Article

Identification of a Representative Stationary Period for Rainfall Variability Description in the Sudano-Sahelian Zone of West Africa during the 1901–2018 Period

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Abstract: Many studies have been undertaken on climate variability in West Africa since the drastic drought of 1970s. These studies rely in many cases on different baseline periods chosen with regard to the reference periods defined by the World Meteorological Organization. A method is developed in this study to determine a stationary baseline period for rainfall variability analysis. The method is based on an application of three statistic tests (on deviation and trend) and a test of shifts detection in rainfall time series. The application of this method on six different gridded rainfall data and observations from 1901 to 2018 shows that the 1917–1946 period is the longest stationary period. An assessment of the significance of the difference between the mean annual rainfall amount during this baseline period and the annual rainfall amount during the other years shows that the "Normal" annual rainfall amount is defined by an interval delineated by ±the standard deviation (STD). With regard to this interval, a very wet/dry year is defined with a surplus/gap over/below the STD. Overall the 1901–2018 period, the 1950–1970 period presents the most important number of significant wet years and the 1971–1990 period presents the most important number of significant dry years.

Keywords: climate variability; climate change; drought; reference period; Sudano-Sahel; West Africa

1. Introduction

Climate variability and climate change become since the end of the first half of the 20th century, common expressions in all earth-water-climate studies [1–4]. This is particularly true for West Africa where the main activity of the population, agriculture, relies on the rainy season [5]. The droughts recorded in the region during the 1970s and the 1980s have entailed a serious decrease in food production and in the potentialities of the different ecosystems [5–8].

These drought periods characterized by a significant decrease in the annual rainfall amount have triggered a great interest on the analysis of the variabilities in the rainfall regime over the region [9–12]. The study of Sircoulon [10] on the comparison between the drought from 1968 to 1973 and the droughts around 1913 and around 1940, is among the first studies made in the Sahelian area on the rainfall regime variability from the analysis of rainfall data recorded in the region. The study showed that the drought over the 1907–1916 (1913) was the most devastating among the three studied droughts. In the same way,

the study of Nicholson [9] on the description of the rainfall fluctuations in Subtropical West Africa over the period 1901–1973, determined a significant decrease in the annual rainfall over the three periods (around 1913, around 1940 and from 1968 to 1973). Furthermore, L'hote et al. [13] analyzed the trends in the Sahelian rainfall over 1896–2000 period from 21 synoptic stations well scattered from Senegal in the West to Chad in the East. They computed the annual rainfall index with regard to a reference period of 80 years (from 1921 to 2000) determined on the basis of data availability at21 stations. Their results showed four main stationary periods: a deficit over 1910 to 1916 (7 years), an excess over 1950 to 1967 (18 years), a deficit over 1970 to 1974 (5 years) and a deficit over 1976 to 1993 (18 years). An update of this study was made by L'Hote et al. [13] and Mahe and Paturel [14] with an extension of the data till 2006. They found, in addition to the four previous cases, a relative recovery of the annual rainfall amount over the mid-1990s in most of the Sahelian area, except that over the 2000s the drought intensity is at the same order with the 1970s drought [14]. More recently, other studies [4,11,12] identified an increase in the annual rainfall amount over the Sudano-Sahelian area since the mid-1990s in comparison to the 1970–1989 period. All these studies showed that the climate condition in the region is characterized with a high interannual variability. However, even if the sign of the changes for a given period remains the same across the studies, it can be noted that the magnitudes are very different. Furthermore, L'hote et al. [13] found that, by changing the reference period of 1921–2000 with the WMO (World Meteorological Organisation) reference period of 1971–2000, the choice of a reference period has a strong effect on the classification of earlier years (1990–2000) as wet or dry year. Thus, studies based on the classical reference periods of 30 years (1901–1930, 1931–1960, 1961–1990 and 1971–2000) defined by the WMO over the 1901–2000 period) [15,16] would produce different results. Livezey et al. [15] stated that the WMO-recommended 30-yrs normals are often unrepresentative of the current climate. Thus, with regard to this high variability in the annual rainfall amount in the Sudano-Sahelian zone of West Africa, it becomes necessary to analyze deeper if a relevant stationary period could be considered as general reference period for rainfall variability description in the region. The identification of a representative stationary period of rainfall variability will contribute to the description of climate variability in West Africa with any climate data. This description will help to revise and update many results [9–12] that have been produced since the beginning of the 1970s on the evolution of rainfall regime in the region.

The present study aims to identify the longest stationary period for the Sudano-Sahelian climate zone through the statistical analyses of some observations from stations and six different gridded data: four generations of CRU grid (Climatic Research Unit—University of East Anglia in United Kingdom), one grid from the IRD (Institut de Recherche pour le Développement, France) and one grid from UDEL (University of Delaware in United States of America). The stationary period is defined or highlighted through the analyses of stationarity, trends and ruptures in rainfall time series over the period from 1901 to 2018.

2. Materials and Methods

2.1. Study Area and Datasets

West African Sudano-Sahelian zone is characterized by a monomodal climate with one rainy season and one dry season. The rainy season occurred over the period from May to October of each year and the dry season covers the other months. The study area considered is defined by the square delineated in the south by the latitude 9.0 °N and 17.5 °N in the north and in the west by the longitude 22.5 °W and the longitude 16.0 °E (Figure 1). This zone concerns 13 countries in West Africa (Cote d'Ivoire, Benin, Burkina Faso, Ghana, Guinea Conakry, Guinea Bissau, Gambia, Mali, Niger, Nigeria, Mali, Mauritania, and Togo). The heterogeneous climate area of Sudano-Sahel is covered by 1188 meshes (corresponding to 1188 grid points) at the spatial resolution of 0.5° longitude × 0.5° latitude. The pattern of the annual rainfall is a north-to-south gradient of 1 mm/km [11]. The annual rainfall

amount varies from about 100 mm at 17 °N to about 1200 mm at 9 °N (averages computed over 1971–2000), with a slight decrease from West to East along the same latitude.

Figure 1. West African Sudano-Sahelian zone and the grids coverage.

The rainfall data used in this study come from four different sources with two different types: three gridded data (CRU, IRD and UDEL) and the punctual observations collected by the national meteorological services in the countries concerned. The gridded data are scattered at a spatial resolution of 0.5° longitude × 0.5° latitude. Three generations of CRU data (1901–1995, 1901–2002 and 1901–2012) are considered in order to assess their improvement over time. The CRU data [17] are produced by the Climate Research Unit and the IRD data are constituted only with rainfall data collected by the IRD [5,12]. These two gridded data have been already used in many studies on climate variability and hydrological modeling in west Africa [18–20]. The third gridded data of UDEL (University of DELaware) for the 1901–2017 period [2] were developed by the University of Delaware (NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/, accessed on 6 May 2021). The gridded data are thereafter designed as from the last year: CRU_1995, CRU_2002, CRU_2009, CRU_2012, IRD_1998, and UDEL_2017. It can be emphasized here that the importance of the interpolated data is that they cover a large area, have no gap and are freely downloaded. Furthermore, with regard to their use in previous studies, the six gridded data are very relevant for the description of climate variability in the region.

The second type of data, the observations come from the regional network of the synoptic stations (with 34 stations). Despite the gaps in most of the time series, the annual rainfall amount data are available for about 34 stations over more than 40 years.

2.2. Methods and Calculations

This study is based on the analyses of different rainfall data, the computation of several indexes and the implementation of some statistical tests for the significance evaluation.

2.2.1. Criticism of the Gridded Datasets

The quality of the six different gridded data (4 grids from CRU, 1 grid from IRD, and 1 grid from UDEL) is assessed from the comparison with the observations at the monthly and the annual time steps. Some studies [12,14,19,20] have shown that even if the gridded data or interpolated data are generated from the observations, they can present some deviations with regard to the raw data. However, only the representativeness of the data is analyzed in this study. Thus, the interpolation methods and the quality of the raw data used by the different institutions are not addressed in this study. The gridded data are compared with observed data of the station located in the mesh and close to the center of the mesh. As there is only one synoptic station per mesh, 34 grid points were selected for the comparison. The classical parameters of deviation assessment between time series, the correlation coefficient and the mean absolute errors are computed for each gridded data. In addition, the significance of the similarity between the gridded data and the observations is assessed through the Pearson test [21] for the correlation and the Wilcoxon test [22] for the significancy of the deviation. For these statistical tests, two time series are significantly different when the p-values are lower than 5%. A detailed presentation of the tests can be found in [21]. Thus, from the two statistical tests, two time series are similar if the correlation is significant and there is no significant difference between their mean magnitudes at the risk level of 5%.

2.2.2. Evaluation of the Changes and Trends in the Annual Rainfall Time Series

The inter-annual variability of climate for a given region or at a station is defined by the changes (decrease or increase) that occurred in the climate parameters (rainfall, temperature, radiation, etc.). In this study, we consider the main climate parameter, rainfall, which is used to describe the trends and changes in climate evolution in many studies [11,23]. The inter-annual variability is described over the 1901–2018 period with regard to three main statistic characteristics:

- Stationarity analysis;

A time series is strictly stationary if its statistical properties (mean, variance) are unaffected by the choice of time origin [24]. More formally, a strictly stationary stochastic processes is one where given $t_1,...,t_\ell$ the joint statistical distribution of $X_{t_1},...,X_{t_\ell}$ is the same as the joint statistical distribution of $X_{t_1} + \tau,...,X_{t_\ell} + \tau$ for all ℓ and τ time steps. This means a flat looking time series, without trend, constant variance over time, a constant autocorrelation structure over time and no periodic fluctuations. Therefore, a stationary time series cannot have a trend or a periodic component [25]. The non-parametric test of Mann-Whitney [26] is applied to the time series for the stationary assessment. For each grid point, this test is applied first between some segments of 30 years (subdivion of 30 years). About 89 different segments of 30 consecutive years can be constituted from 1901 to 2018 with the first segment from 1901 to 1930, the second segment from 1902–1931 and the last segment from 1989 to 2018. Thus, if only one of the 89 segments are significantly different (level of 5%) with another segment from the Mann-Whitney test, we conclude that the time series is not stationary. In case that the 89 segments are similar, the length of the subdivision is decreased to 10 years. The 10 years subdivision produces 109 segments for each grid point.

- Breaks or shifts in the time series;

An abrupt break or shift in a non-stationary time series defines the point at which two consecutive segments are significantly different with regard to their averages. The segmentation procedure of Hubert et al. [27] considered also as a stationarity test enables to determine breaks by subdividing the whole time series into different stationary segments [27,28]. The procedure developed by Pettitt [28] splits the entire time series into two different segments in contrary to the procedure developed by Hubert [27] which splits the time series into several segments. For this study, we use only the segmentation procedure

in order to determine several breaks during the 1901–2018 period. This procedure has already been used in several studies on hydrologic data analysis in West Africa [12,27,29].

- Trends in the time series;

A trend in the time series describes the evolution over time of the given parameter from the beginning of the records to their end. The non-parametric test of Mann-Kendall [30,31] for trend detection is used to identify and evaluate the significance of the main trend in the times series. The test is applied at the risk level of 5%.

3. Results

The study has analyzed several data sets and identified some stationary periods, breaks and trends in the annual rainfall time series recorded in the region. The application of the different statistical tests has helped to highlight the most representative changes.

3.1. Comparison of Rainfall Data from the Different Sources

The first comparison of the annual rainfall data (Figure 2) is done at Ouagadougou station (situated almost at the center of the region) where we have full observed data over the period from 1902 to 2018. The pattern on this figure is similar (in terms of data dispersion around the observations) to the pattern of the other figures (not shown) drawn for the 34 reference stations. Figure 2 shows significant similarities between the observations (black curve) and the gridded data (other curves) for the inter-annual variability and for the magnitude of the annual rainfall amount at Ouagadougou. The correlation coefficients with the observations are higher than 0.7 and the mean deviation is lower than 10% of the average over the whole period.
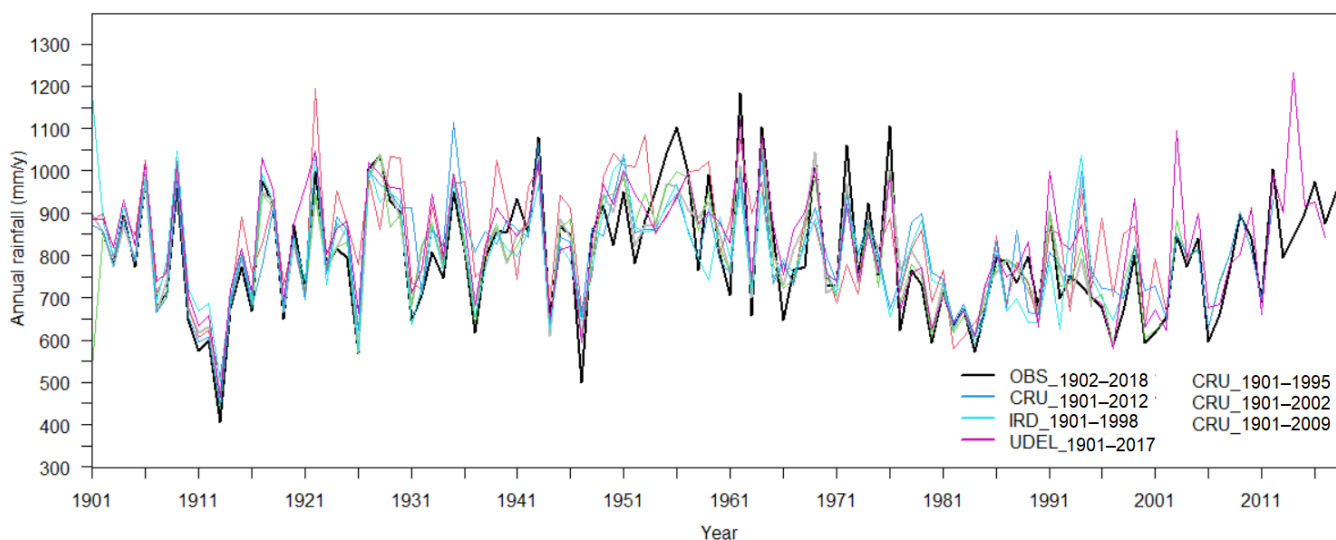

Figure 2. Annual rainfall amount at Ouagadougou station from the different sources.

Figure 2 shows that the inter-annual variability of the annual rainfall amount during the last century (20th century) is characterized by a sawtooth evolution. Thus, there is no linear trend over the whole period from 1901 to 2018 at Ouagadougou. The same result is obtained at other station (Figure S1).

The correlation coefficients and the mean absolute errors are computed at each station with the covering mesh (gridded data). Figure 3 presents the whisker boxes of the 34 correlation coefficients. Three boxes (CRU_1995, IRD_1998 and UDEL_2017) are above the correlation coefficient of 0.8 and two other boxes (CRU_2002 and CRU_2009) are above the correlation coefficient of 0.6. Furthermore, more than 95% of the correlations are significant from the Pearson test at the risk level of 5%. The CRU_2002 presents the lowest correction coefficients with the bottom whisker lower than 0.5 and the third quartile lower than

0.8. The mean absolute errors whisker boxes (Figure 4) show similar deviations with the correlation coefficients. The IRD_1998 presents the lowest boxes. The three data (CRU_1995, IRD_1998 and UDEL_2017 present here also the lowest mean absolute errors (<23%) and the highest errors are presented by the CRU_2002.
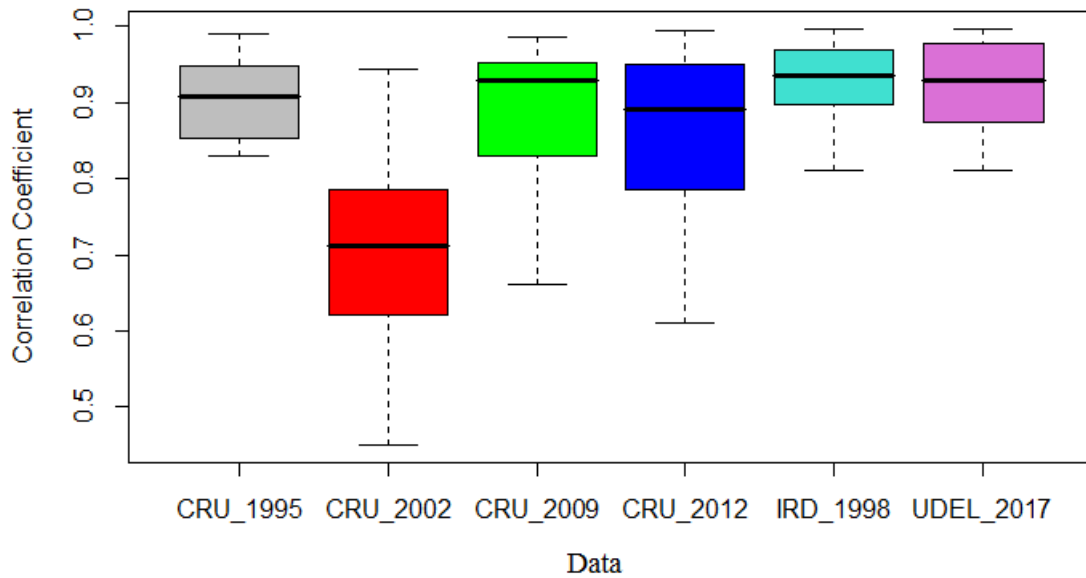

Figure 3. Correlation coefficient between the grids and the observations - The whisker boxes represent the statistical extend of the time series. The bottom whisker represents the minimum between the minimum of the time series and the median − $1.5\Delta Q$ (ΔQ represents the interquartile length). The bottom of the box represents the first quartile (25%). The bold dash represents the median (50%). The top of the box represents the third quartile (75%). The upper whisker represents the minimum between the maximum of the time series and the median + $1.5\Delta Q$.
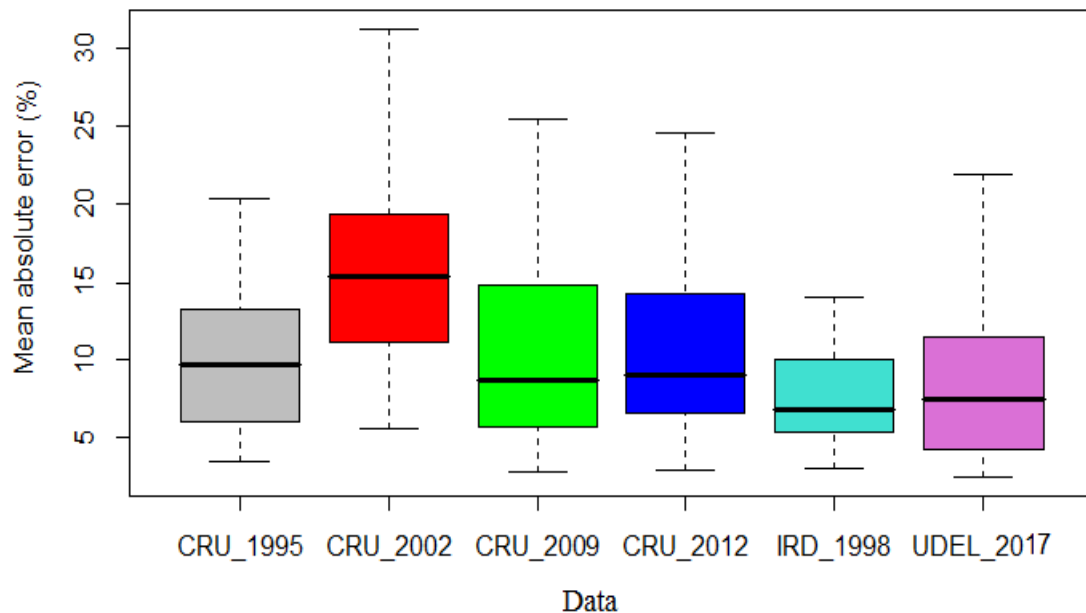
Figure 4. Mean absolute errors from the grids.

Furthermore, the *p*-values obtained from the Wilcoxon test for the 34 selected grid points (Table 1) show that the gridded data are significantly different at 11, 12, 12, 11, 5, and 7 stations respectively for CRU_1995, CRU_2002, CRU_2009, CRU_2012, IRD_1998 and UDEL_2017. This test shows again that the IRD-1998 and UDEL-2017data are close to most of the observations. All the CRU grids (CRU_1995, CRU_2002, CRU_2009, CRU_2012),

present significant deviations at eleven stations and all the six grids present significant deviations at three stations (Conakry, Natitingou and Diffa). However, CRU_1995 is better than CRU_2002, CRU_2009, and CRU_2012 with regard to the correlation coefficient and the magnitude of the deviation.

Table 1. Wilcoxon test *p*-values for the comparison between observations and gridded data.

Stations	CRU_1995	CRU_2002	CRU_2009	CRU_2012	IRD_1998	UDEL_2017
Ouagadougou	0.63	0.14	0.75	0.48	0.87	0.13
Bobo-Dioulasso	0.09	0.09	0.08	0.07	0.72	**0.01**
Dori	0.13	0.11	0.09	0.25	0.05	**0.04**
Niamey	**0.04**	**0.09**	**0.03**	**0.03**	**0.04**	0.36
Tahoua	0.37	0.06	0.37	0.25	0.46	0.40
Zinder	0.39	0.33	0.37	0.39	0.75	0.43
Bandiagara	0.24	0.57	0.14	0.15	0.38	0.99
Toumbouctou	0.76	0.91	0.62	0.80	0.96	0.70
Diourbel	0.95	0.57	0.81	0.96	0.37	0.86
Thies	0.41	0.12	0.23	0.21	0.78	0.22
Ziguinchor	0.33	0.60	0.49	0.54	0.07	1.00
Banjul	0.56	0.13	0.20	0.53	0.32	0.35
Conakry	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Kindia	**0.00**	**0.00**	**0.00**	**0.00**	0.81	0.64
Labe	0.06	0.08	**0.04**	0.10	0.63	0.50
Korhogho	0.46	0.37	0.64	0.47	0.62	0.92
Gambaga	0.81	0.83	0.51	0.73	0.55	0.34
Tamale	0.10	**0.00**	0.11	0.11	0.09	0.36
Mango	0.97	0.85	0.87	0.88	0.77	0.05
Kandi	**0.01**	**0.04**	**0.01**	**0.01**	0.40	0.72
Natitingou	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.01**
Kano	0.46	0.52	0.64	0.49	0.13	0.44
Sokoto	0.67	0.21	0.83	0.77	0.19	0.89
Markala	0.05	0.12	0.14	0.11	0.98	0.08
Konobougou	0.09	0.05	0.08	0.07	0.54	0.74
Diffa	**0.02**	**0.04**	**0.04**	**0.01**	**0.04**	**0.04**
Kaduna	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**	0.31
Yola	**0.00**	**0.00**	**0.00**	**0.00**	0.28	0.31
Faranah	**0.00**	**0.00**	**0.00**	**0.00**	0.78	0.94
Gao	0.06	**0.02**	0.06	0.09	0.90	0.99
Dialakoto	**0.00**	**0.00**	**0.00**	**0.00**	0.37	0.59
Kaolack	0.22	0.40	0.12	0.14	0.96	0.36
Kayes	**0.01**	**0.00**	**0.00**	**0.00**	0.08	**0.00**
Selibaby	0.15	0.60	0.13	1.00	0.50	**0.01**
Number of Stations with Difference	11	13	12	11	5	**7**

Red and bold values indicate significant difference between the time series at the risk level of 5%.

Overall, the three assessment of the deviation between the gridded data and the observations show that the CRU_2002 are the most biased data and the IRD_1998 are +closest to the observations. Thereafter, four grids are retained for the inter-annual variability and changes analyses: CRU_1995, CRU_2012, IRD_1998 and UDEL_2017.

The whisker boxes represent the statistical extend of the time series. The bottom whisker represents the minimum between the minimum of the time series and the median $-1.5\Delta Q$ (ΔQ represents the interquartile length). The bottom of the box represents the first quartile (25%). The bold dash represents the median (50%). The top of the box represents the third quartile (75%). The upper whisker represents the minimum between the maximum of the time series and the median $+1.5\Delta Q$.

The mean absolute error is computed in proportion with regard to the mean of the observed time series.

3.2. Identification of A Relevant Stationary Period for the Rainfall Regime

3.2.1. Assessment of the Stationarity in Rainfall Time Series

The Wilcoxon test is applied on the main four grids (CRU_1995, CRU_2012, IRD_1998 and UDEL_2017) of the rainfall data at each grid point (about 1090). The assessment is firstly done with segments of 30 years (89 segments were constituted over the 1901–2017 period). For each grid point, the proportion of *p*-values lower than 5% is computed from the 89 *p*-values obtained from the Wilcoxon test. Figure 5 presents the weight of *p*-values lower than 5% at each grid point for the CRU_2012 data. For the CRU_2012 and the other data (result not shown), the proportions of grid points with all *p*-values higher than 5% are lower than 1% (Figure 5). Furthermore, when the length of the segment is reduced to 10 years (Figure S2), the weight of the grid points with all *p*-values higher than 5% becomes lower than 0.1%. Hence, the Wilcoxon test shows that the CRU_2012 time series are not stationary over the 1901–2012 periods. The other three grids (CRU_1995, IRD_1998 and UDEL_2017) present the same quality of non-stationarity in the annual rainfall amount time series. Also, all the observed data for the 34 stations present a non-stationary time series over the 1901–2000 period.
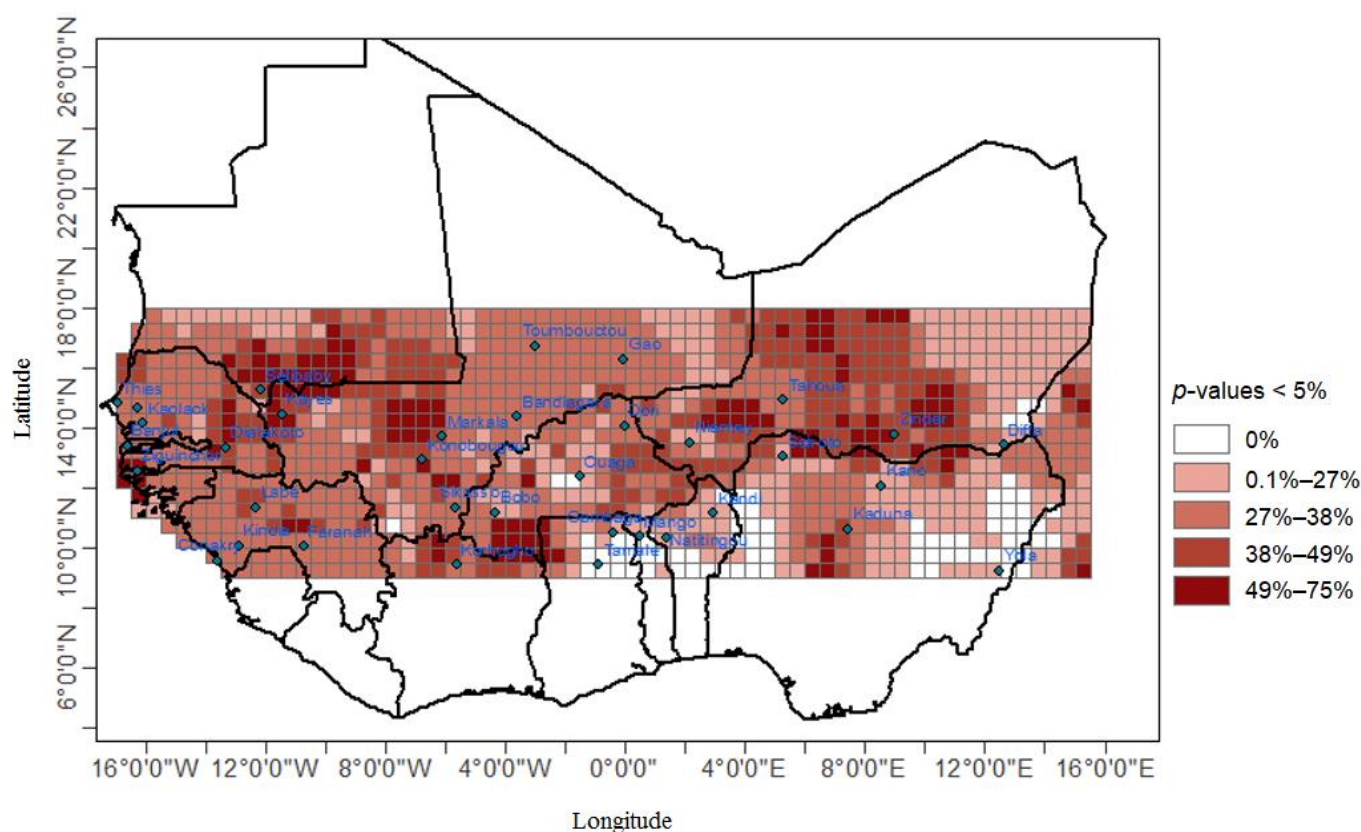
Figure 5. Proportion of *p*-values lower than 5% for the CRU_2012 data with segments of 30 years.

3.2.2. Identification of Breaks in the Annual Rainfall Time Series

The annual rainfall evolution in the region over the 1901–2018 period is characterized by two features: an absence of a linear trend and a lack of stationarity during the whole period. Thus, many breaks (years) can be identified in the time series. Figure 6 presents the histogram of the whole years of break for the 1188 grid points over the 1901–2017 period in the CRU_1995 data. Similar results were obtained with other data (Figures S3 and S5). This Figure 6 highlights two main periods of important frequency of breaks: around 1950 (1948–1952 period, positive change) and around 1968 (1966–1970 period, negative change). The geographical distribution of the meshes (grid point) concerned by breaks around the

year 1950 (Figure 7) shows that these breaks appear in central Mali, Eastern Burkina Faso and in Niger. However, the second period (Figures S4 and S6) of breaks (1966–1970 period) concerned the whole study area with 1967 as the predominant year. The results obtained with CRU_2012 (not shown) are very similar with the results produced by CRU_1995 (Figures 6 and 7).
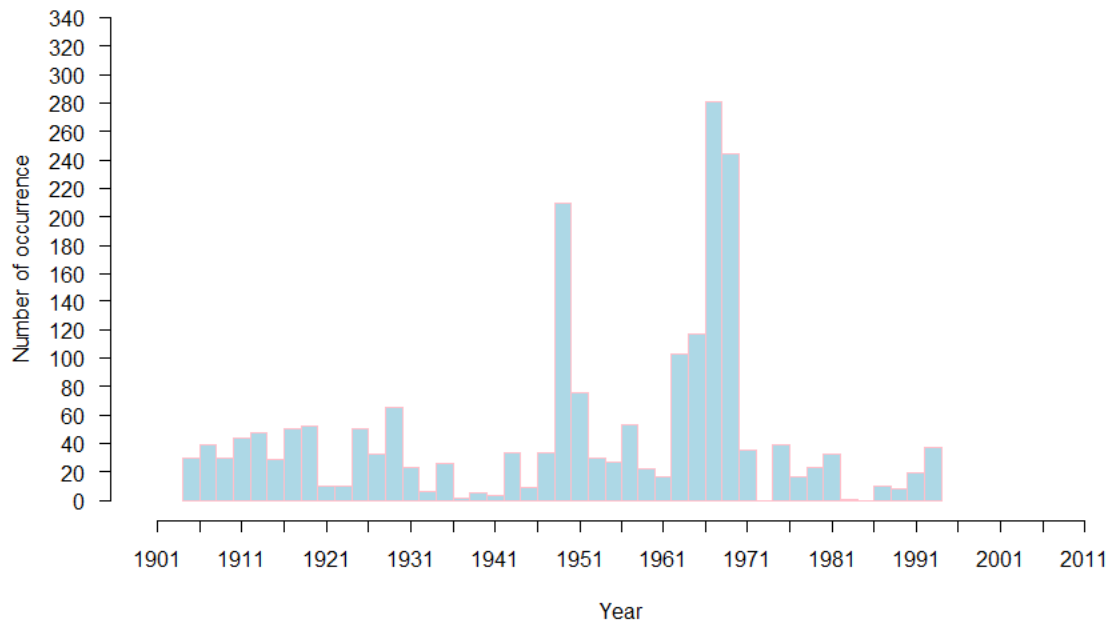

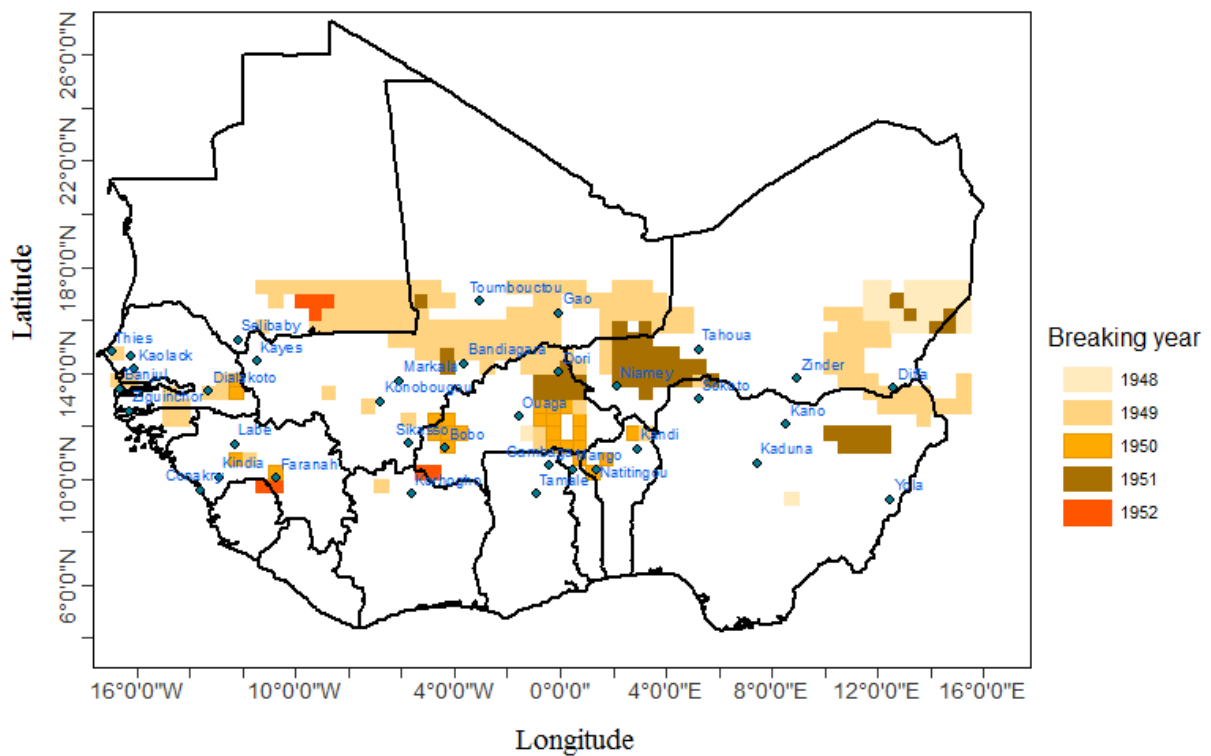**Figure 6.** Histogram of the break years with CRU_1995 data.

Figure 7. Geographical distribution of the breaks between the 1948–1952 period from the CRU_1995 data.

From the other two sources of data, IRD_1998 and UDEL_2017 (same analysis as with the previous data) three main periods of significant break frequency were revealed:

1916–1921, 1948–1952 and 1964–1970. The first two periods are not as intense as the third period. As in the CRU data, the breaks during the 1964–1970 period for the two grids concern the entire region (Figure 8) and the 1967 is the predominant year.
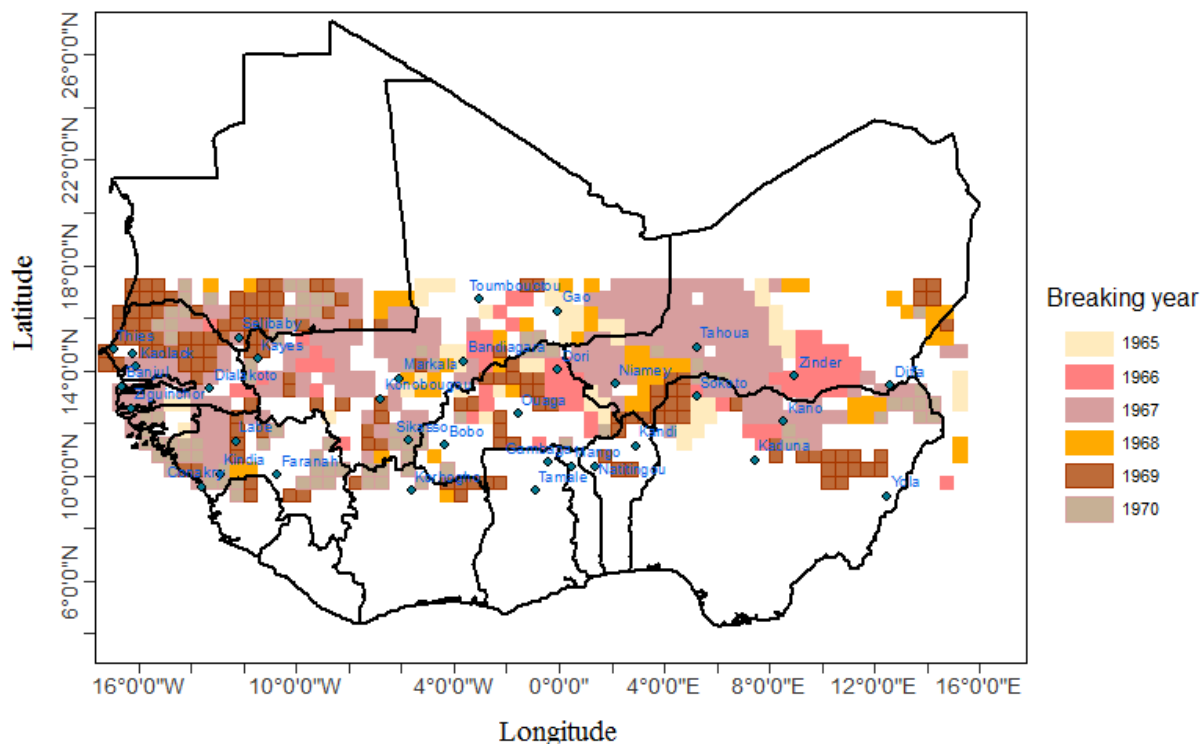
Figure 8. Geographical distribution of breaks during the 1966–1970 period from the CRU_1995 data.

Furthermore, the 1965–1970 period is also the most frequent period of breaks for the observations. The proportion of each year is determined from all the breaks determined at the 34 stations. About 40% of the breaks are within this period and 1967 is the most frequent year. The second period of breaks with regard to the frequency is around 1949 and then the period around 1990.

3.2.3. Assessment of the Breaks Significance

The relevance of a break is assessed through some random permutations of the times series. Thus, we have considered three stations (Dori, Tahoua and Sokoto) that present at least two breaks in the time series and four grid points (CRU_1995, CRU_2012, IRD_1998 and UDEL_2017). For each time series, 100 new times series are generated randomly from the random permutations of the raw data. Then the segmentation procedure is applied to each of the new time series.

For the three stations, less than 11% (Table 2 for Dori) of the permutated samples have presented a break and non-sample has recorded two breaks together. About 89% of the randomly permutated time series have no break. Thus, the breaks in the raw data are not due to the single value recorded at the break point (year of break) but to a significant change over several consecutive years. The same results for Dori were found for the other stations and the gridded data. Overall, the breaks observed in the different times series are not due to an artifact in the data but by the way the time series are organized during the whole period.

Table 2. Number of breaks within Dori time series (breaks in raw data are in 1951 and in 1966).

	1929	1948	1952	1958	1969	1975	1979	1984	1987	1988	Total
Number of Breaks	1	2	1	1	1	1	1	1	1	1	11

3.3. Identification of a Representative Stationary Period

Comparison of breaks produced in the gridded data reveals three main break points: around 1920, around 1950 and around 1967. For the observations, the break points are: around 1950, around 1967 and around 1990. Therefore, the longest period of stationarity (without any break) in the different data should be found before the 1950. The proportion of meshes which don't present a break during the 1901–1947 period is about 70%, 69%, 69% and 73% respectively for CRU_1995, CRU_2012, IRD_1998 and UDEL_2017. However, the longest period with the highest proportion of meshes without break is: 1901–1942, 1901–1944, 1901–47 and 1901–1945 respectively for CRU_1995, CRU_2012, IRD_1998 and UDEL_2017. Furthermore, the spatial extension (Figure 9) of the meshes without break during the 1901–1947 for UDEL_2017 (the lowest proportion) covers almost the whole region. Figure with IRD_1998 (Figure S7) show that overall the region the longest stationary segment ends after the 1947 (same result with the other gridded data).
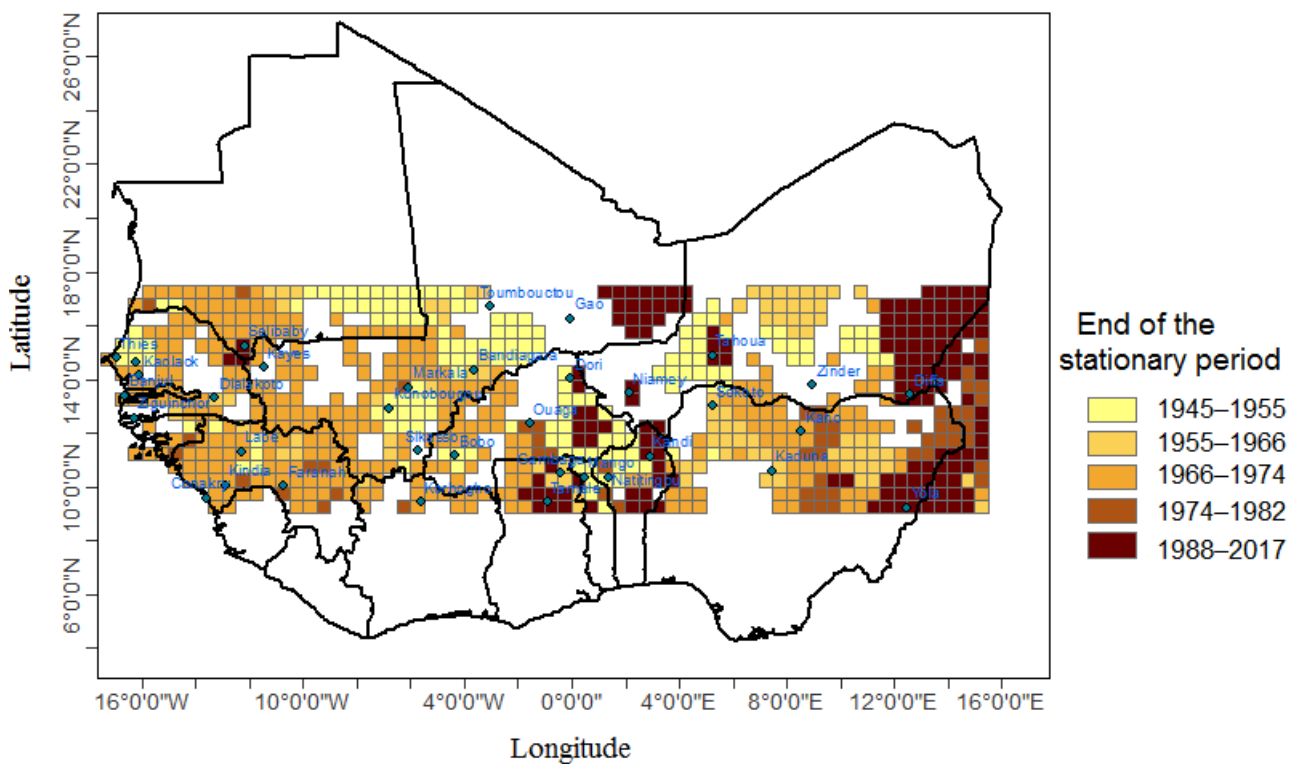

Figure 9. End of the stationary segments (beginning in 1901) with UDEL_2017.

However, as the observed data present a lot of gaps during the first decade (1901–1910) of the 20th century, the period from 1917 to 1946 is retained as the main stationary period. The proportion of meshes in the IRD_1998 that do not present a break during this period is around 75% against 69% for the previous period (1901–1947). Thus, there is an increase of more than 5% in the spatial coverage of the meshes without break. The period from 1917 to 1946 is thereafter considered as the reference period for the inter-annual variability analysis of rainfall.

3.4. Determination of Wet and Dry Year with Regard to the Stationary Period

Many studies determine wet and dry year or period from the deviation between the given annual rainfall and a reference threshold [11,12]. In this case, the wet year is defined as all year with an amount above the threshold while the dry year is the year with an annual rainfall amount less than the same threshold. This definition of wet and dry year from a single threshold is very limited with regard to the high inter-annual variability of the annual rainfall amount in the region. Instead of the single threshold, we propose in this study to define a reference interval (determined around the average on the reference period) that delineates the area of none significant change with regard to the normal amount.

The reference intervals are first assessed from the observed data over the period from 1907 to 1990 at four stations (Ouagadougou, Zinder, Kano and Sokoto). Two confidence intervals of 90% and 95% are considered around the average during the reference period of 1917–1946. For the four stations (Table 3), the first interval (PCI.90%) contains less than 30% of the 30 years of the reference period and the second interval (PCI.95%) contains less than 40%. Thus, more than 60% (19 out of 30) of the 30 years are out of the confidence intervals. However, the interval defines by the standard deviation (PSD.100%) involves about 70% of the 30 years of the reference period. Table 3 shows that for the four stations, the reference interval should be expanded more than four times the standard deviation in order to include all the 30 years.

Table 3. Proportion of years during the reference period involved in the intervals around the reference average.

Intervals	Ouagadougou	Zinder	Kano	Sokoto
PCI.90%	30	23	27	13
PCI.95%	37	30	27	37
PSD.100%	67	73	70	73
PSD.110%	67	73	77	77
PSD.150%	87	87	87	83
PSD.200%	97	97	93	93
PSD.210%	100	97	97	93
PSD.220%	100	97	97	93
PSD.230%	100	97	97	100
PSD.240%	100	100	97	100
PSD.250%	100	100	97	100

PCI.90% proportion of years within the confidence interval of 90%. PCI.95% proportion of years within the confident interval of 95%. PSD.100% proportion of years within the confidence interval defines from the standard deviation (SD). PSD.110% proportion of years within the confidence interval defines from 1.1xSD. PSD.150% proportion of years within the confident interval defines from 1.5xSD.

The same level of coverage of the reference interval is found with the grid data. An analysis of the coverage of the 95% confidence interval for UDEL_2017 (figure not shown) shows that this interval involved less than 40% of the 30 years of the reference period for more than 98% of the grid points. However, the reference interval defines by the standard deviation involves more than 60% of the 30 years of the reference period for about 95% of the grid points (Figure not shown).

From the reference interval determined above, each year can now be classified with regard to this interval (PSD.100%) as a very dry (VD) year (when the annual rainfall amount is below the lower limit) or as very wet (VW) year (when the annual rainfall amount is above the upper limit). The other years that the annual rainfall amounts are included in the reference interval are considered as "Normal" [32].

A classification of the annual rainfall amounts from 1901 to 2018 compared to the reference interval (1917–1946) for UDEL_2017 (Figure 10), shows that the proportion of grid points that present normal amount is higher than 60% at most of the years from 1901 to 1969. The same results were obtained with other data (Figure S8). However, two significant breaks appeared over this period: one in 1909 where the proportion of wet grid points

is about 70% and the other in 1913 where the proportion of dry grid points is about 75%. The following period from 1970 to 2017 is dominated by several peaks of very dry years: 1972–1973, 1983–1984, 1987 and 1990. Furthermore, two significant trends appear from 1990: a decrease in the proportion of grid points recording very dry condition and an increase in the proportion of grid points recording Normal year. The decrease in the proportion of very dry grid points from 1990 translates that the drought is still ongoing in the region but it is decreasing in spatial extension.
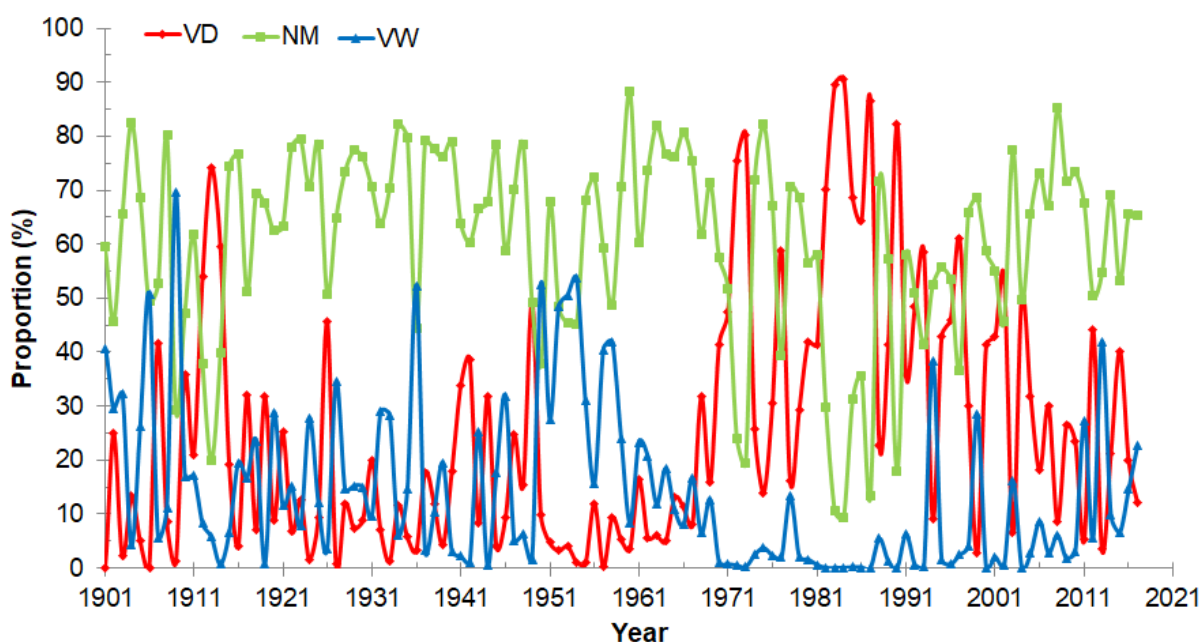
Figure 10. Proportion of grid points for the different type of year with UDEL_2017 data. VD: Very Dry, NM: Normal, VW: Very Wet. The curves represent the proportion of grid points that are under the corresponding climate condition.

Figure 10 shows also that the 1950–1965 period is the wettest period with the proportion of grid points recording very wet year (>40%) higher than the proportion of grid points recording very dry year. Furthermore, three isolated significant wet years in the region are recorded during the last two decades: 1994, 1999 and 2010.

4. Summary and Discussions

The gridded climate data generated by many institutions are now used in several studies on climate change and climate variability [2,12,18,23]. Although, they are processed data, gridded data from CRU, IRD and UDEL have helped to describe the main climate features for many regions around the globe. The comparison of the rainfall gridded data with the observation in the Sudano-Sahelian zone of West Africa shows that some of these data are very relevant. The inter-annual correlation coefficients are higher than 0.8 for CRU_1995, IRD_1998 and UDEL_2017 and the magnitude of the deviations is lower than 10% of the mean average. Furthermore, the Wilcoxon test shows no significant difference between the observations and the gridded data at about 70% of the 34 synoptic stations considered in this study. Thus, the significant similarity of the gridded data in the inter-annual variability and magnitude allows these data to be used in the description of the inter-annual variability of the rainfall regime in the region from 1901 to 2018. In the same way, Akinsanola et al. [33] found also from analysis of five gridded precipitation datasets including CRU_2009 and a previous version of UDEL, that even if these data present some limitations, they could be used for precipitation assessment over West Africa.

An assessment of the stationarity in the annual rainfall amount time series shows that the 1901–2018 period presents some discontinuities. All the gridded data and the observed data are not stationary during this period. The discontinuities highlight the high

inter-annual variability of the rainfall regime in the region [4,11,12]. Hubert segmentation procedure or breaks detection within a time series reveals four main breaks periods: 1913–1916, 1948–1951, 1966–1970 and around 1990. Two break points (1948–1951 and 1990) characterized an increasing change while the 1966–1970 breaks characterized a decreasing change. The breaks during the 1913–1916 period characterized a trough of decreasing rainfall. Thus, the longest likely stationary period during the 1901–2018 period is found from 1917 to 1946 and more than 70% of the grid points do not show a break during this period. This period (1917–1946) is retained as a representative stationary period for describing the rainfall regime variability in the region. In contrast to this period, all the five classical reference periods proposed by WMO (1901–1930, 1931–1960, 1961–1990, 1971–2000 and 1981–2010) contain at least one of the breaks listed above.

The determination of the reference period for climate analysis aims to classify the different years or seasons with regard to the reference climate condition recorded during that period. Therefore, the single amount of the average during the reference period can't represent the statistic of the whole 30 annual rainfall amounts. The SPI (Standardized Precipitation Index), the most used index to characterize the wetness or the dryness of the rainy season is a single value computed from the average and the standard deviation of the time series [11]. With the SPI, a rainy season is considered as wet if SPI > 0 and dry when SPI < 0. Thus, the single value doesn't take into account the uncertainties of the rainfall measurements [34,35]. Cecinati et al. [34] stated that the uncertainty associated with rain gauge measurements is dependent on rainfall intensity and on the characteristics of the devices. A random error up to 10–15% could occur with standard gauges [35]. Thus, the use of single value as a reference threshold is very limited in the identification of significant wet or dry year. Furthermore, the level of the random error is similar to the level of the standard deviation which is about 15% for the annual rainfall amount. Altogether, every year defines as significant wet or dry with the reference interval is also wet or dry with regard to the SPI. An assessment of the representativeness of the 30 records with different confidence intervals around the average show that the interval defined by the standard deviation includes more than 70% of these records. From 1901 to 2018 a year is classified very dry if the annual rainfall amount is below the bottom limit of the reference interval and a year is classified very wet if the annual rainfall amount is above the upper limit. The "Normal" year or season is defined with annual rainfall amount within this reference interval.

From this classification, the 1950–1965 period is the wettest period and the 1971–1990 period is the driest period from 1901 to 2018. However, the geographical extension of the area conserved by very dry years is shrinking during the last two decades (1990–2010) in contrary to the area conserved by normal dry years. Thus, there is a wetting trend of the rainfall regime in the region since the end of the 1990s [4,11].

5. Conclusions

The gridded climate data are relevant data that have been used in many studies of climate variability/climate change analysis. These processed data in combination with the observations have helped to describe the inter-annual variability of climate in many regions in general and in West Africa in particular.

The description of climate variability requires a representative reference period which should be statistically stationary. The identification of ruptures or breaks in the annual rainfall time series and an assessment of the longest stationary period during the 1901–2018 period shows that the 1917–1946 is the longest stationary period for the Sudano-Sahelian zone. However, it must be noticed that it is not in all countries and regions that we can find reliable rainfall time series for years before 1950. Thus, the use of this reference period 1917–1946 is subjected to the availability of data.

The comparison of the annual rainfall amounts recorded during the 1901–2018 period in the region with the reference interval defined over the reference period shows a very dry period from 1970 to 1990 and wet period from 1950 to 1965. The last two decades

(1991–2010) are characterized by a slight wetting trend with a decrease in the geographical extension of the area affected by drought.

References

1. Breuer, L.; Huisman, J.A.; Willems, P.; Bormann, H.; Bronstert, A.; Croke, B.F.W.; Frede, H.-G.; Gräff, T.; Hubrechts, L.; Jakeman, A.J.; et al. Assessing the Impact of Land Use Change on Hydrology by Ensemble Modeling (LUCHEM). I: Model Intercomparison with Current Land Use. *Adv. Water Resour.* **2009**, *32*, 129–146. [CrossRef]
2. Nikulin, G.; Jones, C.; Giorgi, F.; Asrar, G.; Büchner, M.; Cerezo-Mota, R.; Christensen, O.B.; Déqué, M.; Fernandez, J.; Hänsler, A.; et al. Precipitation Climatology in an Ensemble of CORDEX-Africa Regional Climate Simulations. *J. Clim.* **2012**, *25*, 6057–6078. [CrossRef]
3. Gbobaniyi, E.; Sarr, A.; Sylla, M.B.; Diallo, I.; Lennard, C.; Dosio, A.; Dhiédiou, A.; Kamga, A.; Klutse, N.A.B.; Hewitson, B.; et al. Climatology, Annual Cycle and Interannual Variability of Precipitation and Temperature in CORDEX Simulations over West Africa. *Int. J. Climatol.* **2014**, *34*, 2241–2257. [CrossRef]
4. Ibrahim, B.; Karambiri, H.; Polcher, J.; Yacouba, H.; Ribstein, P. Changes in Rainfall Regime over Burkina Faso under the Climate Change Conditions Simulated by 5 Regional Climate Models. *Clim. Dyn.* **2014**, *42*, 1363–1381. [CrossRef]
5. Sultan, B.; Baron, C.; Dingkuhn, M.; Sarr, B.; Janicot, S. Agricultural Impacts of Large-Scale Variability of the West African Monsoon. *Agric. For. Meteorol.* **2005**, *128*, 93–110. [CrossRef]
6. Sivakumar, M.V.K. Climate Change and Implications for Agriculture in Niger. *Clim. Chang.* **1992**, *20*, 297–312. [CrossRef]
7. Nicholson, S.E. Climatic and Environmental Change in Africa during the Last Two Centuries. *Clim. Res.* **2001**, *17*, 123–144. [CrossRef]
8. Ouédraogo, E.; Mando, A.; Zombré, N.P. Use of Compost to Improve Soil Properties and Crop Productivity under Low Input Agricultural System in West Africa. *Agric. Ecosyst. Environ.* **2001**, *84*, 259–266. [CrossRef]
9. Nicholson, S.E. The Nature of Rainfall Fluctuations in Subtropical West Africa. *Mon. Weather Rev.* **1980**, *108*, 473–487. [CrossRef]
10. Sircoulon, J. Les Données Hydropluviométriques de La Sécheresse Récente En Afrique Intertropicale. Comparaison Avec Les Sécheresses «1913 et 1940». *Cah Orstom Ser. Hydrol. XIIII2* **1976**, *13*, 75–174.
11. Ali, A.; Lebel, T. The Sahelian Standardized Rainfall Index Revisited. *Int. J. Climatol.* **2009**, *29*, 1705–1714. [CrossRef]
12. Paturel, J.E.; Boubacar, I.; L'Aour, A.; Mahé, G. Analyses of Pluviometric Grids and Main Features of the Changes Occurring in West and Central Africa during the 20th Century. *Hydrol. Sci. J.* **2010**, *55*, 1281–1288. [CrossRef]
13. L'Hôte, Y.; Mahé, G.; Somé, B.; Triboulet, J.P. Analysis of a Sahelian Annual Rainfall Index from 1896 to 2000; the Drought Continues. *Hydrol. Sci. J.* **2002**, *47*, 563–572. [CrossRef]
14. Mahé, G.; Paturel, J.-E. 1896–2006 Sahelian Annual Rainfall Variability and Runoff Increase of Sahelian Rivers. *Comptes Rendus Geosci.* **2009**, *341*, 538–546. [CrossRef]
15. Livezey, R.E.; Vinnikov, K.Y.; Timofeyeva, M.M.; Tinker, R.; Dool, H.M. van den Estimation and Extrapolation of Climate Normals and Climatic Trends. *J. Appl. Meteorol. Climatol.* **2007**, *46*, 1759–1776. [CrossRef]
16. Arguez, A.; Vose, R.S. The Definition of the Standard WMO Climate Normal: The Key to Deriving Alternative Climate Normals. *Bull. Am. Meteorol. Soc.* **2011**, *92*, 699–704. [CrossRef]
17. Harris, I.; Jones, P.D.; Osborn, T.J.; Lister, D.H. Updated High-Resolution Grids of Monthly Climatic Observations—The CRU TS3.10 Dataset. *Int. J. Climatol.* **2014**, *34*, 623–642. [CrossRef]
18. Mahe, G.; Paturel, J.-E.; Servat, E.; Conway, D.; Dezetter, A. The Impact of Land Use Change on Soil Water Holding Capacity and River Flow Modelling in the Nakambe River, Burkina-Faso. *J. Hydrol.* **2005**, *300*, 33–43. [CrossRef]

19. Paturel, J.E.; Barrau, C.; Mahé, G.; Dezetter, A.; Servat, E. Modelling the Impact of Climatic Variability on Water Resources in West and Central Africa from a Non-Calibrated Hydrological Model. *Hydrol. Sci. J.* **2007**, *52*, 38–48. [CrossRef]

20. Ibrahim, B. Caractérisation des Saisons de Pluies au Burkina Faso Dans un Contexte de Changement Climatique et Evaluation des Impacts Hydrologiques sur le Bassin du Nakanbé. Ph.D. Thesis, Université Pierre et Marie Curie—Paris VI, Paris, France, 2012.

21. Milot, G. *Comprendre et Réaliser Les Tests Statistiques Avec R*; De Boeck: Brussels, Belgium, 2009.

22. Ansari, A.R.; Bradley, R.A. Rank-Sum Tests for Dispersions. *Ann. Math. Stat.* **1960**, *31*, 1174–1189. [CrossRef]

23. Giorgi, F.; Bi, X.; Pal, J. Mean, Interannual Variability and Trends in a Regional Climate Change Experiment over Europe. II: Climate Change Scenarios (2071–2100). *Clim. Dyn.* **2004**, *23*, 839–858. [CrossRef]

24. Dahmen, E.R.; Hall, M.J. *Screening of Hydrological Data: Tests for Stationarity and Relative Consistency*; ILRI: Wageningen, The Netherlands, 1990; ISBN 978-90-70754-23-5.

25. Machiwal, D.; Jha, M.K. Time Series Analysis of Hydrologic Data for Water Resources Planning and Management: A Review. *J. Hydrol. Hydromech.* **2009**, *54*, 237–257.

26. Kundzewicz, Z.W.; Robson, A.J. Change Detection in Hydrological Records—A Review of the Methodology/Revue Méthodologique de La Détection de Changements Dans Les Chroniques Hydrologiques. *Hydrol. Sci. J.* **2004**, *49*, 7–19. [CrossRef]

27. Hubert, P. The Segmentation Procedure as a Tool for Discrete Modeling of Hydrometeorological Regimes. *Stoch. Environ. Res. Risk Assess.* **2000**, *14*, 297–304. [CrossRef]

28. Pettitt, A.N. A Non-Parametric Approach to the Change-Point Problem. *J. R. Stat. Soc. Ser. C Appl. Stat.* **1979**, *28*, 126–135. [CrossRef]

29. Hubert, P.; Servat, E.; Paturel, J.-E.; Kouame, B.; Bendjoudi, H.; Carbonnel, J.P.; Lubes-Niel, H. La Procédure de Segmentation, Dix Ans Après. *IAHS Publ.* **1998**, *252*, 267–274.

30. Burn, D.H.; Hag Elnur, M.A. Detection of Hydrologic Trends and Variability. *J. Hydrol.* **2002**, *255*, 107–122. [CrossRef]

31. Yue, S.; Pilon, P.; Cavadias, G. Power of the Mann–Kendall and Spearman's Rho Tests for Detecting Monotonic Trends in Hydrological Series. *J. Hydrol.* **2002**, *259*, 254–271. [CrossRef]

32. Paturel, J.E.; Ouédraogo, M.; Servat, E.; Mahé, G.; Dezetter, A.; Boyer, J.F. The Concept of Hydropluviometric Normal in West and Central Africa in a Context of Climatic Variability. *Hydrol. Sci. J.* **2003**, *48*, 125–137. [CrossRef]

33. Akinsanola, A.A.; Ogunjobi, K.O.; Ajayi, V.O.; Adefisan, E.A.; Omotosho, J.A.; Sanogo, S. Comparison of Five Gridded Precipitation Products at Climatological Scales over West Africa. *Meteorol. Atmos. Phys.* **2017**, *129*, 669–689. [CrossRef]

34. Cecinati, F.; Moreno-Ródenas, A.M.; Rico-Ramirez, M.A.; Ten Veldhuis, M.; Langeveld, J.G. Considering Rain Gauge Uncertainty Using Kriging for Uncertain Data. *Atmosphere* **2018**, *9*, 446. [CrossRef]

35. Dreaver, K.R.; Hutchinson, P. Random and Systematic Errors in Precipitation at an Exposed Site. *J. Hydrol. N. Z.* **1974**, *13*, 54–63.