Journal of Geoscience and Environment Protection, 2023, 11, 1-14
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Study of the Spatio-Temporal Variability of Rainfall in the Northern Region of Senegal

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How to cite this paper: Diop, A. D., Mbodji, A. K., Deme, E. H., Wade, M., Moussa, M. A., Diop, A. B., Biaye, Y., Sarr, D., Farota, A. K., Diakhaby, A., & Diop, B. (2023). Study of the Spatio-Temporal Variability of Rainfall in the Northern Region of Senegal. *Journal of Geoscience and Environment Protection, 11,* 1-14.
https://doi.org/10.4236/gep.2023.114001

Received: August 29, 2022
Accepted: April 10, 2023
Published: April 13, 2023

Abstract

Senegal is a country of the Sahel. In this region, most of the populations live from agro-pastoral activities. The northern zone of Senegal is strongly influenced by river cultures. And the dynamics of the Senegal River are dependent on rainfall. The rainfall in the area is very closely linked to the dynamics of the atmosphere. The study of the spatio-temporal variability of rainfall in the northern region of Senegal requires quality rainfall observation data. It includes the Ferlo and the Senegal River valley, in particular the regions of Louga (department of Linguère included), Saint-Louis (departments of Dagana and Podor included) and Matam. These stations have been defined since Le Borgne (1988). The difficulty of having quality rain observation data can be resolved by using more accessible and good quality satellite data. Using satellite data, namely MSWEP, CRU, TAMSAT, ARC and PERSIANN, we showed the return of precipitation that appeared in 2000 and the unimodal cycle of precipitation in our study area. These data were validated using the correlation coefficient, the bias, the RMSE and the Nash index with observation data from the Regional Study Center for the Improvement of Adaptation to Drought (CERASS). The CRU data is then retained. Thus, this study made it possible to show the zonal distribution of rainfall in the northern zone of Senegal.

Keywords

Rainfall in the Northern Region of Senegal, Variability of Rainfall, Satellite

Data, The Zonal Distribution of Rainfall

1. Introduction

Senegal has a strong agricultural vocation due to its significant water and land potential. Senegalese agriculture is essentially rainfed. It is based on both cash crops (peanuts, cotton) and subsistence food crops (millet, sorghum, maize). Rice, a traditional crop in Casamance, grows strongly in the valley of the Senegal River which is located in the North. The latter is considered the breadbasket of Senegal (delta of the Senegal River, lots of agricultural land, more or less rich land for agriculture). It is located at the 400 mm isohyet (Dieng, Roucou, & Louvet, 2008). After Senegal's independence in 1960, the Senegalese government continued to develop the Senegal River with the Autonomous Organization of the Delta (OAD), reestablished in 1964 by the Delta Development and Exploitation Company (SAED), the Organization for the Development of the Senegal River (OMVS, 1972), the Office du Lac de Guiers (OLAG, 2010). The north of Senegal is located in the Sahelian strip of West Africa watered by the Atlantic monsoon flow which undergoes very strong variations on very variable time and space scales. These variations are reflected in notable differences in terms of precipitation. However, the rain constitutes the most important factor of the climate and the main element of regional differentiation.

The study of the spatio-temporal variability of rainfall in the northern region of Senegal requires quality rainfall observation data. This zone is between 12˚62 16˚52 longitude and 14˚4 - 16˚67 latitude. It includes the Ferlo and the Senegal River valley, in particular the regions of Louga (15˚37N - 16˚13W) (department of Linguère (15˚23N - 15˚07W) included), Saint-Louis (16˚27W - 16˚03N) (departments of Dagana (16˚47N - 15˚6W) included), Podor (15˚37N - 16˚13W) and Matam (15˚39N - 13˚15W). These stations have been defined since Le Borgne (1988). The difficulty of having quality rain observation data can be resolved by using more accessible and good quality satellite data.

After validating the satellite data, namely CRU, with the CERAAS observation data, we showed the zonal distribution of rainfall in the northern zone of Senegal.

2. Data and Methods

2.1. Data

The CRU database is one of the most widely used today, particularly for work on climate change (Moisselin et al., 2002) and its economic consequences (Dell et al., 2014) and precipitation variability (Akinsanola et al., 2017). The raw geolocated data of CRU relates to a grid of 0.5˚ latitude and longitude (approximately 50 * 50 km at the equator). Each grid cell has data for each month over the period 1901-2013 generated by interpolation. Each of these data corresponds to a weighted average of the observations of stations located in the cell, and of observations of stations outside but close to the cell.

2.2. Methods

Anomalies and the seasonal cycle are represented to characterize the evolution of precipitation variability. Several authors have used rainfall anomalies to analyze this variability (Janicot and Fontaine, 1993; Salack et al., 2012).

Wavelet analysis is a common tool for decomposing a time series into space-time-frequency and detecting time-frequency variations. The wavelet transformation makes it possible to compare a signal to a wavelet function called the mother wavelet (here, we use the Morlet wavelet; Torrence and Compo, 1998). After having tested different mother wavelets, the results obtained are similar. Since the wavelet transform is a band-pass filter with a known response function (the wavelet function), it is also a powerful filtering technique. In order to identify the dominant synoptic modes, the wavelet analysis method is therefore employed during the period 1979-2003, because in signal processing, wavelets are very useful for processing non-stationary signals.

Also called Principal Component Analysis (PCA), Empirical Orthogonal Function (EOF) is a multivariate statistical technique that involves reducing a data set containing a large number ($K \times 1$) of data vectors to a data set containing fewer new ($M \times 1$) vectors u variables, and which are linear combinations of the original vectors and which contain most of the information of the original collection of ×. The elements of these new vectors u are called the principal components (PC). Most of the time, the principal component is calculated using the anomalies. The first PC, u_1 is the linear combination of [×]' having the greatest variance. The next principal component u_m, $m = 2, 3, 4, \ldots$, are the linear combinations with the largest possible variance, provided they are uncorrelated with the principal components with lower indices.

The m^{th} principal component of the elements u_m of u is obtained by projecting the data vector ×' onto the m^{th} eigenvector, e_m, of the covariance matrix of ×, by the relation (Wilks, 2011) (Equation (1)):

$$u_m = e_m^{\mathrm{T}} x' = \sum e_{k,m} x'_k \,, \quad m = 1, 2, \cdots, M \tag{1}$$

where the transposition operation is denoted by the exponent T and each of the M eigenvectors contains an element relative to each of the K variables, $\times_m$.

The Mann-Kendall Trend Test (MKTT) is a non-parametric alternative used to study the possible trend of a time series. In the case for example of a time series $\times_i$ (i varying from 1 to n), the static test for the MKTT is obtained using the formula (Wilks, 2011) (Equation (2)):

$$\tau = \sum_{i=1}^{n-1} \operatorname{sgn}\left(\times_{i+1} - \times_i\right) \tag{2}$$

In the case where the time series $\times_i$ decreases or increases, sgn takes the value −1 or +1 respectively. When the time series $\times_i$ is constant, sgn is zero.

We applied the MKTT to test the presence of the precipitation trend and to analyze the local seasonal trends of this parameter. The magnitude of the precipitation trend is estimated by linear regression, and the trends included in the analysis have their probability to exceed the 95% significance level.

Moving (or sliding) averages are used to analyze a statistical time series by removing transient fluctuations, in order to identify long-term trends. This is a smoothing method that is computed in turn on each subset of N consecutive values ($N \leq n$). There are different moving averages (simple, arithmetic, exponential, triangular or weighted) which differ from each other in the weight given to the data over the period considered.

Monte-Carlo methods are a class of computational algorithms that rely on random samplings. They are particularly useful for simulating systems with many degrees of freedom and do not have the constraints of parametric tests. The theoretical justification of the Monte-Carlo method is the law of large numbers, which makes it possible to assess the probability that the statistical results obtained from a very small sample exceed a certain threshold. In this study, the Monte-Carlo test is used to test the significance of statistical dependencies between two variables. In other words, it makes it possible to verify that the evolution of the variables is not solely due to the sampling. Thus, to evaluate a correlation between two series, we will permute these series a large number of times (1000 or 10,000). According to certain criteria, the Monte-Carlo test returns the probability that this correlation has of passing the threshold, while taking into account the rank 1 autocorrelation in each of the series. The significance of the linear correlation between the two series is determined by its position with respect to the distribution of correlations (Ebisuzaki, 1997) and is represented for the bilateral thresholds of 90%; 95%; 99%, etc.

Correlation measures the degree of association between two variables. The value of the correlation can vary from +1 to −1, we will speak of positive or negative correlation. In the case of a positive correlation ($0 < Cor \leq 1$), if the value of the first increases, then the value of the second increases and in the case of a negative correlation if the first increases, then the second decreases. If the value of the correlation is zero then there is no relationship between the two variables.

For lagged correlations, one variable is "lag" in relation to the other, i.e. the correlation between these two variables is created by a time lag. Thus, we can observe whether certain phenomena have an influence on others in the long term.

Autocorrelation, which is defined as the lag correlation of a variable on itself, makes it possible to observe the persistence of a phenomenon. In fact, we look over time at how this variable is correlated with respect to the beginning when the correlation was maximum and equal to 1.

Finally, regression is the operation which consists in adjusting a straight line (or another mathematical curve) "as close as possible" to a certain number of observed points. One of the most used methods to obtain an estimated model is that of least squares. In our analysis, the regression maps make it possible to observe spatially the strength of the relationship between two variables.

3. Results

Figure 1 illustrates the average spectrum of wavelets over the period 1900 to 2010 of precipitation from the different stations. It can be seen that the largest annual oscillations are observed:

- The Louga station, over the 1920s and 1950s with an average annual variation of 10 years;
- The Saint-Louis station, in 1940 with a variation of 05 years and in the 1920s and 1980s with an average annual variation of 10 years;
- The Linguère station, between the years 1920 to 1930 with a variation of 10 years;
- The station of Matam, between the years 1910 and 1920 with a variation of 05 years;
- The Podor station, between the years 1900 and 1910, 1940 and 1950, 1970 and 1980 with respective variations of 5 years by 10 years between the years 1920 and 1930 and between the years 1970 and 1980;
- The Dagana station, between the years 1900 and 1910 for respective variations of 05 years and 10 years in 1920 and between the years 1970, 1980 and 1990.

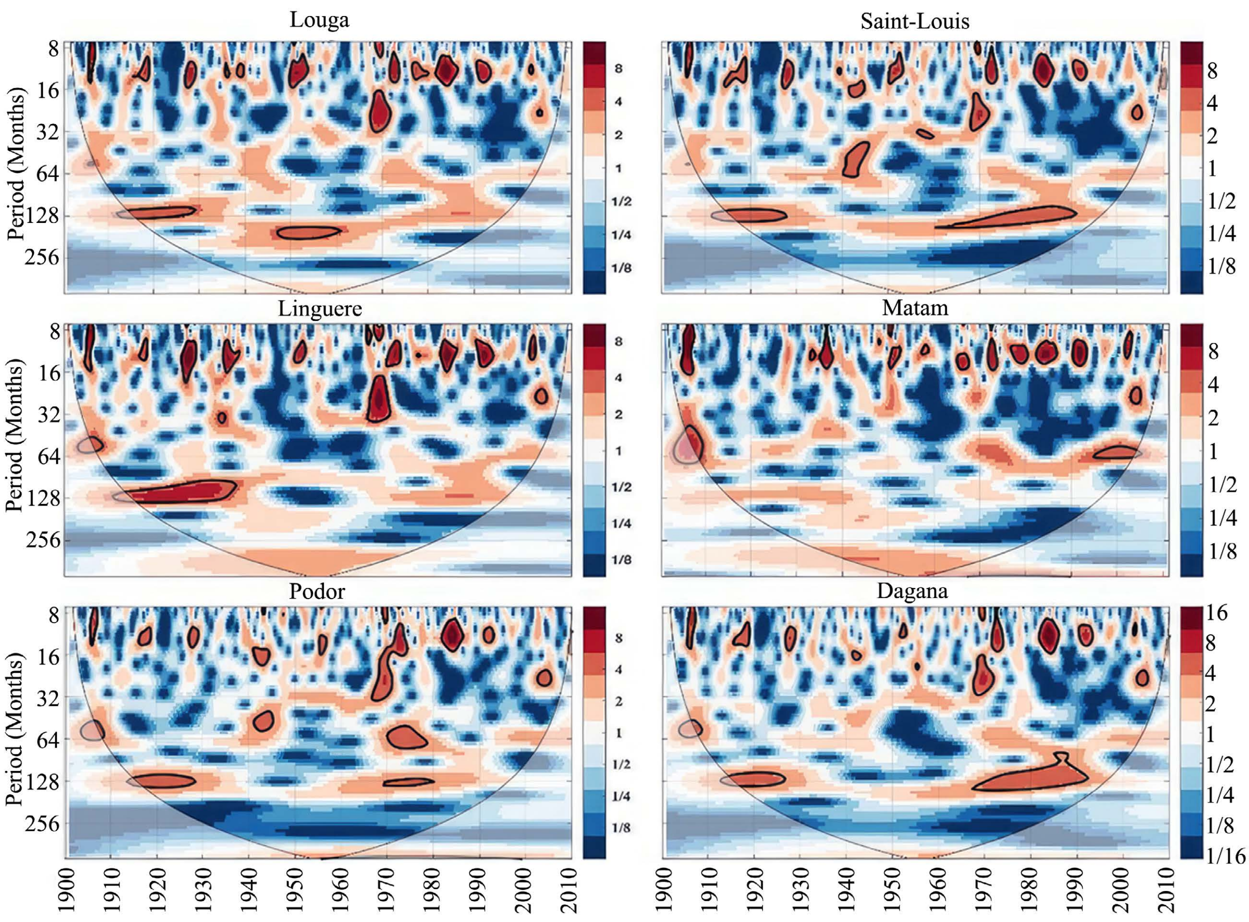

Figure 1. Average spectrum of wavelets over the period 1900 to 2010 of the different stations.

The decadal variability noted in our study area is confirmed by the results of Bigot et al. (1997). They have shown that the drier climate of Africa south of the Sahara at the end of the 1960s coincides with changes in ocean surface temperatures, particularly in the Atlantic basin, falling within decadal-scale rhythms.

We note a variability of 2 years on Louga, Saint-Louis, Linguère, Matam, Podor, and Dagana. A variability of 4 years is noted on Saint-Louis (1940), Linguère (1900-1910), on Matam (1900-1910 and 2000), Podor (1900-1910; 1940-1950; and on Dagana (1900-1910) These results are consistent with those of Fontaine et al. (2012) who showed that there was a variability of 2 to 4 years and slower oscillations (8 - 16 years) in the Sahel.

Figure 2 shows the 10-year rolling correlation of the zonal and meridian wind at 850 hPa and 700 hPa. Our choice of the 10-year correlation is justified by:

- The results of Nicholson (2009)
- **Figure 2** where the return of precipitation from 2000 in the Sahel does not appear.

The main circulation features associated with rainfall variability in the Sahelian monsoon season on interannual and decadal time scales are related to JET, JEA, JOST and the hot dry harmattan trade winds (Nicholson, 2008a, 2008b, 2009).

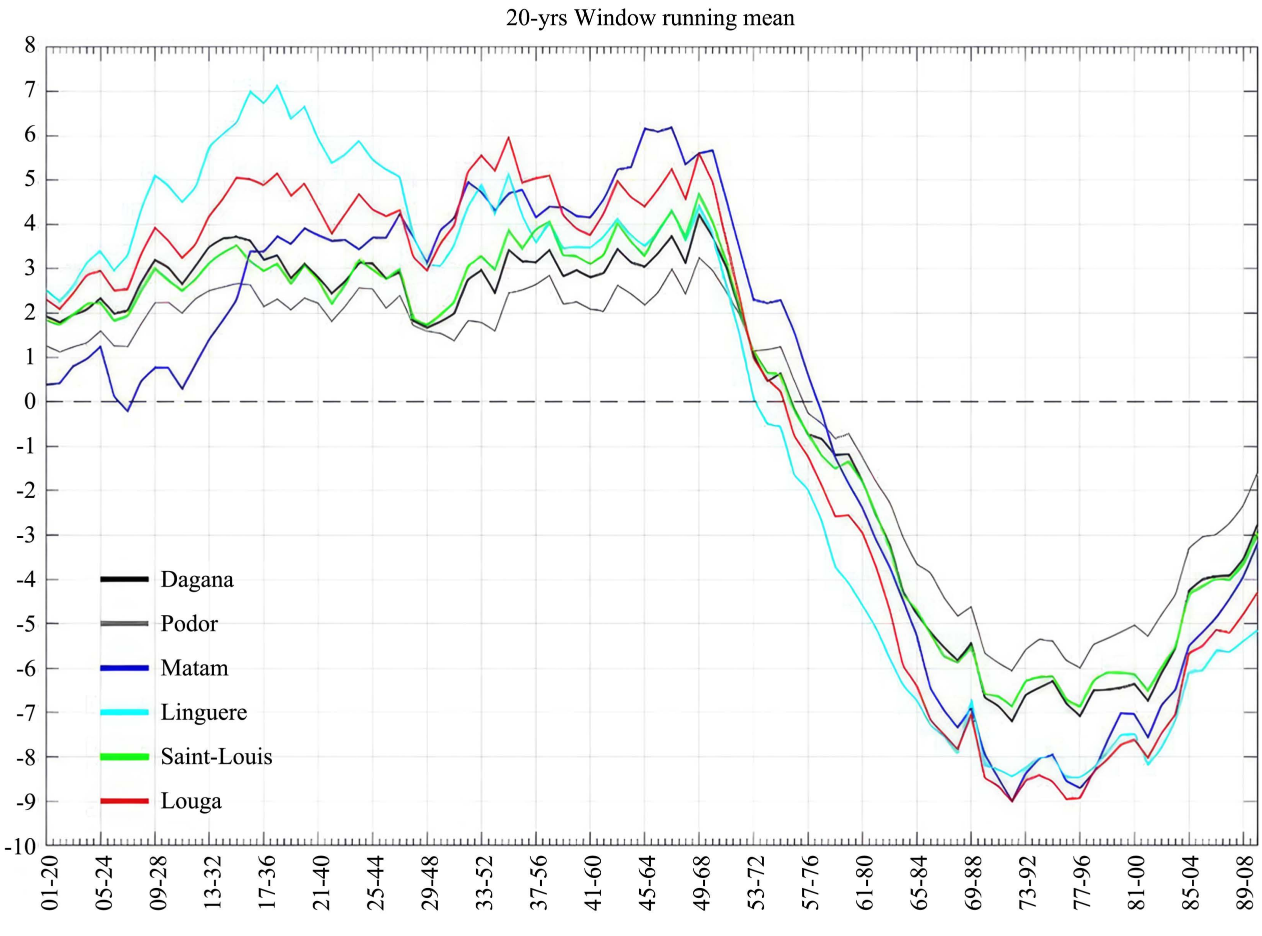

Figure 2. Moving average over 20 years of precipitation during the period 1901 to 2008 of the different study stations.

On **Figure 3** corresponding to the study of the correlation between the rain and the wind at 850 hPa (Corr Pluie vs U850; cpu850: zonal wind correlation at 850 hPa)), we observe that there is significance for the stations of:

- Matam, during the periods of 1960-1969 and 1968-1977.
- Saint-Louis, during the periods 1990-1999, 1994-2003 and 1996-2005.
- Podor, during the periods 1978-1987, 1980-1989, 1981-1990, 1996-2005 and 1997-2006.
- Linguère, at a point corresponding to the ten-year period 1948-1957.
- Louga, during the periods 1991-2000, 1994-2003 and 1996-2005.

Note that the Dagana station does not have any significant points over the entire 1948-2009 series.

The African monsoon season is characterized by two main flows: the harmattan and the monsoon flow in the lower layers of the atmosphere. If the years are wet, then the wind at 850 hPa is from the West (Grist and Nicholson, 2001; Akinsanola and Zhou, 2020).

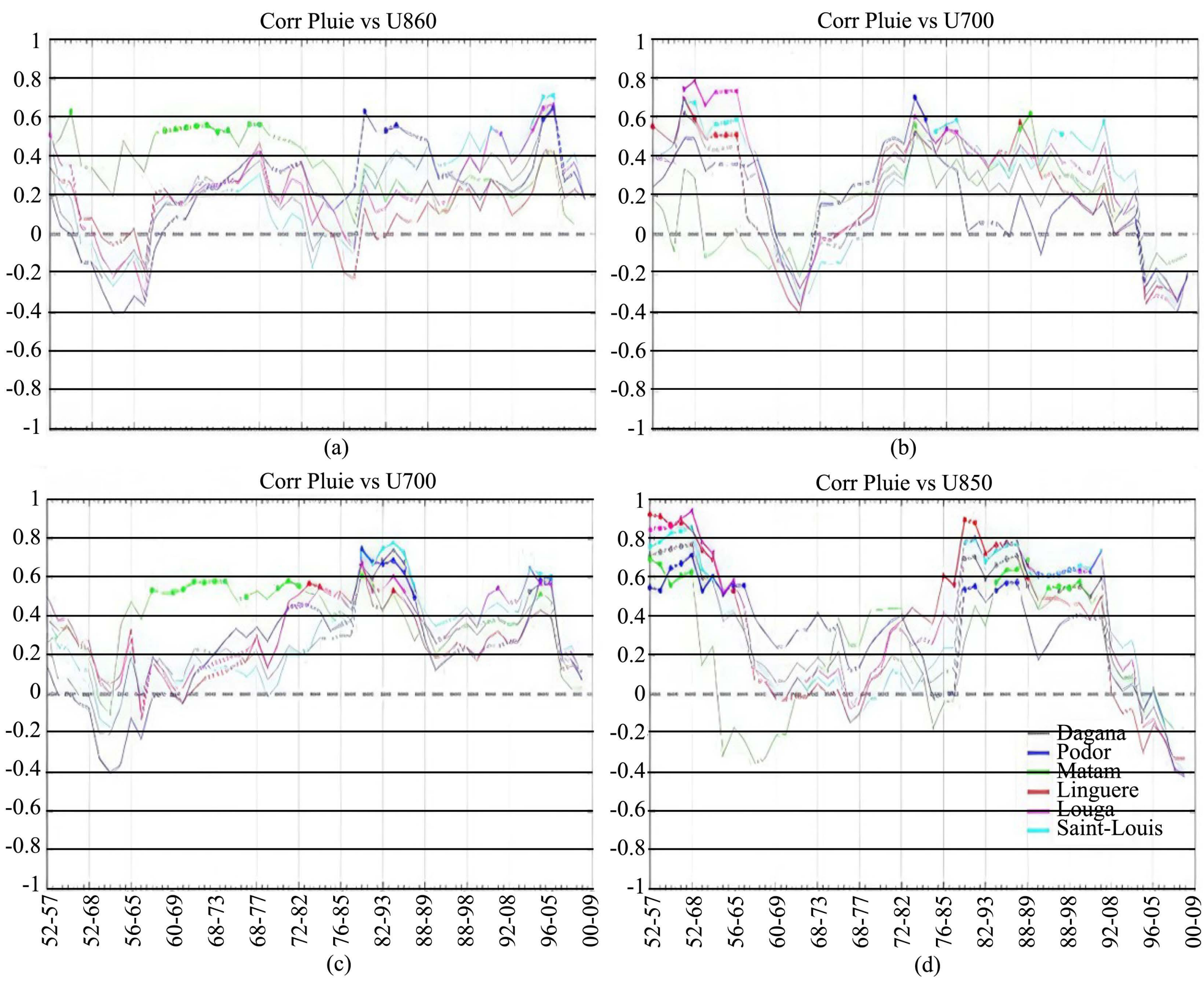

Figure 3. Rolling correlation over 10 years of precipitation and zonal and meridian wind at 850 hPa and 700 hPa during the period 1948 to 2008 at the various study stations. The points in the figures represent the 95% significance from the Monte Carlo test.

From 1965 (average 1960-1969) to 1973 (average 1968-1977), the correlation (precipitation and zonal wind JJAS at 850 hPa) for the Matam station is significant. Matam's precipitation anomalies are also positive over this period, and note wet years. There is a strengthening of the zonal wind at 850 hPa corresponding to the monsoon flow.

For 1995 (average 1990-1999), 1999 (average 1994-2003) to 2001 (average 1996-2005) where the cpu850 of the Saint-Louis station has significant points, the precipitation anomalies are negative. And the correlation is positive. We note a weakening of the zonal wind at 850 hPa during these dry years in Saint-Louis.

The year 1953 (average 1948-1957), where the cpu850 of the Linguère station has significant points, the precipitation anomalies at this station are positive. The correlation is positive. There is a strengthening of the zonal wind at 850 hPa at this station during these dry years.

The years 1983 (average 1978-1987), 1985 (average 1980-1989), 1986 (average 1981-1990), 2001 (average 1996-2005) and 2002 (average 1997-2006) where the cpu850 of the Podor station is significant compared to the zonal wind at 850 hPa, the precipitation anomalies are negative because they correspond to dry years. The correlation is positive. We note a weakening of the zonal wind at 850 hPa.

The years 1996 (average 1991-2000), 1999 (average 1994-2003) to 2001 (average 1996-2005) where the cpu850 of the Louga station has significant points, the precipitation anomalies at this station are negative. The correlation is positive. We note a weakening of the zonal wind at 850 hPa on this station during these years.

It is shown that the cpu850 has significant points during wet years only for the stations of Matam and Linguère.

In **Figure 3** highlighting the correlation between rain and wind at 700 hPa (Corr Pluie vs U700, cpu700: zonal wind correlation at 700 hPa), we observe that there is significance for the stations of:

- Matam for the different periods that are 1958-1967 to 1972-1981, 1978-1987 and 1979-1988.
- Linen worker for 1973-1982, 1974-1983 and 1981-1990.
- Podor for 1978-1987 to 1983-1992.
- Saint-Louis from 1978-1987 to 1983-1992.
- Dagana 1978-1987 to 1983-1992.
- Louga 1978-1987 and 1983-1992 to 1982-1991.

The zonal wind U at 700 hPa shows the JEA (De Felice et al., 1993; Diédhiou et al., 1998; Nicholson, 2012). The JEA is related to convective activity and precipitation in West Africa.

The years 1963 (average 1958-1967), 1964 (average 1960-1968), 1965 (average 1960-1969) to 1970 (average 1965-1974), 1972 (average 1967-1976) and 1975 (average 1970-1979) to 1977 (average 1972-1981) where the cpu700 of the Matam station is significant compared to the zonal wind at 700 hPa, the precipitation anomalies of Matam are positive because they correspond to wet years. The correlation is positive and the zonal wind at 700 hPa is negative. We note a weakening of the zonal wind at 700 hPa during these years. In 2000 (average 1995-2005) where the cpu700 is significant and the correlation negative. We note a strengthening of the zonal wind at 700 hPa, because the year 2000 (average 1995-2005) corresponds to a wet year in Matam.

For the years 1978 (average 1973-1982), 1979 (average 1974-1983) and 1986 (average 1981-1990), we note that the significant points of the Linguère station correspond to negative anomalies of precipitation. The correlation is positive, there is a strengthening of the zonal wind at 700 hPa.

There is also a strengthening of the zonal wind at 700 hPa for the station of Saint-Louis, Dagana and Louga from 1983 (average 1978-1987) to 1985 (average 1983-1992), from 1983 (average 1978-1987) to 1988 (average 1983-1992), from 1983 (respectively 1978-1987) to 1988 (average 1983-1992) and from 1987 (average 1982-1991) respectively.

It is shown that the cpu700 has significant points during wet years than with the station of Matam and Linguère.

For Corr Pluie vs V700 (cpv700: meridian wind correlation at 700 hPa), the significance is present for the stations:

- Saint-Louis, Linguère and Louga from 1956 (average 1951-1960) to 1961 (average 1956-1965).
- Podor in 1978 (average 1973-1982) and 1979 (average 1974-1983).
- Saint-Louis in 1980 (average 1975-1984) to 1982 (average 1977-1986), 1992 (average 1987-1996) and in 1995 (average 1990-2000).
- Matam in 1978 (1973-1982 average) and 1989 (1984-1993 average).
- Dagana in 1956 (average 1951-1960) to 1957 (average 1952-1961).

We note that the cpv700 has many more significant points on the stations of Saint-Louis, Linguère and Louga. On Saint-Louis, there are significant points for wet years and dry years.

The meridian wind at 700 hPa is characteristic of East African waves (Janicot and Fontaine, 1993; De Felice et al., 1993; Diédhiou et al., 1998; Foamouhoue and Buscarlet, 2006).

Precipitation anomalies at the stations of Saint-Louis, Linguère and Louga are positive from 1956 (1951-1960) to 1961 (average 1956-1965). For these years, we find that the correlation is positive. There is strong easterly wave activity.

From 1978 (average 1973-1982) to 1979 (average 1974-1983), where the cpv700 of Podor admits significant points, the precipitation anomalies are negative because they correspond to dry years. The correlation is positive. We note a weak activity of the east waves. The same phenomenon can be seen in Saint Louis from 1980 (1975-1984 average) to 1982 (1977-1986 average), in 1992 (1987-1996 average) and in 1995 (1990-2000 average) where negative precipitation anomalies are observed.

The weak activity of the waves from the East is also observed on Podor during the years 1978 (average 1973-1982) and 1979 (average 1974-1983) and on Matam during the years 1978 (average 1973-1982) and 1989 (average 1984-1993).

On **Figure 3**, Corr Pluie vs V850 (cpv850: meridian wind correlation at 850 hPa), we observe that the correlation is significant from 1953 (average 1948-1957) to 1957 (average 1952-1961) for all the stations and the significance continues for the other stations except on Matam until 1961 (average 1956-1965). It continues on Podor until 1971 (average 1957-1966). There are other significant points on:

- Linguère, from 1981 (average 1976-1985) to 1986 (average 1981-1990).
- Saint-Louis and Dagana, from 1982 (average 1977-1986) to 1997 (average 1992-2001).
- Podor, from 1983 (average 1978-1987) to (average 1983-1992).
- Matam, from 1986 (average 1981-1990) to 1989 (average 1984-1993) and from 1991 (average 1986-1995) to 1994 (average 1989-1998).
- Louga, from 1989 (average 1984-1993) to 1994 (average 1989-1998).

The meridian wind field has 850 hPa corresponding to waves coupled to convective activity (Dia-Diop et al., 2020).

From 1956 (average 1951-1960) to 1961 (average 1956-1965) when the precipitation anomalies are positive and the correlation positive, there is convective activity linked to the westerly wind at 850 hPa.

We also notice significant points on all the stations during the dry years and that the correlation is positive. We note a disappearance of the meridian wind from the West at 850 hPa. This is related to the work of Grist and Nicholson (2001).

The cpv850 is shown to have significant points in wet and dry years with all stations.

According to our study, there is a significant sliding correlation over 10 years of rainfall in our area with:

The zonal wind at 850 hPa:

- A strengthening of the zonal wind at 850 hPa for wet years (much more numerous significant points on Matam and one significant point on Linguère);
- A weakening of the zonal wind at 850 hPa for dry years as noted by Fontaine and Janicot, 1992; Akinsanola and Zhou, 2020.

The zonal wind at 700 hPa:

- A weakening of the zonal wind at 700 hPa (it is a negative wind) for wet years (significant points much more numerous on Matam);
- A strengthening of the zonal wind at 700 hPa for dry years as noted by Fontaine et al. (1995).

The meridian wind at 850 hPa:

- An appearance of the meridian wind at 850 hPa for wet years would correspond to strong convective activity (Zebaze et al., 2017; Dia-Diop et al., 2020) represented by the presence of significant points at all stations;
- A disappearance of the meridian wind at 850 hPa for dry years as noted by Kidson & Newell (1977) (presence of significant points on all stations).

The meridian wind at 700 hPa:

- Strong easterly wave activity for wet years (absence of significant points on Matam and the opposite on Linguère, Louga and Saint-Louis);
- Low activity of easterly waves for dry years.

This study, made by the spectral analysis of the CRU data of **Figure 4**, shows that the station of Matam is much more rainy. This figure shows the first three components (PC) of the CRU data over our study area (14˚25N - 16˚75N and 16˚25W - 12˚25W) during the summer (JAS) from 1983 to 2010. PC1 is in a positive phase throughout the study period. The stations located above 16N are much more rainy (PC1 between 0.16 and 0.24) that is to say the Linguère and Matam stations. PC1 represents 71.7% of the total variance. The PC2 of the CRU data was generally in its positive phase between 13˚W - 14˚W and 14˚N - 17˚N. Only the Matam station is located in this area. Note that the negative phase includes the other study stations. While the PC3 of the CRU data was in its positive phase between 12˚W - 13˚W and 15˚N - 17˚N grouping Matam (13˚15W - 15˚39N) and between 15˚5W - 16˚5W and 14˚N - 17˚N including Saint-Louis (16˚27W - 16˚03N), Dagana (15˚6W - 16˚47N). PC2 and PC3 represent respectively about 8.8% and 6.9% of the total variance. The three PCs still include the Matam station.

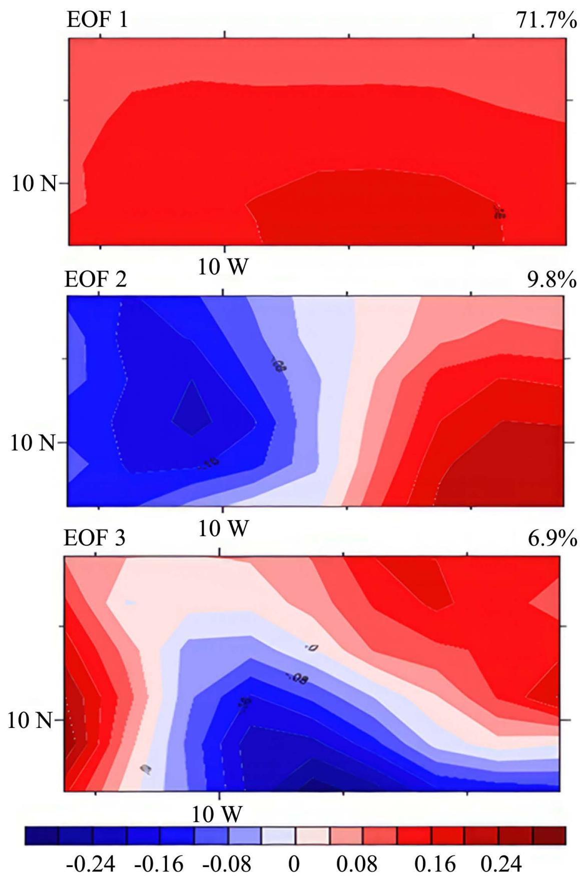

Figure 4. EOFs of CRU data (Latitude and Longitude) over our study area in July-August-September from 1983-2010. The percentage of the total variance explaining the pattern appears in the upper right corner.

4. Conclusion

Senegal is a country of the Sahel. In this region, most of the populations live from agro-pastoral activities. The northern zone of Senegal is strongly influenced by river cultures. And the dynamics of the Senegal River are dependent on rainfall.

The rainfall in the area is very closely linked to the dynamics of the atmosphere.

In the climatic region of Senegal we used CRU data to study the variability of precipitation in the NS. This is how we have shown at the station of Matam (Main city of the North East region), a strengthening of the monsoon flow during wet years accompanied by a weakening of JEA and an absence of the succession of more 10 years of dry years. On the coast (Saint Louis station) we noted a succession of more than 10 dry years and a weakening of the monsoon flow during wet years, a strengthening of the JEA during wet years

Using the 10-year rolling correlation of the 850 and 700 hPa wind and precipitation, the average wavelet spectrum and the factor analysis (EOF), we can divide the NS into a continental zone and another coastal zone. Hence the zonal distribution of rainfall which appears in addition to the meridian distribution already exists in the literature.

In perspective, we can study the correlation between the wind data at 200 hPa and the precipitation at NS. It is also important to consider the factors that block convection at the level of the NS.

Acknowledgements

Our sincere thanks to CEA MITIC, UFRSAT and LMI ECLAIRS2 for supporting this work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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