evapotranspiration (Törnros and Menzel, 2014). The standardized index of precipitation and evapotranspiration (SPEI), proposed by Vicente-Serrano et al. (2010), is considered an appropriate alternative to SPI. Mathematically, the SPEI is similar to the SPI, but it incorporates temperature data for the calculation of potential evapotranspiration. Therefore, it combines sensitivity to changes in evapotranspiration demand (caused by fluctuations and trends in air temperature) with the multi-temporal nature of SPI (Potopová et al., 2015).

In recent decades, Senegal has experienced a growing drought trend and large areas have experienced prolonged and severe droughts at different timescales (Faye *et al.*, 2015; Faye *et al.*, 2017; Faye, 2017; Faye, 2018). The situation continues to Deterior st despite the return to wet years over the 2000 period (Faye *et al.*, 2017). Nationwide droughts occur almost every year, resulting in crop losses and a shortage of water resources (Faye, 2017). Especially in northern Senegal, where monthly, annual and interannual variations in rainfall and temperature are important, drought has become one of the major natural disasters . Droughts of different duration and severity strike the Senegalese territory frequently and each year resulted in a significant reduction in the drinking water supply of the inhabitants and has a destructive effect on agricultural production, which has led to considerable ecological losses and harmful socio-economic impacts.

In Senegal, the effects of drought are also exacerbated by poor management of water resources and agriculture (Kala, 2017). The agricultural sector, which is heavily dependent on water sources, is severely affected by drought. However, the effects of drought are not limited to the agricultural sector, they also spread to other sectors. For example, the forest and environment sectors suffer from drought. The social sector is also affected in terms of changes in agricultural commodity prices, production structure, livestock production capacity, migration flows between rural and urban areas and other measures of well-being (Faye, 2017). Faced with the frequency of drought since the 1970s (Faye *et al.*, 2015 ; Faye *et al.*, 2017 ; Faye, 2017 ; Faye, 2018), its impact on the country's economy through its effects on agricultural production and natural resources (Faye, 2017) and the eventual increase of its impacts in the coming years, mitigation or adaptation measures are essential .

Below-normal rainfall is a trigger for these severe droughts, while rising temperatures can generally worsen droughts (Xing *et al.,* 2015). Particularly in recent years, many droughts have started with a deficit in rainfall and have been aggravated by high temperature (Yu *et al.,* 2015). Therefore, to monitor and quantify drought on Senegalese territory, the drought index must be integrated into the temperature information. In this study, our first objective is to provide a complete analysis of drought conditions in the entire Senegalese territory during the period 1950-2018 .Based on the series of SPEI for different time shifts, multi-scale models, the trend and the spatiotemporal extent of drought are successively analyzed. The second objective is to provide reliable information about the performance of SPEI. In this case, a correlation analysis between the SPEI and the SPI that does not take into account the temperature is performed.

Zone Study

The study area, Senegal, bordering the North Atlantic, is located in the extreme west of the African continent between longitudes 11°21 and 17°32 West and latitudes 12°8 and 16°41 North (Figure 1). It covers an area of 196,722 km2. Located in the tropical zone, Senegal has a Sudano-Sahelian climate with an annual rainfall varying between about 1250 mm in the South to just over 200 mm in the North (Faye et al., 2017). This climate is marked by an alternation between a rainy season and a dry season. The rainy season, which is the monsoon period, extends roughly from June to October with a peak in August-September. The rain varies degressively depending on the latitude. The dry season that lasts from November to June is marked by the presence of a hot and dry wind: the harmattan. The highest temperatures are observed during the summer of the hemisphere, during the rainy season, and the lowest in January. On the coast, the ocean brings freshness and temperatures are around 16 ° C to 30 ° C while in the center and east of the country they can reach 41 ° C average maximum.

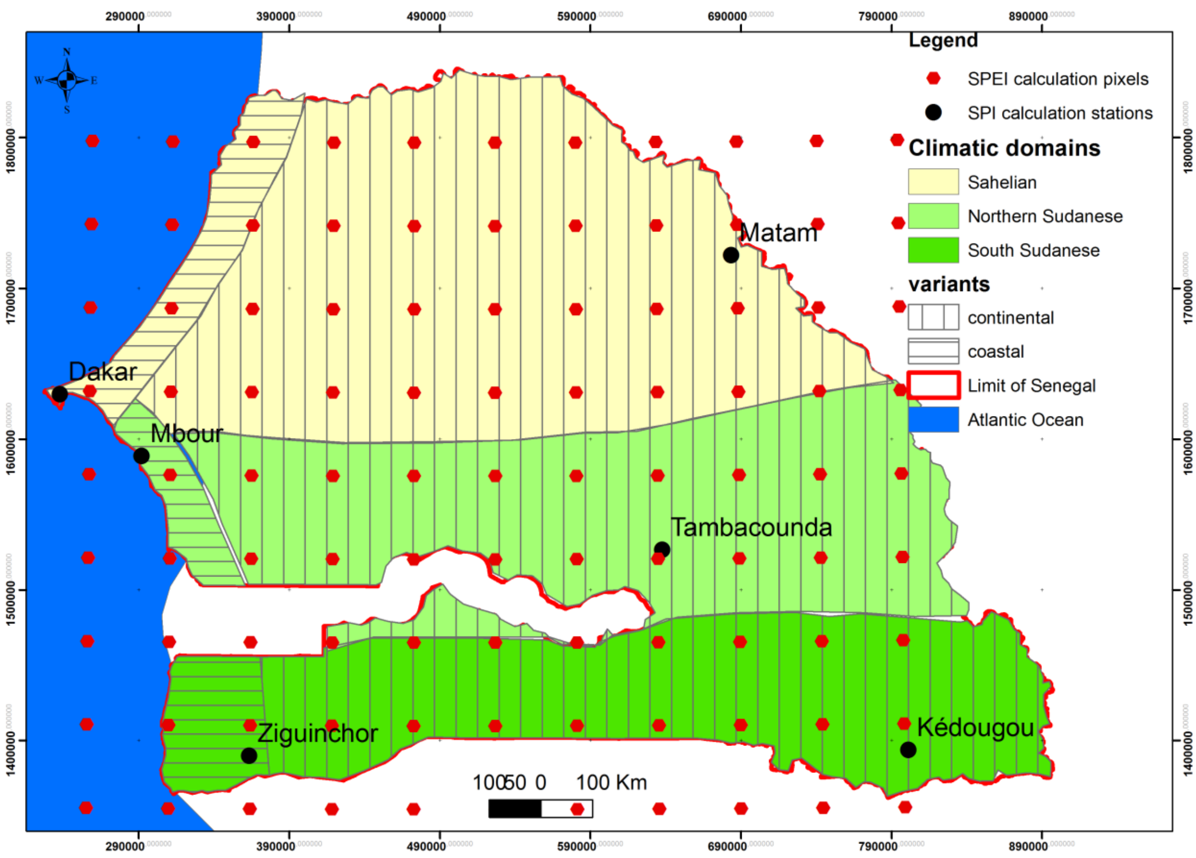

Figure 1

Location of Senegal, pixels and SPEI computing stations and by SPI of climate REAS

Senegal's major climatic characteristics are the combined result of geographical and aerological factors (Leroux 1983, Sagna 2005). The former are expressed by the latitude that gives the territory of tropical characters, and by the position of "West African Finistère" which determines different climatic conditions on the coast and inland. The second are expressed by alternating the country with three flows whose movements are facilitated by the flatness of the relief. Given the variations in rainfall in space and time, in Senegal, from south to north, there are three climatic domains, namely the southern Sudanian, northern Sudanian and Sahelian domains, each domain having two variants (a coastal and a a continental) (Figure 1).

In recent years, with a substantial reduction in rainfall and a constant rise in temperature, drought frequently occurs in Senegalese territory. It has been reported that these severe droughts have caused obvious changes in regional water and heat conditions, reducing the supply of drinking water to local inhabitants, disrupting the operation of the vegetation service and even leading to a reduction in biodiversity and vegetation degradation (Faye, 2017). Therefore, characterizing Senegal's moisture conditions is of great importance for risk management of water resources and agricultural production, and also has the advantage of providing early warning for the protection of the ecological environment.

2. DATA AND METHODS

Standardized Precipitation and Evapotranspiration Index (SPEI) Data

In this study, the SPEI was used to monitor and quantify drought in Senegalese territory, and an additional comparison was made with the SPI to test its performance. The data are taken from the World Drought Monitor SPEI: http://spei.csic.es/index.html. This monitor provides near real-time information on drought conditions worldwide, with a spatial resolution of 0.5 degrees and a monthly time resolution. SPEI time scales between 1 and 48 months are provided. The calibration period for the SPEI is from January 1950 to December 2010.

SPEI values are calculated with temperature and precipitation data. The average temperature data is obtained from the NOAA CPC NEC data set GHCN_CAMS gridded dataset. Data on monthly precipitation amounts are obtained from the Global Precipitation Climatology Center (GPCC). The data of the "first hypothesis" GPCC product, with an original resolution of 1°, are interpolated at a resolution of 0.5°.

Currently, the SPEI Global Drought Monitor is based on the Thortnthwaite equation for estimating potential evapotranspiration, ETP. This is due to the lack of real-time data sources to compute more robust FTE estimates that require larger data. The main benefit of SPEI Global Drought Monitor is therefore its near real-time nature, which is best suited to drought monitoring and early warning. The SPEI is considered an improved drought index, particularly suitable for analyzing the effect of global warming on drought conditions (Beguería et al., 2015). The calculation of the SPEI in this study follows the method mentioned in the study by Vicente-Serrano et al. (2010).

SPEI is based on a climatic water balance that is determined by the difference between precipitation (P) and potential evapotranspiration (FTE) for month i:

$$D_i = P_i - PET_i \qquad (1)$$

D_i provides a simple measure of the water surplus or deficit for the month analyzed. PET is calculated according to the Thornthwaite equation (Thornthwaite, 1948).

Calculated values D_i are aggregated at different time scales, following the same procedure as for the SPI. The difference, $D_{i,j}^k$ in a given month j and year i depends on the time scale chosen, k. For example, the difference accumulated during a month of a given year, with a time scale of 12 months, is calculating e using the formula :

$$X_{i,j}^k = \sum_{I=13-k+j}^{12} D_{i-I,j} + \sum_{I=1}^{j} D_{i,j}\,, \quad si\ j < k, et \qquad (2)$$

$$X_{i,j}^k = \sum_{I=j-k+j}^{j} D_{i,j}, \quad si\ j \geq k \qquad (3)$$

Where $D_{i,j}$ is the difference of P-PET of the 1st month of year i, in mm.

And then the log-log distribution is selected to standardize the D series to get the SPEI. The probability density function of the log-logistic distributed variable is expressed as follows:

$$f\ (x) = \frac{\beta}{\alpha}(\frac{x-\gamma}{\alpha})^{\beta-1}\left[1 + (\frac{x-\gamma}{\alpha})^{\beta}\right]^{-2} \quad (4)$$

Where α, β and γ are respectively the scale, shape and origin parameters for the D values in the range (γ> D <∞).

Thus, the probability distribution function of the D series is given by:

$$F\ (x) = \left[1 + (\frac{\alpha}{x-\gamma})^{\beta}\right]^{-1} \quad (5)$$

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

$$SPEI = W - \frac{C_0+C_1W+C_2W^2}{1+d_1W+d_2W^2+d_3W^3} = \quad (6)$$

Where $W = \sqrt{-2\ln(p)}$ for p ≤ 0.5 and p is the probability of exceeding a given value D, p = 1 - F (x). If p> 0.5, p is replaced by 1 - p and the sign of the resulting SPEI is reversed. The constants are: C0 = 2.515517, C1 = 0.802853, C2 = 0.010328, d1 = 1.432788, d2 = 0.189269 and d3 = 0.001308. Positive SPEI values indicate above-average moisture conditions, while negative values indicate drought conditions. A drought event is defined when the value of SPEI is less than or equal to -1 during a certain period.

The drought categories based on the SPEI values are presented in Table 1. The SPEI indices calculated from the monthly rainfall and temperature data for the period 1950-2018 are extracted from the SPEI World Drought Monitor.

Table 1 Categorization of the degree of drought / moisture based on standardized precipitation and evapotranspiration index

SPEI values	Sequences of drought	SPEI values	Wet sequences
SPEI <-2.00	Extremely dry	2.00 <ISP	Extremely wet
-1.50 <ISP <-1.99	Severely dry	1.50 <ISP <1.99	Severely wet
-1.00 <ISP <-1.49	Moderately dry	1.00 <ISP <1.49	Moderately moist
0.00 <ISP <-0.99	Slightly dry	0.00 <ISP <0.99	Slightly wet

SPI indices are calculated using rainfall data from Kedougou, Ziguinchor, Tamba, Mbour, Dakar and Matam, which are located in the Southern Sudanian, Sudan and Sahelian climatic domains (Figure 1). These data were made available by the National Agency for Climatology and Civil Aviation (ANACIM) Senegal. The SPI is mathematically expressed as follows (McKee *et al.* 1993) :

$$SPI = \frac{(P_i-P_m)}{S} \quad (7)$$

With P_i : the rain of the month or year i; P_m : the average rainfall of the series on the time scale considered; S: the standard map of the series on the time scale considered.

Methods: A new statistical approach to assess climate variability

At first, in order to detect a change in the SPEI database, the standardized variable statistical test was selected. Second, in order to understand long-term data trends, the Mann-Kendall statistical test was used. Third, the magnitude of the trends was detected by calculating the slope of the line. Fourth, the t-point of change of the SPEI data was detected by Student's t-test. The Mann-Kendall and Student tests were performed with TREND computer software (Kundzewicz and Robson, 2000). These basic visual programs available through www.toolkit.net.au are designed to facilitate statistical testing of the trend, change and randomness of hydrological data and time series. TREND has 12 statistical tests, based on the WMO / UNESCO Expert Workshop on Trend / Change Detection and the publication of the CRC for Catchment Hydrology publication Hydrological Recipes (Grayson et al., 1996).

The non-parametric Mann-Kendall test (Mann 1945, Kendall 1975) was applied to detect the drying or wetting tendency of the study area on the basis of the SPEI. To determine the magnitude of the change, the slope method of Sen (1968), available on the

Mann Kendall test on Xlstat, was applied. Student's test allows us to highlight a change point by checking if the averages of two different periods are different. The test assumes that data is normally distributed (Ross, 2015).

In addition, in order to provide reliable information on the performance of SPEI, Pearson's correlation analysis was performed between the monthly SPI / SPEI at a 1, 3, 6, 12 and 24 month accumulation period. The correlation coefficients were obtained during the rainy season (June to October) from 1950 to 2018.

3. RESULTS AND DISCUSSION

Multi-scale models of drought

According to the aforementioned methodology, the monthly SPEI was calculated from 1950 to 2018 at 5 time scales (1, 3, 6, 12 and 24 months) for the entire Senegalese territory subdivided into a hundred pixels distant by 0.5°. These SPEI series of these pixels have been averaged to characterize the dry or wet conditions in Senegal (Figures 2 and 3).

Figures 2 and 3 explicitly show an upward trend of drought sequences in Senegalese territory. SPEI series with different time scales all indicate a drying tendency in the country. According to the SPEI values, the humidity conditions were very contrasted before and after 2005. However, this desiccation is much more apparent at the time scales 12 and 24 months which show a dry character almost every month on each year, especially on the period 1990-2018. Before 1970, the study area was mainly characterized by mild to severe (and rarely extreme) moisture conditions as noted on the 1 and 3 month time scales: this was the case in October 1951 with 2.15 to time scale 1 month). However, droughts have really started since 1970 and are generally of a mild to moderate nature, although severe to extreme drought occurs in some months on different time scales. If droughts are moderate over the period from 1970 to 2000, they will worsen during the period 2010-2018.

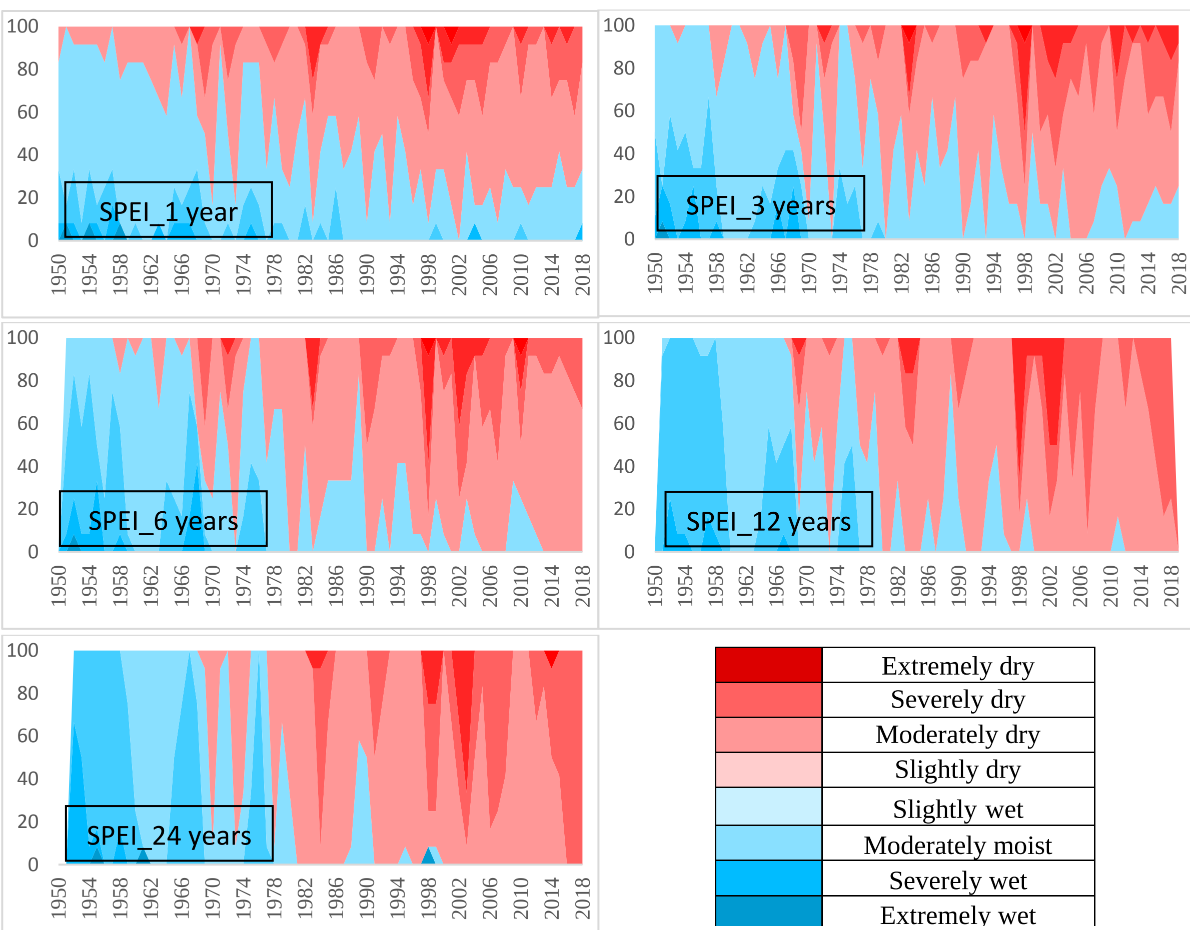

Figure 2

Evolution frequency of drought categories with SPEI from 1950 to 2018 on the territory of Senegal

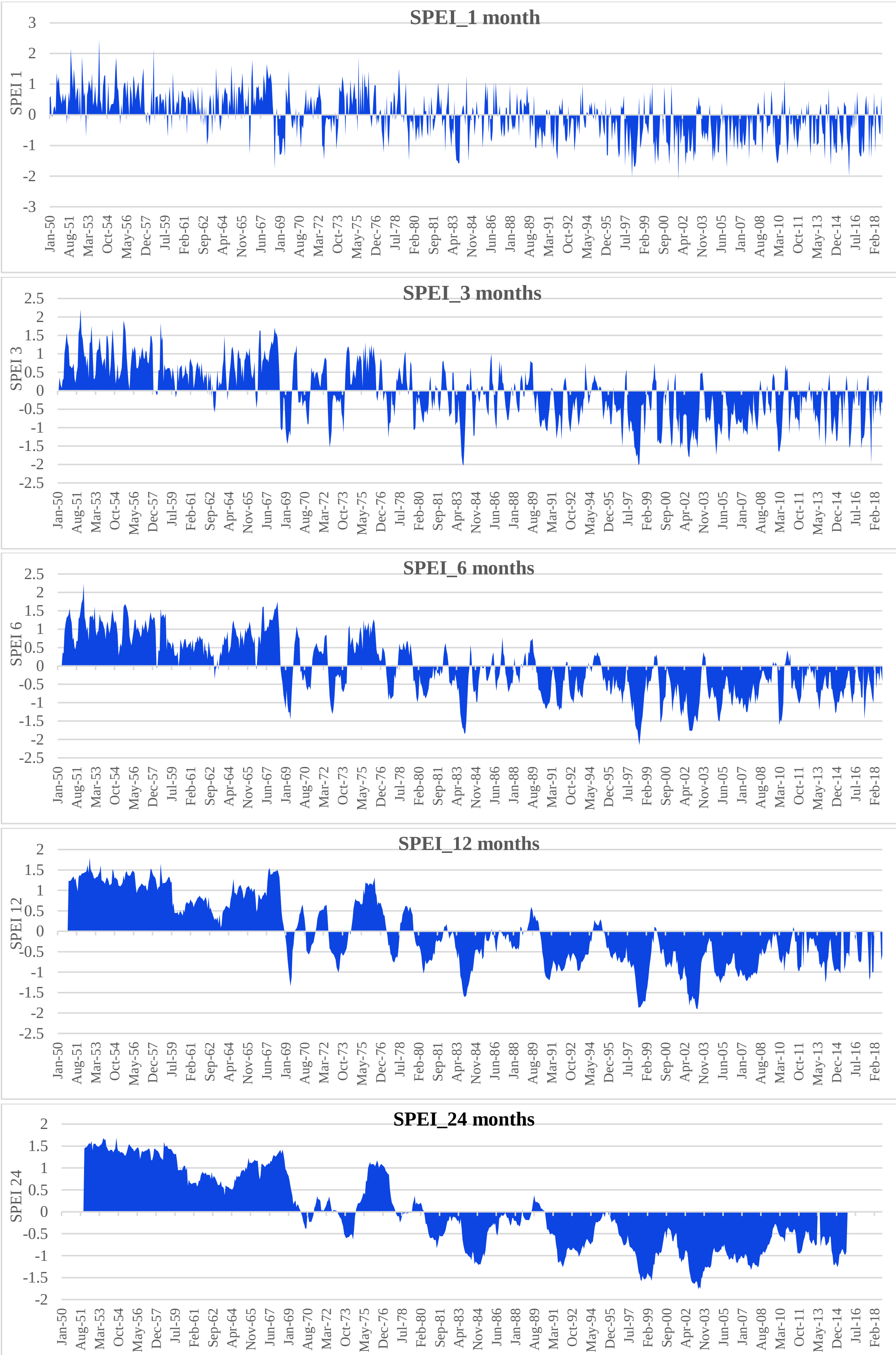

Figure 3 Temporal Evolution of SPEI values on time scales of 1, 3, 6, 12 and 24 months from 1950 to 2018 Senegalese territory

Figure 3 shows the temporal evolution of SPEI with shifts of 1, 3, 6, 12 and 24 months. The most severe drought was recorded between 2010 and 2018 with several monthly averages of SPEI approaching -1.5. Table 2, which shows the average values of SPEI with different time scales from 1950 to 2018 in Senegalese territory, makes it clear that if the periods 1950-1959, 1960-1969 and 1970-1979 are of a wet character, those between from 1980 to 2018 are rather dry. Although the period 1950-1959 remains the wettest on the various time scales, the period 2000-2009 remains the driest. Thus, the last period (2010-2018) although being dry is less than the previous one (2000-2009), which shows a decrease of the drought on the Senegalese territory before the increase of the rainfall noted during the period recent. This improvement in rainfall conditions is in concert with the work of some authors (Ali and Lebel, 2009; Ozer et al., 2009 and Ouoba, 2013) who suggest the end of the Sahelian drought during the 1990s.

Table 2 Average values of SPEI on time scales of 1, 3, 6, 12 and 24 months from 1950 to 2018 in the Senegalese territory

periods	SPEI 1	SPEI 3	SPEI 6	SPEI 12	SPEI 24
1950-1959	0.61	0.81	1.03	1.25	1.44
1960-1969	0.33	0.48	0.55	0.65	1.39
1970-1979	0.13	0.15	0.14	0.17	0.18
1980-1989	-0.13	-0.19	-0.27	-0.36	-0.41
1990-1999	-0.37	-0.47	-0.58	-0.66	-0.20
2000-2009	-0.54	-0.69	-0.78	-0.87	-0.98
2010-2018	-0.44	-0.61	-0.63	-0.76	-1.91

These results confirm the research done by many studies that have already reported this serious drought in West Africa (Servat et al., 1999 ; Sighomnou 2004 ; Goula et al., 2005 ; Soro et al.2014) in Senegal (Faye et al., 2015 ; Faye et al., 2017 ; Faye, 2017 ; Faye, 2018), indicating that the 1970s, 1980s and 1990s were dry periods marked by a high rainfall deficit.

The temporal evolution of the SPI at the time scale of 12 months was also calculated through the mean of the rainfall of the 6 rainfall stations located on the different climatic domains of Senegal. Its representation on the same graph with the SPEI_12 month (Figure 4) allows to see the similarities and temporal differences between the SPEI and the SPI difference.

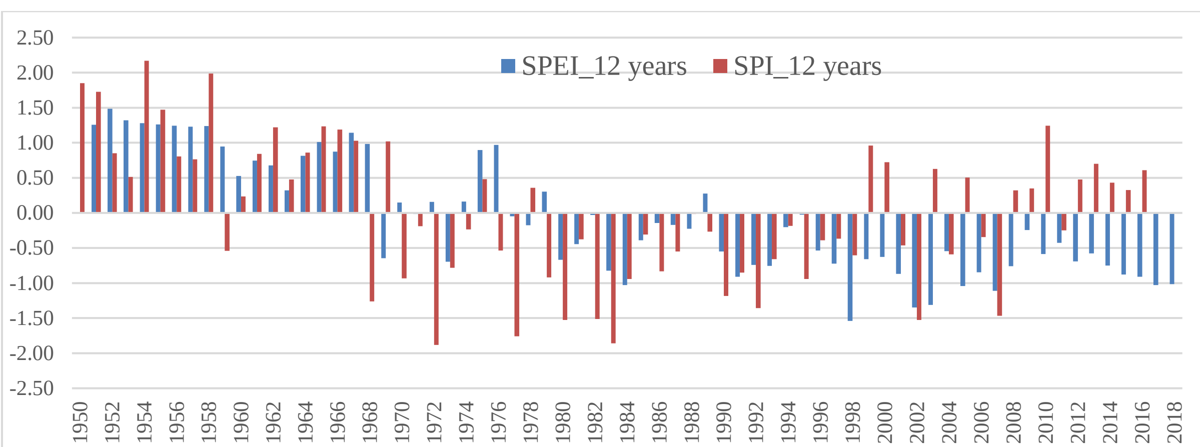

Figure 4 Difference between SPEI and SPI at the time scale 12 months from 1950 to 2018 in the Senegalese territory

The analysis in Figure 4 shows that the SPI was progressively lower than the SPEI and that the difference decreases until the mid-1990s, a period from which the SPI indices become positive and above the SPEI indices (in line with the rise of rain) until 2018. In the period 2000-2018, the statistical indices in Senegal detected important wet sequences even if the optimum of the 1960s is not yet reached (Faye et al. 2017 ; Faye 2017 ; Faye 2018). Therefore, during the 2000s, and particularly between 2010 and 2018, the difference between positive and negative PISIs was as high as 1.94 (in 2003). This is probably related to the reported temperature increase, with climate change (IPCC, 2013). This increase in temperature improved FTE, making the water deficit high and thus lowering the value of SPEI (Xing et al., 2015). This global warming would probably lead to the intensification of the hydrological cycle

(Yeh and Wu, 2018), leading to changes in the availability of water resources and the frequency and intensity of droughts and the amplification of global warming, the feedback of water vapor (Huntington, 2006).

Analysis of the significance and magnitude of series trends

To study the general trend of PIEs in the Senegalese territory, the Mann Kendal nonparametric test method, the Sen slope and the Student t test were applied to the different time scales from 1950 to 2018. The Monthly SPEI series were first averaged for each year at each SPEI time scale (1, 3, 6, 12 and 24 months). The results of the dewatering trend and failure tests are shown in Table 3. The mean values of the five-time SPEIs all decreased significantly between 1950 and 2018. Downward trends are statistically significant at a confidence level of 99.9% for the five time scales (SPEI_1, SPEI_3, SPEI_6, SPEI_12 and SPEI_24). The absolute value of the trend increases gradually when the SPEI is calculated with more lagged months (-0.6019 per year for 1 month, -0.6040 per year for 3 months, -0.6081 per year for 6 months, - 0.6462 per year for 12 months and -0.6716 per year for 24 months). It is evident that the memory of moisture conditions in previous months had accumulated until recent months (Xing et al., 2015). Thus, the drying conditions on the Senegalese territory are more remarkable if one envisaged longer delays. In terms of SPI (SPI_12 in particular), trends in drying were also detected. However, the downward trend is statistically significant only at a 95% confidence level. Thus, the SPEIs decreased more significantly than the SPI due to the increase in temperature, which is consistent with Figure 4.

Table 3

Trend and year of change of the SPEI (and SPI) series on time scales of 1, 3, 6, 12 and 24 months from 1950 to 2018 in Senegal

variables	Mann Kendall test and Sen slope					Student test t				
	Z_{MK}	p-value	Slope of Sen	Test result		t	p-value	Test result		Year of change
				α = 0.05	α = 0.1			α = 0.05	α = 0.1	
SPEI 1	-7.31	<0.0001	-0,0 189	drop	drop	+ infinity	<0.0001	breaking	breaking	1984
SPEI 3	-7.28	<0.0001	-0.0255	drop	drop	3.52	<0.0001	breaking	breaking	1985
SPEI 6	-7.32	<0.0001	-0.0295	drop	drop	4.04	<0.0001	breaking	breaking	1985
SPEI 12	-7.79	<0.0001	-0.0349	drop	drop	4.76	<0.0001	breaking	breaking	1985
SPEI 24	-8.03	<0.0001	-0.0414	drop	drop	3.34	<0.0001	breaking	breaking	1985
SPI 12	-1.84	0.03	-0.0349	drop	No	1.45	<0.0001	breaking	No	1984

For trend amplitudes (with the slope of Sen), they are relatively low (less than -0.1 everywhere) and negative, thus confirming the fall in the values of the SPEI, in margin with the drought. The statistical method of Student's t-test on the series generally showed 1985 as the breaking point for four time scales (SPEI_3, SPEI_6, SPEI_12 and SPEI_24). Only SPEI_1 and SPI_12 had a one-year break in 1984. From these break years, the values of SPEI on the different time scales fell sharply.

The temporal and spatial extent of drought

To better evaluate the interannual variability of drought, two experiments were conducted to obtain duration and severity. In addition, they were considered to represent the temporal and spatial extent of drought.

Time scale

In this study, the duration of drought events (defined as SPEI ≤ -1) was calculated for each year. The duration is expressed in number of months. Figure 6 shows the average number of dry months per year from 1950 to 2018. For each year, the different time scales of SPEI were taken into account.

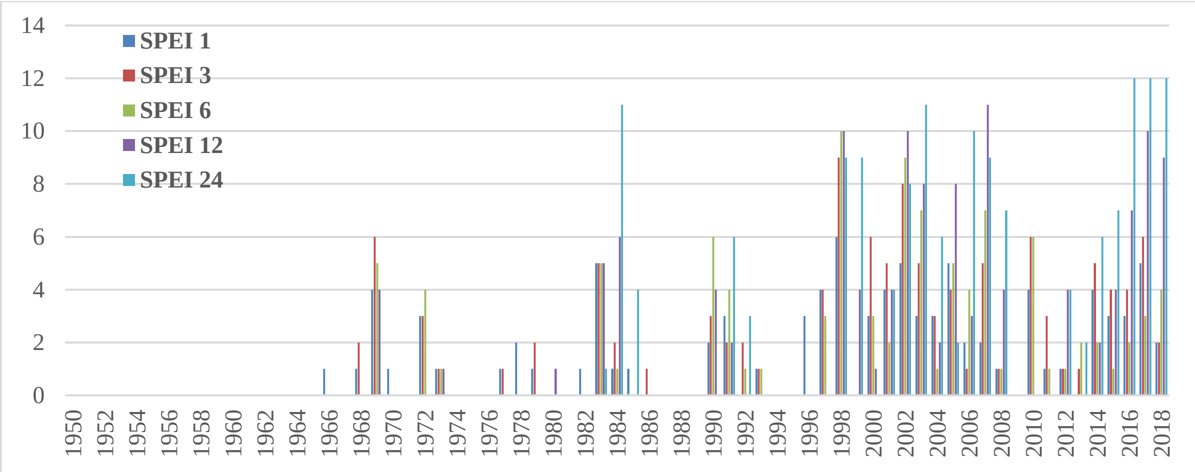

Figure 6

Average annual number of dry months (SPEI ≤ -1) on time scales of 1, 3, 6, 12 and 24 months from 1950 to 2018 in Senegal

An aggravating situation of drought has been explicitly realized. While the number of dry months (SPEI ≤ -1) generally did not exceed 2 before 1968, this number of dry months has increased considerably, especially in recent years where all the months of a year can be affected on certain scales of time (this is the case between 2016 and 2018 for the SPEI_24). The average number of dry months reached 1.8 for SPEI_12 and 2.25 for SPEI_24 and the maximum number even went up to 9 months for SPEI_3, 10 months for SPEI_6? 11 months for SPEI_12 and 12 for SPEI_24. The different time scales of SPEI can represent drought conditions in different aspects. SPEI with one month reflects meteorological drought. On 3- to 6-month time scales, agricultural drought is observed, while 6-12-month scales correspond to a hydrological drought index, useful for monitoring surface water resources (McKee et al. 1993; Potop et al., 2014). In the Senegalese territory, the meteorological (26.1%) and agricultural (27.54%)% drought was slightly more severe than the hydrological drought (23.19%) (Table 5). However, a quick transition has occurred. The lack of moisture in the hydrological aspect exceeded that of meteorological and agricultural aspects (Xing et al. 2015).

Table 5

Percentage of years with more than three dry months (SPEI ≤ -1) by sub-periods on time scales of 1, 3, 6, 12 and 24 months from 1950 to 2018 in Senegal

	SPEI 1	SPEI 3	SPEI 6	SPEI 12	SPEI 24
1950-1959	0	0	0	0	0
1960-1969	1.45	1.45	1.45	1.45	0
1970-1979	1.45	1.45	1.45	0	0
1980-1989	1.45	1.45	1.45	2.90	2.9
1990-1999	5.8	4.35	5.80	4.35	5.8
2000-2009	8.7	10.14	8.70	10.14	10.1
2010-2018	7.25	8.70	4.35	7.25	8.7
Total	26.1	27.54	23.19	26.09	27.5

The results in Table 5 shows that the percentage of years with more than three months of drought increases from 1950 to 2018. Between 2000-2009, the average number of years with more dry months for SPEI_12 and SPET_24 was 7 years everywhere, slightly higher than that of the SPEIs with shorter time scales (6 years for SPEI_1 and for SPEI_6). The previous water deficit had accumulated when calculating SPEI with longer time scales. The lack of moisture has caused meteorological and agricultural drought and has aggravated the hydrological drought. Before 1990, the average number of dry months was generally low on the various time scales of SPEI, the frequencies of years with more than three dry months (SPEI ≤ -1) being less than 1.5% per sub-period and even none on some (Table 5). On the other hand, between 1990 and 2018 (especially between 2010-2009), these frequencies increased sharply, reaching a value of 10.14% of the years for SPEI_3 and SPEI_12, exceeding SPEI frequencies with less time scales. long (7.25% for SPEI_1).

Spatial extension

To always assess the severity of drought, spatialization has been used to assess the spatial extent of drought. To characterize the spatial extent of drought, the average values of SPEI_12 months from the period 1950-2018 were spatialised on Senegalese territory and the results, extracted from the global monitor of the drought SPEI, are indicated in Table 6 and on Figure 7.

Table 6

Mean SPEI values on the 12-month time scale by sub-periods at different sites selected in Senegalese territory from 1950 to 2018

Points	Coordinates		Average values of SEPT 12 months by decade							
	Latitude	Longitude	1950-2018	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2018
1	12.75	-12.25	0.022	1.241	0.666	0.043	-0.351	-0.623	-0.824	0.012
2	12.75	-13.75	-0.077	0.930	0.774	0.270	-0.276	-0.620	-1.028	-0.662
3	12.75	-15.25	-0.021	1.171	0.455	0.529	-0.410	-0.615	-1.040	-0.369
4	12.75	-16.75	-0.071	1.164	0.468	0.291	-0.572	-0.493	-0.738	-0.705
5	14.25	-12.25	-0.218	1.235	0.843	0.202	-0.403	-0.618	-1.030	-1.974
6	14.25	-13.75	-0.138	1.335	0.696	0.111	-0.390	-0.729	-0.803	-1.295
7	14.25	-15.25	0.110	1.424	0.609	0.233	-0.301	-0.889	-0.829	0.612
8	14.75	-16.75	-0.035	0.506	-0.013	0.523	-0.060	-0.518	-0.357	-0.564
9	15.75	-13.25	-0.167	1.391	0.994	-0.031	-0.525	-0.840	-0.688	-1.541
10	15.75	-14.75	0.032	1.338	0.707	0.065	-0.152	-0.787	-1.008	0.196
11	15.75	-16.25	-0.180	1.515	0.062	0.169	-0.268	-0.556	-0.755	-1.917
12	16.25	-14.75	0.067	1.052	0.820	0.070	-0.371	-0.552	-0.852	0.479
13	16.25	-15.75	0.053	0.995	0.503	0.525	-0.289	-0.609	-0.866	0.272

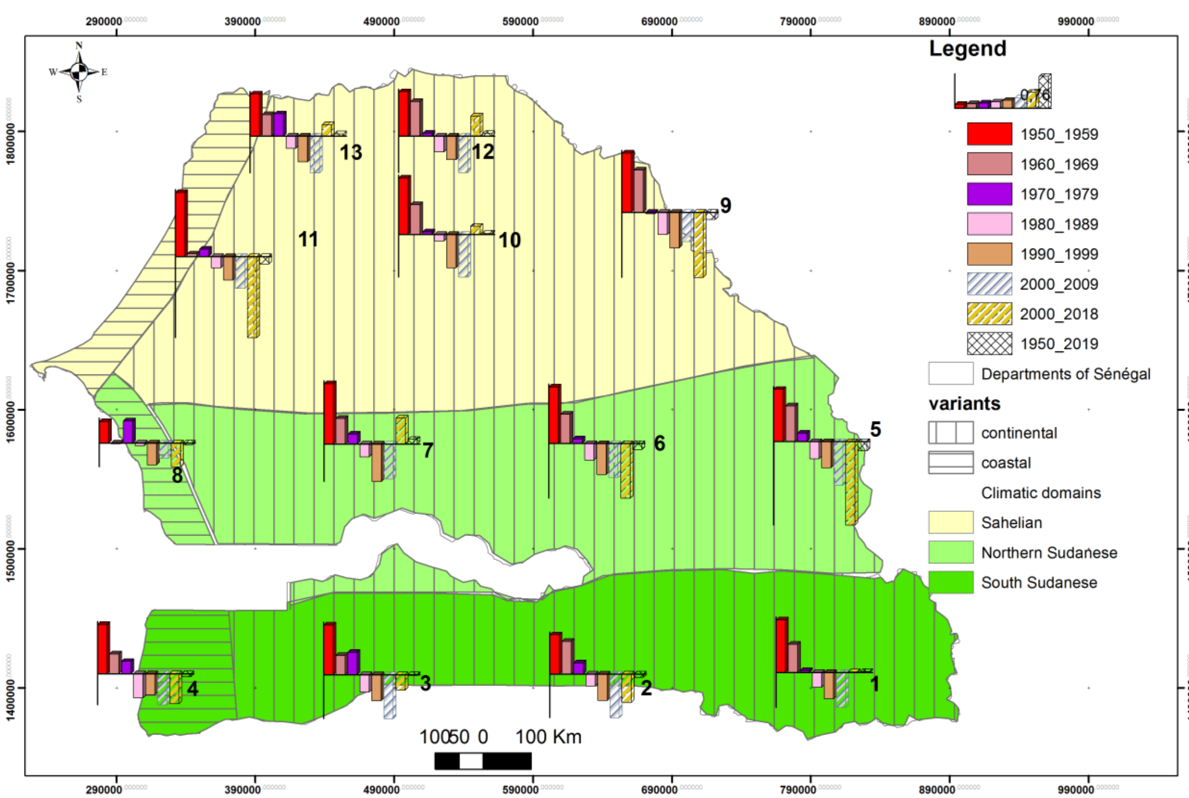

Figure 7

Spatial evolution of SPEI_12 values by periods in Senegalese territory

Their analysis shows the persistence of drought from 1980 to 2018, regardless of the geographical area indicated, compared to the period from 1950 to 1970. However, the most apparent drought is located on the eastern and northern part of the territory. , where the Senegalese part of the Senegal River Basin is generally located. In contrast, the southern part, from Ziguinchor to the center of the country, generally has less severe drought conditions. The results in Figure 7 are consistent with those in Table 5, which show that the largest droughts were recorded after 1990, and that between 1990 and 2018, about 21.8% of the years experienced the three-month meteorological drought, 23.2% agricultural drought and 18.9% hydrological drought.

SPEI's performance in monitoring soil moisture

The correlation analysis was performed annually between the SPEI and the SPI over the different sub-periods. The results provide relatively weak average correlations between SPEI and SPI in Senegalese territory (Table 7).

Table 7

Mean SPE correlations between the SPI and the SPEI at the 12-month time scale by sub-period from 1950 to 2018 in the Senegalese territory

Sub-periods	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2018	1950-2018
Coef of determination	0.21	0.01	0.05	0.21	0.0005	0.13	0.18	0.21

These low to medium values of the correlations between the SPEI and the SPI on the Senegalese territory thus show that the only use of the rain seems insufficient forever explains the different trend between the SPEI and the SPI, as noted the period 2000-2018 marked negative SPEIs, whereas SPIs are positive, hence the use of temperature.

To better characterize the performance of SPEI in soil moisture monitoring and explain the differences between SPEI and SPI over the recent period, the trend in temperature and its statistical significance for each month are shown in Table 8. Over the past three decades, Senegal's temperature has been rising statistically significantly every month to a 95% confidence level. This increase is greater in the months of December (0.5274 ° C per year), November (0.4389 ° C per year), April (0.4274 ° C per year), July (0.3902 ° C per year) and October (0.3504 ° C per year). At the annual scale (Figure 8), the same statistically significant upward trend (and even at 99.9% confidence level) is noted on the maximum temperature (0.5379 ° C per year), minimum (0.4975 ° C per year) and average (0.3133 ° C per year). The significant increase in temperature during each year has worsened the drying conditions of the study area over the recent period as indicated by the SPEI. For this reason, the SPEI, integrating temperature into the calculation of potential evapotranspiration, could be more representative of dry and wet conditions.

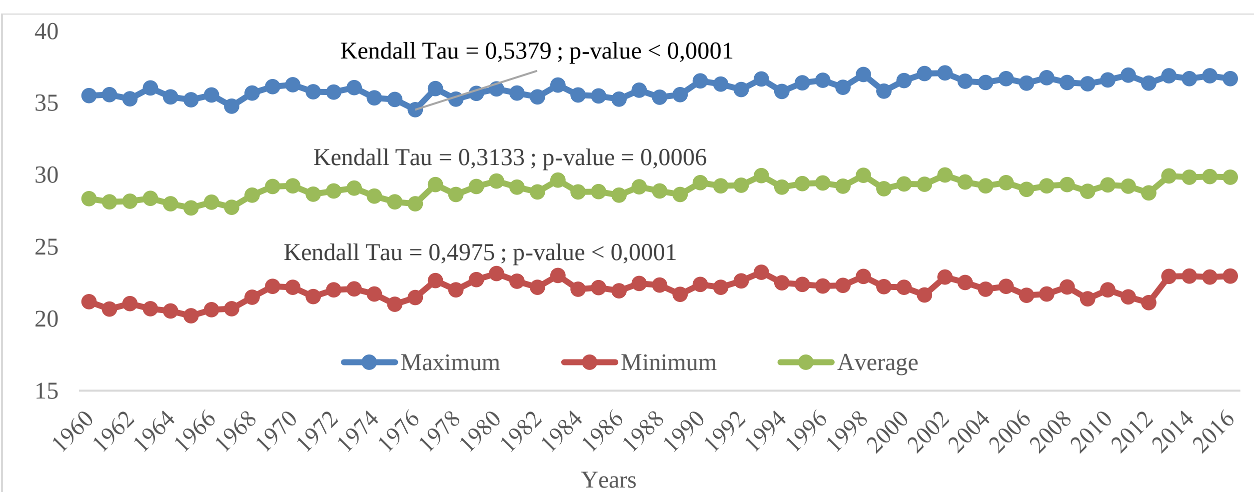

Figure 8

Evolution of the maximum, minimum and average annual temperature from 1960 to 2018 in Senegalese territory.

Table 8

Trend and statistical significance of the monthly temperature from 1960 to 2018 in Senegalese territory

Month	Jan.	Fé v.	March	April	May	June
Kendall Tau	.2760	.2040	.3090	.4274	0.2285	.2214
p -value	0.0025	0.0257	0.0007	<0.0001	0.0124	0.0154
Month	July	August	Seven.	Oc t.	N ov.	De c.
Tau from Kendall	.3902	.3069	.2469	.3504	.4389	.5274
p -value	<0.0001	0.0008	0.0070	0.0001	<0.0001	<0.0001

4. CONCLUSION

The fact that the increase in temperature contributes to some serious droughts in recent years is recognized. In this study, a drought index, the SPEI, calculated with both precipitation and temperature, was used to provide a comprehensive analysis of the characteristics of drought in Senegalese territory. Multi-scale models, trend and spatio-temporal extent of drought were evaluated, respectively. In addition, a correlation analysis between SPEI and SPI was conducted to study the performance of SPEI. The main conclusions are summarized as follows:

(1) A drying tendency in Senegal has been explicitly detected by SPEI series at different time scales. Some moderate and severe droughts were recorded after 1990 and were even aggravated during the period 2010-2018.

(2) The Mann Kendall test results indicated that the average SPEI values at five time scales (1, 3, 6, 12 and 24 months) all decreased significantly between 1950 and 2018. The absolute value of the downward trend gradually increased when the SPEI was calculated with more months behind schedule.

(3) The aggravating condition of the drought was realized by examining the spatio-temporal extent. The number of dry months increased significantly and the percentage of the year having recorded more than three dry months also increased to a large extent.

(4) The analysis of the correlations between the SPEI and the SPI at the 12-month time scale showed that the correlation was overall medium to low and the highest was obtained for the sub-periods 1950-1959, 1980- 1989 and 1950-2018 with a value of 0.21. In this case, the SPEI tended to perform better than the SPI, given the significant increase in temperature over the months.

The performance of SPEI in the monitoring of drought in Senegalese territory has been well demonstrated. Because the sensitivity of vegetation growth to precipitation naturally increases in some semi-arid and arid regions of Senegal, with the increase in temperature, the SPEI index should be further improved to better characterize the drought of these regions in future work.

In this study, we used SPEI to monitor drought because it is an improved index that considers both precipitation and temperature, and its multi-temporal feature allowed for analysis at different scales, the different types of drought. Other widely used in situ drought indices, such as the Palmer Drought Index (PDSI) and its improved variants, are not currently considered. In our subsequent research, comprehensive analyzes of performance between different indices of in situ drought should be performed.

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