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Applying the CUSUM to a Hundred Years of Rainfall Data in Senegal

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ABSTRACT

The Senegalese territory is exposed to highly variable rainfall on which depend farmers in a country where crops are mainly rainfed. Previous studies on rainfall shifts have generally not placed the break years observed in the 1990s and 2000s within the context of century-long rainfall records. Such a long-term perspective is necessary to assess the significance of these recent shifts, which have been interpreted as marking the onset of a wetter period. In this study, an innovative approach was adopted to highlight the trends by minimizing the influence of erratic years. To this end, the Cumulative Sum (CUSUM) of the deviations from the mean annual rainfall was calculated using approximately a century of data (1921-2025). When plotted, the CUSUM series reveal long-term trends while mitigating the effect of interannual variability and outlying values. Consequently, beak years appear as maxima or minima on the CUSUM curves. In the arid and semiarid regions of Senegal, which account for about two-thirds of the country's area, highly erratic rainfall often obscures long-term trends because individual years may depart markedly from the overall tendency. By analyzing the CUSUM curves, break years can be identified directly without the need for formal changepoint tests. The CUSUM method was applied to rainfall records for ten stations representing the main climatic zones of Senegal .The results indicate that the recent increase in rainfall does not constitute a sustained upward trend comparable to that which culminated in the late 1960s. Although annual rainfall totals have generally improved since the 2000s, the persistence of frequent below-average years prevent the emergence of a regular increasing trend. This high variability poses a major challenge for local authorities and government agencies seeking to implement effective measures to mitigate the impacts of both heavy rainfall events and droughts.

INTRODUCTION

Rainfall analyses in West Africa, in Senegal precisely, revealed an upward trend since the late 1990 or mid 2000s (Sagna *et al.*, 2015; Nouaceur & Muraresc u, 2020; Descroix *et al.*, 2024). The increase is associated with heavy rain between 1982 and 2021 (Descroix *et al.*, 2013; Ndiaye *et al.*, 2023). In fact, a noticeable increase has been recorded since 2005 (Sarr *et al.*, 2022). It caused flooding in many cities, which to this day are still facing major challenges (Schaer *et al.*, 2018). Rural areas are not spared by heavy rains and above-average annual totals. They experience severe floods in low-lying areas close to river banks where rice and banana are grown (Bruckmann *et al.*, 2022, 2025). These hydrological challenges, namely excess water, should not obscure the episodic droughts that affect sustenance farming and food security. Senegal faces a dual exposure to flood risk and dry spells, underscoring the need to integrate both of these hazards into management plans.

Thanks to the studies on rainfall variability in Senegal and in West Africa in general, there is a clear understanding of the changes that occurred since the first data recordings in the late 1700s (Rodrigo & Millán, 2022). Systematic weather observations since the late 1800s made it possible to highlight the several phases in the rainfall evolution for about a century (Dacosta *et al.*, 2002; Le Borgne, 1988; Sagna *et al.*, 2021; Mendy, 2023). However, the methods applied may not show the recent trend – increase in precipitation - because of the possibility to have exceptionally below-average years. In fact, even though the annual totals of rainfall are increasing, some years like 2011, 2014, and 2019 exhibited noticeably low annual total rainfall (Nakalembe *et al.*, 2025). Using indices that apply to individual years does not show the overall trend, for it does not factor in the values of the previous years.

In this present analysis, the general trend is highlighted so to indicate how much the previous years of the series influence an individual year. Negative indices will then show deficits that are well represented in the series. Dry years like 2019 should not display a negative value except if there are enough previous dry years. The abrupt changes in rainfall have implications in farming, migration, health conditions, and flooding, but it matters to know if a single change is likely to happen again so that the adaptation methods and plans can be designed accordingly. In fact, a stand-alone rise or drop in rainwater should not obscure the general trend that guides long-term planning. In this study, the CUSUMs are compared to the SPIs for the rainfall records 1921-2025.

MATERIALS AND METHODS

The rainfall analysis is based on weather station data. The chosen stations are evenly distributed in Senegal and present the longest records. They cover the arid, semiarid

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and semihumid areas of the country (Figure 1).

Table 1 shows that rainfall ranges from 240 mm to 1378 mm from the north to the south of Senegal. The variability is higher in the Sahel region (38 percent in Saint-Louis and 21 percent in Ziguinchor) but all stations recorded a shift marking the onset of the severe drought of the 1970s and a second break year starting the "recovery"

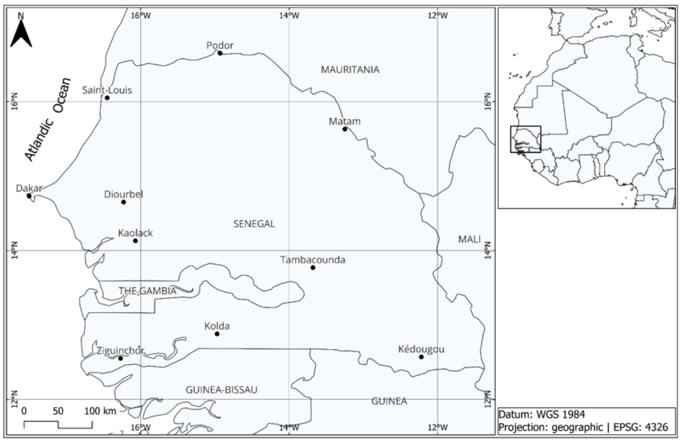

Figure1: Location of the selected stations

Table1: Selected stations

Region	Station	Longitude	Latitude	Mean 1991-2020 annual rainfall in mm	Coefficient of Variation	Record
Sahel	Podor	-14.93	16.65	240	30	1921-2025
	Saint-Louis	-16.45	16.05	274	38	1921-2026
	Matam	-13.25	15.63	405	32	1921-2027
	Dakar	-17.50	14.73	401	37	1921-2028
Semiarid	Diourbel	-16.23	14.65	521	24	1921-2029
	Kaolack	-16.07	14.13	633	23	1921-2030
	Tambacounda	-13.68	13.77	735	23	1921-2031
Semihumid	Kolda	-14.97	12.88	1118	24	1921-2032
	Kédougou	-12.22	12.57	1226	17	1921-2034
	Ziguinchor	-16.27	12.55	1378	21	1921-2033

period.

The rainfall data collected for the CUSUM analysis contains some missing data. To preserve the integrity of the original observations and avoid bias, no missing-data infilling technique was employed. Kriging-based and regression-based methods offer gap-filling realistic solutions that take into account neighboring stations (Fagandini *et al.*, 2024). Advanced AI also requires neighboring stations or other climate elements. Even though, these methods offer realistic infills, they cannot be used in this study because of the scarcity of stations and the highly spatial variability of the rainfall in the Sahel region (Lebel *et al.*, 1996). In fact, the missing data are found before 1936. Only ten stations meet the records' length criteria (starting year: 1921). The scarcely distributed stations cannot provide a satisfactory infilling technique relying on neighboring measurements. By the same token, AI models using satellite data are excluded because of the recordings that date back the years before the satellite era, the early 1980s (Nelson *et al.*, 2017; Berges, 2019). Filling the gaps is necessary in changepoint detection (Ismail *et al.*, 2024) if the years may fall around the break years. Actually, missing data can obscure real changepoints or give unreal changes in the evolution of the rainfall (Ismail *et al.*, 2024). They give the impression that, especially when they appear in successive years, the curve is stationary, which can conceal changes in the rainfall trend. The break years for the study area are around the 1960s, 1970s, 1990s and 2000. No missing data were reported from those periods. A total of ten stations meet the time series criteria (1921 onward). Among the stations selected, the missing data rate is less than 6 percent. All the gaps in the records appeared within the fifteen first years of recording. With such low missing data rates, it is not necessary to use heavy AI models. The regression is not suitable because the correlation between target stations and reference stations is not strong (Mital *et al.*, 2020). Furthermore, it treats the series as a regular evolution, which is not the case in the West African region, especially in the Sahel, where a drop in rainfall can happen between two consecutive years. Infilling the series would create a smoothing effect of the droughts, weaken the breaks or move the changepoints, all the more the study includes many different stations.

The CUmulative SUM (CUSUM) was introduced by Page in 1954 (Page, 1954). It is a sequential procedure based on the cumulative sum of deviations. It represents the sum of scores attributed to observations up to the nth value.

In a set of observations of size N at regular intervals, xk is the score assigned to the kth observation. The Cumulative Sum is then Sn:

$$S_n = \sum_{k=1}^{n} x_k \quad (1)$$

The CUSUM is plotted on a chart to detect changes in an evolution. The CUSUM chart incorporates all the information in the sequence of rainfall values by plotting the cumulative sums of the deviations of the annual values from the average value up to a given year (Montgomery, 2009). It has been applied by Buishand in analyzing rainfall evolution in the Netherlands from 1951 to 1980 (Buishand, 1982).

The Standardized Precipitation Index (SPI) is compared to the CUSUM to show how the CUSUM displays a change in the trends before and after the break year. The SPI is widely used to show droughts or wet periods in the time series in the Sahel (Ali & Lebel, 2009; Descroix *et al.*, 2015; Meroni *et al.*, 2017; Miko, 2023; Ugwu *et al.*, 2023). Comparing the SPIs and the CUSUM is a way to display the evolution of the cumulative deviations in contrast to the stand-alone SPI values.

RESULTS AND DISCUSSION

The CUSUM is used to illustrate the trend from the 1990s without the high interannual variability. It is then compared to the Standard Precipitation Index (SPI). Finally, the changes from the 1970s to the early 2020s are examined within a longer time series spanning from 1921 to 2025.

Break years marking the recent increase in rainfall

The rainfall evolution between 1970 and 2025 appears clearly with a decrease followed by an upward trend starting from the recent change point (Figure 2). The CUSUM curve generally showed the changepoint year as the minimum value of the CUSUM.

The break year depends on the station, without distinction between the climatic zone it belongs to or the position on the coast or in the hinterland. In the north (Podor), there is an increasing trend from 1970 to 2025 with an average rainfall of 222,2 mm. The break year (1994) separates two periods. The first one (1970-1994), which is dry, recorded an average rainfall of 190,6 mm. The second one (1995-2025) is humid with an average rainfall of 247,6 mm. In different parts of the country (Saint-Louis, Matam, Kaolack, Kolda, and Kédougou), a similar pattern has been noticed with a changepoint year detected in the 1990s. For the rest of the territory, the shift occurred later, in the 2000s. In Tambacounda, the rainfall started increasing in 2002, the year of the minimum CUSUM. In Dakar, Diourbel, and Ziguinchor, the changepoint year is 2004.

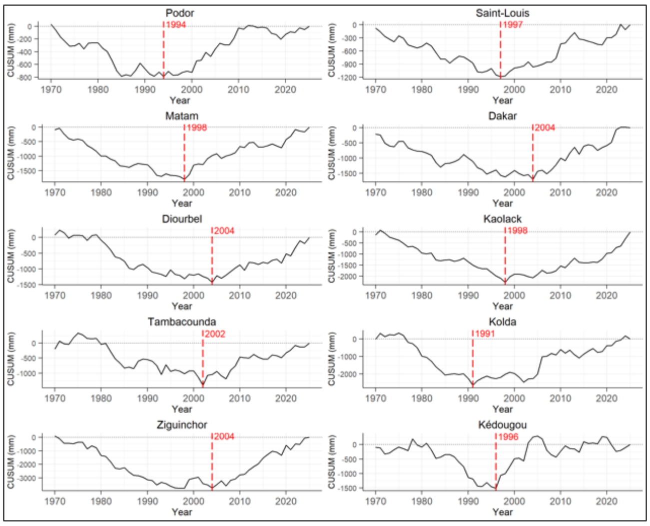

Figure 2: CUSUMs between 1970 and 2025 in Senegal

In spite of the interannual variations of the CUSUMs, the decreasing and increasing trends appear clearly in all stations. By cumulating the deviations of previous years, the CUSUM shows the cumulative effect of decrease or increase in rainfall from 1970 to 2025.

SPIs and CUSUMS in 1970-2025

The SPI is used to analyze rainfall evolution, but as the annual values do not count for previous years it does not reflect the long-term trend. By overlaying the SPI values on the CUSUMs, the negative SPI value corresponding to the break year appears as the year with the lowest CUSUM (Figure 3).

There is a relationship between the CUSUMs and the SPIs. Indeed, the shape of the precipitation curve obtained

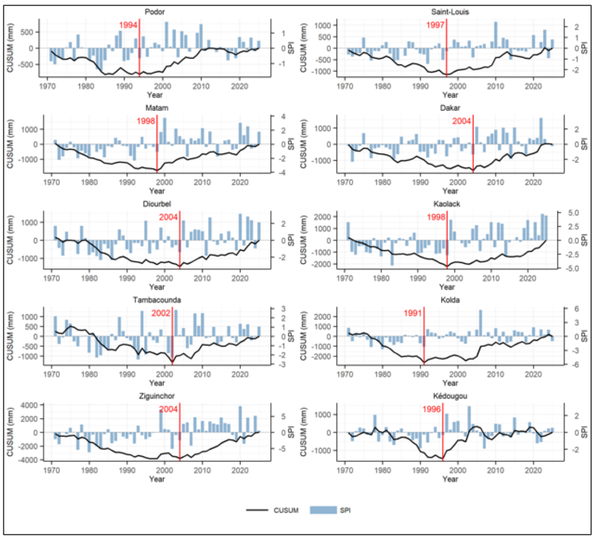

Figure 3: SPIs and CUSUMs from 1970 to 2025

using the CUSUM follows the dynamics depicted by the SPI. Therefore, for all the stations studied, the break year identified by the CUSUM is in perfect agreement with that detected by the SPI. However, the downward trend of the CUSUM curve from the beginning of the record to the break point at each station, followed by an upward trend from that date onward, indicates an increase in rainfall amounts. This finding suggests that the CUSUM is more effective than the SPI in illustrating changes in rainfall trends.

The changepoint does not seem to display any geographical pattern. In fact, a shift in the 1990s occurred in the north (Sahel region) as well as in the center (semiarid region) or in the south (semihumid region). The same is true for the 2000s changepoint.

Replacing the recent break in a century trend

Through the CUSUM lines, the two breaks in rainfall in Senegal can be compared (Figure 4). The CUSUMs show that the changepoints are different in two ways. The first shift in rainfall, in the late 1960s is more significant displaying a decrease in rainfall followed by dry years. The second shift, in the 1990s or 2000s, indicates an increase in rainfall with a lesser extend compared to the fall in the 1960s. In fact, even though the rainfall amounts started to increase after about two decades of a dry phase, the upward trend of the CUSUM shows that the values are still negative. Actually, the percentages of increase after the second break are lower than after the first. They range from 9.3 percent (in Kédougou) to 39,6 percent (in Saint-Louis), whereas the drop in rainfall could be as great as 41.8 percent. They are higher in the north of Senegal than in the south-est.

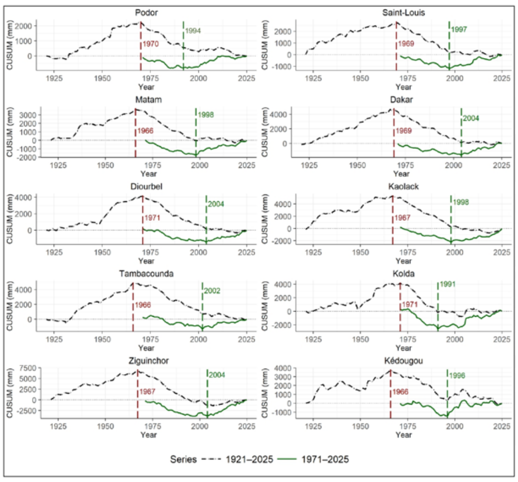

Figure 4: CUSUMs of 1921-2025 and 1970-2025

The long-term trend does not show the second shift at all stations. Actually, the break year appears as a decrease in the slope of the line representing the CUSUM. Therefore, it was necessary to draw a second line of CUSUM applied to the period after the main shift, that is the 1971-2025 subset. After the dry period, the long-term change shows a stabilization of the CUSUM, indicating a null deviation or a positive deviation from the mean. However, the positive deviations from the 1990s and the 2000s do not offset the decline of the 1960s.

Discussion

The CUSUM curve shows the changepoint year as a minimum value of the Cumulative Sum (CUSUM). From 1971 to 2025, a shift is detected in the 1990s or in the 2000s marking the beginning of the increasing phase of the rainfall in all climatic zones of Senegal. The CUSUM method has been introduced in climatic data analysis by Buishand in 1982 (Buishand, 1982). By using the CUSUM for 30-year-long rainfall records, Buishand showed the effectiveness of this statistical method. Representing the CUSUM values in a line graph illustrates the downward trend followed by an upward trend. Therefore, the break year appeared as the minimum that the CUSUM could reach in its downward trend. In Senegal, that minimum value is the beginning of the increasing trend after the dry years of the 1970s and 1980s. These changepoint years are consistent with the findings of previous studies. Badou *et al.* referred to them as the post-1970 rainfall trend in the Niger river basin. In fact, by plotting the rainfall evolution of six stations (Bembereke, Kalale, Kouande, Kandi, Banikoara, and Gaya) located in southwestern Niger and northern Benin, Badou *et al.* identified a break year in the late 1980s, in the 1990s or in the 2000s.

The CUSUM method is effective in detecting the break year by separating the time series into phases of different rainfall values. McGilchrist & Woodyer (1975) applied the CUSUM to detect changes in rainfall at Walgett, New South Wales, Australia. They identified two break years in 88 years (1878-1966). The CUSUM chart of annual mean rainfall was used by Mohd Arif *et al.* (2017) in North Kedah, Malaysia, and detected 2002 as a shift in the rainfall evolution between 1985 and 2008. In fact, after a decreasing trend, the rainfall started to increase in North Kedah. This pattern is similar to the change that has been observed in Senegal in the last 55 years with the shift of the 1990s and the 2000s. The findings are consistent with previous studies regarding the rainfall evolution in the arid, semiarid and subhumid regions of West Africa (Hulme, 2001; Mahé & Paturel, 2009).

The application of CUSUM at the global scale gave opposite outcome as for the long-term trend. The shift identified between 1955 and 1987 marks the beginning of an upward trend in the 1891-2019 records (Nazeri Tahroudi, 2025). For the West African region, the shift occurred in the same period (1960s and 1970s) but it was the onset of a downward trend. The CUSUM proved its effectiveness in revealing the extreme values of the rainfall. In addition to the trends and the breaks, the CUSUM illustrates both the negative values and the positive values of a variable. In an environmental study, by representing on the same chart the CUSUM and the standardized total phosphorus concentrations Regier *et al.* (2019) demonstrated that the downward trend reflects the negative values while the upward trend illustrates the positive ones. For regions with erratic rainfall like the climatic zones of Senegal, the CUSUM smooths the effect of isolated extreme values, thereby highlighting trends and significant changes more clearly. Even though the ten stations chosen in this study are spread all around the country, large areas are uncovered, especially the center-north. Given the erratic character of the rainfall in the region, the findings cannot be generalized. While station data offer long records of rainfall, they lack representativeness for considerable areas of the country. The CUSUM can be applied on series with missing data, but some information is lost as the missing years are mainly clustered at the beginning of the time-series. Furthermore, the CUSUM is primarily a graphical and exploratory method and therefore does not indicate the significance levels of the changes in rainfall.

CONCLUSION

The shapes of the lines representing the CUSUMs for ten stations in Senegal reveal that the shifts in the rainfall evolution can be illustrated with a simple addition of the deviations of annual amounts from the mean. In fact, the application of the Pettitt test confirmed the relevance of the CUSUM method to display the changepoints in the rainfall evolution. The findings indicate consistency between the minimal values of the CUSUMs and the break years detected by the Pettitt test. The main changepoints of the last century (1960s and 1970s) as well as the secondary ones (1990s and 2000s) are in line with the extreme CUSUMS of the time series.

Since the 1990s, the annual rainfall has been increasing after a couple of decades of dry years. However, the present annual totals are not as high as the rainfall amounts of the 1950s in Senegal. As a consequence, the CUSUMs increased from the 1990s, but they do not go beyond the zero line of the chart. They do not compensate for the droughts recorded in the 1970s and 1990s. Actually, the rainfall has not increased in recent years. It just stopped decreasing.

Being primarily a graphical and exploratory method, the CUSUM does not provide any indication of the significance levels of the changepoints. Therefore, it needs complementary analyses such as the Standard Normal Homogeneity Test (SNHT) or a Bayesian Changepoint Method. Despite these limitations, the CUSUM method applied to the arid, semiarid, and semihumid areas of Senegal offers a better understanding of the recent increase in rainfall within the context of the long-term evolution of rainfall in West Africa.

The CUSUM could be applied to temperature data in Senegal to illustrate the hypothetical minimum temperature of the late 1960s. In fact, while rainfall amounts decreased, temperatures exhibited an upward trend. It is likely that these contrasting trends would be reflected by inverse curves.

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