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Research Article

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Assessments of Climate Indices on the Characterization of Extreme Rainfall in Senegal

Mamadou Sarr[1], El Hadji Deme[1, 2], Adoum Mahamat Moussa[1, 3], Bouya Diop[1*] and Abdoulaye Sy[1]

[1]*LSAOMED, Université Gaston Berger de Saint-Louis, Senegal*

[2]*LERSTAD, Université Gaston Berger de Saint-Louis, Senegal*

[3]*ENASTIC, Ecole Nationale Supérieur des TIC, N'Djamena, Tchad*

[*]Corresponding Author
Bouya Diop, LSAOMED, Université Gaston Berger de in recent years, Senegal.

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Abstract
In recent years, Senegal has experienced a considerable increase in extreme events. The context of climate change, we conducted this study to characterize the extreme rainfall events in Senegal through nine (9) indices of extreme precipitation calculated, using R software (Rclimdex) for the period 1950 to 2010 on several stations. These analyses show that the annual precipitation totals describe a decreasing trend. However, a return of these accumulations have been noted in 1999 in almost all stations of rainfall in Senegal. The extreme rainfall indices show also a linear decreasing trend over the period 1950 to 2010, with the exception of consecutive dry days (CDD). However, non-linear trend analysis (Loess curve) shows increasing trends in rainfall indices over the last decades (from 1991), except for consecutive dry days (CDD) and extremely wet days (R99p) which show a decreasing trend over the last decade.

Keywords: Climate Change, Extreme Rainfalls, Trend, Senegal

1. Introduction

In a world where people are increasingly exposed to natural hazards and high climate variability, weather risk assessment is becoming a major social issue. Numerous climate projections have shown that West Africa will experience a significant increasing temperature associated with high variability of rainfall [1, 2]. These changes could lead to an increasing extreme weather events such as droughts, heat waves and extreme rainfall events, with disastrous impacts 1 2 Sarr et al. on socio-economical development and environment [3]. Indeed, agriculture, which is a very important source of income in West Africa, is likely to be compromised by these climate changes and their variabilities [4]. In Senegal, most foods come from to small, traditional productors that are mainly rain-fed. This country has been hit by an unprecedented drought in years around 1970 and 1980.

Some studies have been established to analyse the behaviour of extreme rainfalls in Senegal, for example analysed the extreme rainfalls in West Africa over the period 1950-1990 [5]. introduced a different method to the one of the previous author and give a comparative assessment study for drought meteorological sequences using the SPI indices. Recently, adopt the approach proposed by to analyse trends and return levels of extreme rainfalls in Senegal over the period 1951-2005 [5-7]. However, this present work focuses more on extreme dry than extreme wet, while extreme rainfalls heavy rainfall become more frequent as a result of climate change [8]. This leads us to use the extreme rainfall indices recommended by the World Meteorological Organization (WMO), which allow to take into account the extreme dry or wet. The scope of this paper is organized as follow: Section 2 presents the rainfall data, and the methods. Section presents the main results. The discussion and conclusions are introduced in sections 4 and 5 respectively.

2. Data and Methods

2.1. Data

The daily rainfall data used in our study were obtained from the database of the Regional Centre for the Study of Adaptation to Drought (CERAAS). They come from in various observation networks, including that of the National Agency for Civil Aviation and Meteorology (ANACIM) and that set up by ISRA/CERAAS in the framework of agrosylvopastoral monitoring. These data cover the period from 1950 to 2010. The spatial distribution of the different stations in Senegal is presented on figure 1.

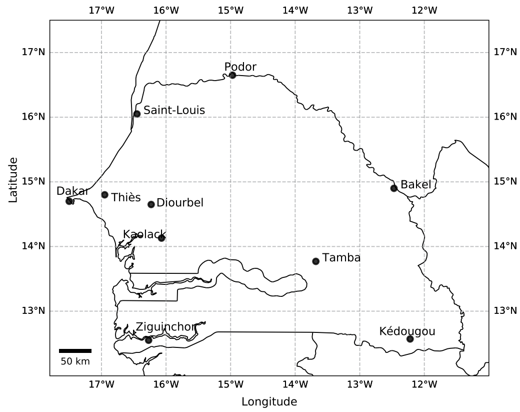

Figure 1: Spatial Distribution of the Different Stations on the Study

2.2. Methods

For the analysis of extreme rainfalls, the method used in this study is taken from the "Guidelines on Analysis of extremes in a climate change in support of informed decisions for adaptation", developed by the World Meteorological Organisation for use by policy makers [9]. This method has been successfully used in many studies on extreme precipitation analysis [10, 11]. The methodology of this study is organized as follow: First, we study the stationarity of our daily rainfall data. Second, we choose the Lamb's indice to analyse the rainfall variability [12]. Finally, we focus on the assessment of the extreme rainfall indices and their selection.

2.2.1. Stationarity Test

Before we study the stationarity of our rainfall data, it is necessary to look at their quality, which helps us to have good analysis and relevance results. The rainfall data of the selected stations in our database have been submitted in the Rclimdex software to construct a time series without outliers. This software was developed by the Meteorological Service of Canada, it allows us to detect possible erroneous values (e.g. negative values and daily precipitation), which can lead to very probable errors in the records [13]. In this study, two method of stationarity test are used: The Pettitt's test which shows the existence of a break in a time series, and the Mann-Kendall's test which examines the existence of a linear trend (increasing or decreasing) in the series [14, 15].

• Pettitt's Test of Stationarity

Based on the Mann-Whitney's test the Pettitt's test is used to detect the breaks in the time series [16]. The null hypothesis H_0 is corresponds to "there is no break". The test is based on the sign of the differences between the observations that constitute the sample. The resulting time series is constructed and the maximum observed is likely to be the break time. Thus, the p-value of the statistical test indicates whether this break is significant at level α=5%. This test considers a sequence of independent random variables $X_1, X_2, ..., X_N$, which is assumed to contain a break point at time τ if the X_t, for t=1,...,τ have a common distribution function F_1, and the X_t, for $t=\tau+1,...,N$ have a common distribution function F_2, different to F1. The null hypothesis of 'no break', H_0: $\tau=N$ against the alternative hypothesis ' presence of break', H_1, is tested from a non-parametric statistical test. No special conditions are required for the functional forms of F_1 and F_2, except for continuous points. It shows that how an appropriate formulation of test can be used under H_0. If D_{ij} =sgn(X_i -X_j), where sgn(X)=1 if X>0; 0 if X=0 and -1 if X<0, then, the variable:

$$U_{(t,N)} = \sum_{i=1}^{t} \sum_{j=t+1}^{N} D_{ij}, \quad (1)$$

is equivalent to the Mann-Whitney statistic for testing whether the two sample $X_1,...,X_t$ and $X_{t+1},...,X_N$ belong to the same population. The U_t, N statistic is considered for values of t between 1 and N. To test H_0 against $H1$,

Pettit proposes to use the variable:

$$K_N = \max_{1 \le t < N} (|U_{t,N}|). \quad (2)$$

Using theory, Pettitt gives the approximate probability of exceeding a K value as:

$$(K_N > K) \simeq exp(\frac{-6k^2}{N^3 + N^2}). \quad (3)$$

For a given first-species risk α, H_0 is rejected if this probability is less than α. In this case, the series has a break at time $t=\tau$ defining K_N. The test is more sensitive to a change in the mean.

• Mann-Kendal's Test

The Mann-Kendal's test is used to examine the existence of a linear trend (increasing or decreasing) in a time series [15]. The null hypothesis H_0 corresponds to "there is no trend". If the p-value< α, were α is chosen significance level, the H_0 hypothesis is rejected and it is concluded that there is a significant trend at the chosen level. MannKendall's rate (τ_M) uses the same assumptions as Spearman's corelation coefficient R, but they are often different. In the case where the Spearman's coefficient is considered as a standard Pearson linear correlation coefficient, i.e. it can be interpreted in term of the share explained variance part, when the Spearman's coefficient R is calculated from the ranks. The Kendall's coefficient τ_M represents also the difference between the probability that two variables have the same order in the observed data compared to the probability that these two variables have a different order, this leads that the Kendall's coefficient M is expressed as:

$$\tau_M = \frac{2S}{n(n-1)}, \quad (4)$$

with

$$S = \sum_{k}^{n-1} \sum_{k+1}^{n} sign(x_i - x_j), \quad (5)$$

where S is the value of the statistical test that gives us an indication of whether the trend is up or down and n is the length of the dataset and x_j and x_k indicate the observations at times i and j. The correlation test for the rank is based on the number P of pairs (X_i ,X_j) for which ($X_j > X_i$, $j>i$, i=1...,N-1). Under the null hypothesis (H_0) of stationarity time series, the variable ω defined by:

$$\omega_n = \frac{4P}{n(n-1)} - 1, \quad (6)$$

follows a centred normal distribution with variance equal to:

$$\sigma^2 = \frac{2(2n+5)}{9n(n-1)}. \quad (7)$$

For a given first-order risk α, the acceptance of H_0 is defined by the membership of ω_n in the interval: $\left[-\sigma^2 U_{1-\frac{\alpha}{2}}; \sigma^2 U_{1-\frac{\alpha}{2}}\right]$ where $Z_{1-\alpha/2}$ denotes the fractil of order 1- $\alpha/2$ of a standard normal random variable. Thus, the alternative hypothesis is that of a trend.

2.2.2. Rainfall Variability Analysis

The evolution of the annual rainfall can be determined from wet and dry years [12]. proposed a regionalized analysis of rainfall called the 'deficiency rainfall indice'. This index is expressed as follows:

$$I = (P(i) - P)/\sigma, \quad (8)$$

where $P(i)$ represents the average annual accumulation of year i, P and represent respectively the average and the standard deviation of the serie considered. Thus, a year will be considered normal if its index is between -0.1 and +0.1; it will be said to be wet if its index is greater than 0.1 and dry less than -0.1. On the other hand, it will be in surplus if its value is greater than +1 and in deficit if it is less than -1. The study of the evolution of annual rainfall totals requires break and trend tests on the time series of each station. These tests allow the detection of abrupt changes and trends. In West Africa, they have demonstrated their performance, particularly for detecting the onset of drought [17].

2.2.3. Assessment of the Extreme Rainfall Indices

In this section, we shall select the indices which characterize the extreme rainfall on the stations under study. we proceeded to choose indices. Many climate indices are introduced by the climate science community and some of them are developed by the Expert Group for Climate Change Detection and Monitoring. In this work, we concentrate on those used on the rainfall frameworks. The used of these indices in the context of extreme rainfall in West Africa is not new. For example, studied the recent evolution of extreme rainfall in Mauritania [18]. studied also the extreme rainfall and flood in Ouagadougou (Burkina Faso country) when the urban development is mismanaged [11].

This study, nine (09) indices evaluated annually from Rclimdex software are used to analyse the extreme rainfall in Senegal. There identification and names are presented in the Table 1 below.

Acronyme	Definition	Unit
PRCPTOT	Total annual rainfall on wet days (RR ≥ 01.0mm)	mm
RX1day	Maximum total precipitation of a rainy day	mm
Rx5day	Maximum total precipitation on 5 consecutive rainy days during the year	mm
R95p	Total annual precipitation with rainfall > 95th percentile	mm
R99p	Total annual precipitation with rainfall > 99th percentile	mm
CDD	Maximum number of consecutive days with daily rainfall < 1 mm	Day
CWD	Maximum number of consecutive days with daily rainfall ≥ 1mm	Day
R10mm	Number of days with RR ≥ 10mm	Day
R20mm	Number of days with RR x≥ 20mm	Day

Table 1: List of Indices Selected for the Study of Rainfall Extremes

A linear trend analysis has been realized from 1950 to 2010 by linear regression model between the different rainfall indices and the evolution of the time (in years). Thus, the estimated slope coefficients are grouped into two classes indicating significant and non-significant trends. In order to verify the relevance of the trends observed on the calculated indices, the Mann-Kendall's test has been used.

3. Results

3.1. Testing the Stationarity of the Daily Rainfall

In this section, we study the stationarity of the rainfall series from eleven (11) stations in Senegal using the Pettitt and the Kendal test. The results are given in the Table 2 below. Recall that, the Kendal's test for trends and the Pettitt's test for breaks are considered as significant when the associated probability (P-value) less than 5%. As for the sign of M for the Kendall's test, it allows us to know whether the trend is increasing (τ_M >0) or decreasing (τ_M <0). The analysis of the results of the previous two tests show that all stations present a decreasing trend and an abrupt change in average except the Bakel station, which presents a break point but not a significant trend.

Station		Pettit's test		Kendal's test	
	P-value	Rupture	Date	Tau	P-value
Dakar	0.0004	Significative	1971	-0.285	0.001
Thies	0.0003	Significative	1966	-0.287	0.001
Diourbel	9.675e-06	Significative	1971	-0.331	0.0001
Kaolack	0.0005	Significative	1967	-0.219	0.012
Saint-Louis	0.0033	Significative	1969	-0.155	0.078
Podor	0.0006	Significative	1971	-0.236	0.0073
Bakel	0.1866	Non Significative	—	0.131	0.136
Ziguinchor	0.0004	Significative	1967	-0.232	0.008
Tamba	0.00016	Significative	1975	-0.34	0.0001
Kédougou	0.013	Significative	1969	-0.227	0.0098
Matam	0.0012	Significative	1969	-0.183	0.038

Table 2: Results of the Different Tests for Trend and Break Detection

4. Evolution of Annual Rainfall in Senegal

The analysis of the rainfall anomalies made it possible to distinguish a wet and a dry period. A comparison of the number of dry and wet years before and after the breaking shows a very significant increase in the number of dry sequences and a considerable decrease in wet sequences (Table 3).

Station	Increase in dry years after rupture	Decrease in wet years after rupture
Dakar	+44,1%	-49,5%
Thies	+53,1%	-52,8%
Diourbel	+59,6%	-64,7%
Kaolack	+41%	-50,8%
Saint-Louis	+43,5%	-41%
Podor	+39,7%	-46,3%
Matam	+46%	-50,9%
Ziguinchor	+48%	-49,5%
Tamba	+43,7%	-49,5%
Kédougou	+35%	-35%

Table 3: Comparison between the Number of Dry and Wet Years, Before and After the Rupture

This change is most visible in Diourbel where there is an increase (+59.6%) in dry years and a strong decrease (-64.7%) in wet years. On the other hand, at the Kédougou station, it is less marked with an increase (+35%) in dry years and a decrease (-35%) in wet years. The analysis of the loess curves showed the duration of the dry phase, but above all a return of annual rainfall totals from the 1990 onwards at almost all the stations. At the Podor station (FIGURE 2), an increase in annual rainfall is noted from 1999, as is the case for the other stations (not shown) except Kaolack (2002), Dakar (2007).

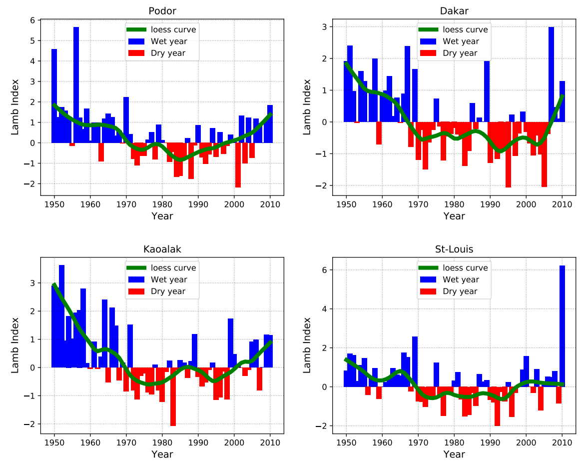

Figure 2: Annual Precipitation Trends at Selected Stations

4.1.Trends in Rainfall Indices

The observation of the linear trends of the nine (09) indices shows that only the CDD's indice is increasing on all stations (see, table 4).

Stations	PRCPOT	CDD	CWD	RX1day	RX5day	95p	R99p	R10	R20
Dakar	-4.97	+1.35	-0.019	-0.48	-1.02	-1.86	-0.271	-0.12	-0.12
Thiès	-5.77	+1.1733	-0.03	-0.871	-1.43	-2.781	-1.5	-0.14	-0.085
Diourbel	-5.63	+0.78	-0.01	-0.39	-0.83	-2.31	-0.513	-0.13	-0.095
Kaolack	-4.5	+1.32	-0.05	-0.36	-0.5362	-0.84	-0.756	-0.13	-0.08
Saint-Louis	-0.68	+1.73	-0.02	+0.2	-0.13	+0.006	+0.54	-0.03	+0.007
Podor	-2.53	+1.4	-0.024	-0.22	-0.43	-0.57	-0.13	-0.084	-0.043
Bakel	+1.324	+1	+0,01	+0, 97	+0,39	+0,96	+0,01	+0.001	+0.06
Matam	-2.39	+1.26	-0.007	+0.06	+0.012	-0.81	+0.15	-0.083	-0.029
Tamba	-5.153	+0.68	-0.03	-0.23	-0.65	-1.33	-0.8	-0.16	-0.074
Ziguinchor	-6.3	+0.74	-0.05	-0.37	-0.844	-1.89	-1.093	-0.19	-0.12
Kédougou	-4.4	+1	+0,009	-0.15	-0.37	-1.99	-1.462	-0.104	-0.09

Table 4: Slope values expressed in mm/year for each indices

Indeed, the station of Podor recorded the highest increasing trend (+1.4 days/year) in CDD's indice, while the station of Tamba leads to the lowest increasing trend (+0.68 days/year). For the station of Bakel, we observe increasing linear trends for all indices. In the otherwise the station of Matam, except the CDD indice, only the Rx1day, Rx5day and R99p indices present increasing trends. Again, we observe increasing trend given only for the CWD's indice in the station of Kedougou. Similary, decreasing trends are observed in the station of Saint-Louis from four (04) indices (R95p, R99p, R20, Rx1day). The decline in trends of total annual rainfalls, on rainy days (PRCPTOT) is greatest in stations: Ziguinchor (-6.3 mm/yr), Thiès (-5.77 mm/yr) and Diourbel (-5.63 mm/yr), but it is less significant in the station of Saint-Louis (-0.68 mm/yr). For the Rx1day and Rx5day indices, the decrease in trends is more significant at the Thiès station (-0.871 mm/year for Rx1day and -1.43 mm/year for Rx5day) and less pronounced at the stations of Kédougou (-0.15 mm/year for Rx1day) and Saint-Louis (-0.13 mm/year for Rx5day). When analysing changes in days of heavy rainfall (R10) and very heavy rainfall (R20), the decline in trends is more pronounced in the station of Ziguinchor (-0.19 days/year for R10 and -0.12 days/year for R20). The decline in trends for the R95p and R99p indices is greater in the station of Thiès station (-2.71 mm/year for R95p and -1.5 mm/year for R99p). For consecutive rainy days, the CWD's indice shows decreasing linear trends at most stations. The decreasing trends is more significant in the station of Ziguinchor with -0.05 day/year, unlike in the station of Matam with -0.007 days/year. In order to better assess the evolution of the trends, smoothing curves have been made. It is thus possible to see that the trends in the indices have not always been regular. For example, in the station of Podor, there exit two major trends in the PRCPTOT and CDD indices (see, FiGURE 3): a first decreasing trend from 1950 to 1984 and a second increasing trend from 1984 to 2010 for the PRCPTOT indice, and an increasing trend in consecutive dry days (CDD) from 1980 to 1988, followed by a decreasing trend from 1988 to 2010. For the CWD and RX-1day indices, an increasing trend was noted from 1984 to 2010 even though the linear trends of these indices are decreasing. In fact, this observation of the increasing trend of different indices over the last decades was also noted for the other stations except for the CDD and R99p indices, which show a decreasing trend over the last decade.

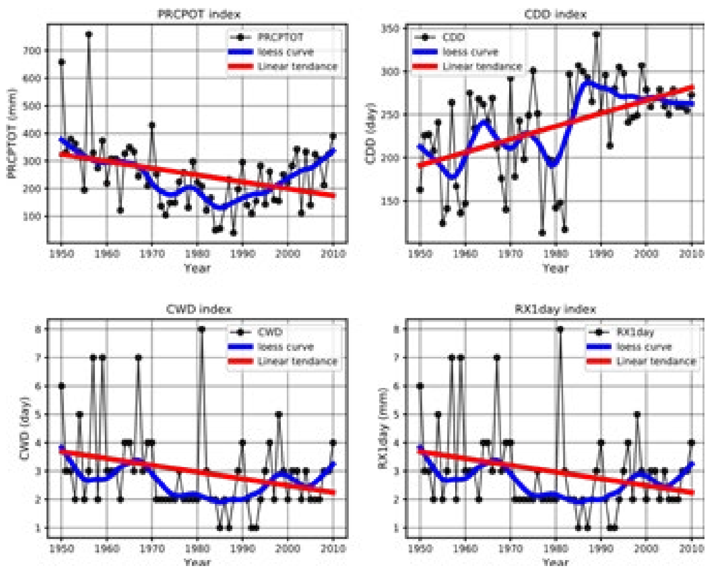

Figure 3: Annual Precipitation Trends at Selected Stations

5. Discussion

For the eleven (11) stations studied, the analysis of annual rainfall data shows that they all experienced a break between 1966 and 1975, with exception of the station of Bakel. The analysis of rainfall anomalies showed the difference between the number of wet years before and after the break. Indeed, there was a significant decreasing trends in wet years for all stations. These observations are in agreement with the studies of who showed a progressive decreasing trend in wet sequences over the Sahel since 1960 [1]. The smoothing curves, which are a good indicator of large interannual fluctuations, showed an improvement in total annual rainfall from the 1990s onwards at most stations. These results are also in agreement with the work of who showed that the Sahelian drought may have ended during the 1990s. On the basis of these results, one may wonder whether this return of total rainfalls is not due to the intensification of extreme rainfalls. Indeed, the analysis of non-linear trends (smoothing curve) in total annual rainfalls on wet days (PRCPTOT) showed a rather upward trend from the 1990s onwards [19]. This could suggest a return to better rainfall conditions in our study area. The observation of linear trends of the maximum duration of wet sequences (CWD) showed a decreasing trend of the indice on the different stations. This decreasing seems to be consistent with the evolution of the maximum duration of dry sequences (CDD), as a strong decreasing in the maximum duration of wet sequences. This could favour an increasing in the maximum length of dry sequence [20]. For the R95p and R99p indices, smoothing revealed an increasing trend from the 1990s for very wet days (R95p), but for extremely wet days (R99p) they show a downward trend at the various stations from 2000 onwards, except for stations Thies, Dakar, Bakel and Podor, which show an upward trend over the last few decades (from 1991). Similary results can be found in the frameworks of [21]. However, we cannot really say an evolution trend, but this could well 10 Sarr et al. be the beginning of a change; and it cannot be observed on our data, which stop in 2010.

6. Conclusion

We conducted a study to characterise as clearly as possible the extreme rainfalls in Senegal. This work was carried out on daily rainfall data from 1950 to 2010 at several sites in Senegal. The analysis focused on rainfall anomalies and extreme rainfall indices. The results show that the dramatic drought that had affected the country (Senegal) since 1970 ended in 1999 without, however, reaching the pre-drought total rainfall. This return to wetter conditions is currently being confirmed across West African countries. However, this increase in total rainfall appears to be influenced by extreme rainfall events. Indeed, eight (08) of the nine (09) rainfall indices studied show decreasing trends and only one (the CDD's indice) shows an increasing trend over the period 1950-2010. On the other hand, a careful analysis of the smoothing curves of the different indices shows an increasing in trends over the last decades, except for extremely wet days (R99p) and consecutive dry days. The approach used allowed us to obtain innovative results that should support innovations for the consideration of rainfall events in urban land use planning. Nevertheless, it would be desirable to extend these analyses to the whole of Senegal. Unfortunately, long series are not available. Indeed, such data would provide a scientific value that would legitimise and allow a detailed analysis of extreme events in Senegal. The main unknown is the future evolution of the intensity and frequency of these events in a context of climate change. The latest studies by [21] highlight that these features will be more intense in future horizons in the West African Sahel. There is a need to deepen this work in order improved studies of the impact of climate change on the natural ecosystem and on certain human activities such as agriculture in Senegal, which is known for its low adaptive capacity.

Conflict of Interest

You may be asked to provide a conflict of interest statement during the submission process. Please check the journal's author guidelines for details on what to include in this section. Please ensure you liaise with all co-authors to confirm agreement with the final statement.

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