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Stochastic Modelling of Annual and Maximum Daily Rainfall Using Markov Chain Model: Case of Ivory Coast

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Abstract: This work aims to simulate both annual rainfall and annual extreme daily rainfall, inside homogeneous climatic zones in Ivory Coast, for two intervals of period in the future: years 2031-2060 and 2071-2100. The methodological approach is based on the Markov Chain Model. Regarding the annual maximum daily rainfall, it is found that Nash-Stucliffe values range between 94.56% (Attiean Inside zone zone) and 97.36% (Sudanese zone zone), meanwhile the Markovian model at the annual scale was very conclusive with results performances ranging from 97.15% (Baoulean zone zone) to 98.83% (Mountain's zone zone). These values are all greater than 60% and are very close to 100%, thus reflecting a good match between the observed values and the simulated values. In other words, the observed values and the model are consistent. These very satisfactory results make it possible to certify the performance of the designed model. The predicted rainfall amounts vary between 52.95 mm (Baoulean zone) and 244.10 mm (Attiean Littoral zone) with averages ranging from 69.41 mm (Baoulean zone) to 160.78 mm (Attiean Littoral zone) for the period 2031-2060. For the period 2071-2100, the heights of simulated extreme rainfall vary between 44.46 mm (Baoulean zone) and 222.9 mm (Attiean Littoral zone) with averages ranging from 70.85 mm (Baoulean zone) and 222.9 mm (Attiean Littoral zone). The different biases between the past annual maximum daily rainfall (1931-2020) and that of the middle of the 21st century (2031-2060) and that of the end of the 21st century (2071-2100) have been calculated. These bias values for the period 2031-2060 vary from -16.56% (Attiean Inside zone) to +36.74% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -34.13% (Mountain's zone) and +37.89% (Attiéen du littoral). These biases are significant and reflect an increase in extreme rainfall to come. The years 2031-2060 will then experience an increase in extreme daily rainfall in the areas of Attiean Littoral zone, Sudanese zone from the middle of the 21st century (2031-2060) to the end of the 21st century (2071-2100). Annual rainfall forecast heights range between 1,003 mm (Sudanese zone) and 1,155.84 mm (Attiean Littoral zone) with averages ranging from 1240.51 mm (Sudanese zone) to 1630.21 mm (Mountain's zone) for the period 2031-2060. For the period 2071-2100, the simulated annual rainfall amounts vary between 1,007 mm (Attiean Inside zone) and 2179.66 mm (Attiean Littoral zone) with averages ranging from 1,214.07 mm (Baoulean zone) to 1,570.35 mm (Attiéen du littoral).

Keywords: Rainfall Simulation, Climate Change, Markov Chain, Ivory Coast

1. Introduction

According to Dai et al. (2004), Paturel et al. (2003), Goula et al. (2010) in some of West Africa's regions (Ivory Coast, Mali, Burkina Faso, Senegal, etc.), annual rainfall has decreased by 20 to 40 percent compared to the interannual average [1-3]. Goula et al. (2009) noticed that despite this climatic context characterized by a rainfall deficit, many West African countries (Benin, Burkina Faso, Ivory Coast, Niger, Ghana, Senegal, Togo) are facing serious flooding problems in both urban and rural areas [4]. For Kieffer (1998) it should be noted that the rainfall hazard is often the cause of these natural disasters [5].

In this context of modified climatic parameters, it appears necessary to review the design parameters of hydraulic structures. The knowledge of hydrological norms, such as quantiles of extreme rainfall as well as normals of extreme and annual rainfall, is necessary in the framework of development projects for the design of hydraulic structures (flood protection structures, storm sewer systems, etc.) and in many engineering applications. The simulation of extreme daily rainfall and future annual rainfall seems to be very important for future projects. These simulated rainfalls are therefore an indicator or an aid tool for all decision makers and projectors.

Hussain (2008) mentioned that the need to model synthetic rainfall data is justified by the fact that the available data contains only a limited amount of information. This information only concerns the variability of rainfall in the past [6], which does not allow for projections. Knowledge of the future probability of precipitation occurrence could be useful in planning, crop management, water management and forecasting certain hydro-meteorological disasters such as floods. For Dash (2012), this would therefore help to reduce the risk due to uncertainty of significant weather events [7]. The authors such as Richardson (1981, 1984), Rascko et al. (1991) used stochastic rainfall weather generators to develop and produce synthetic time series of climate variables such as precipitation, temperature, and solar radiation [8-10]. The underlying assumption is that the synthetic time series is statistically close to that of the observed series.

There are many model developments, which represent precipitation continuously in space. Cox D and Isham (1994) presented an interesting classification of precipitation models into three types, namely empirical statistical models, dynamic models, and intermediate stochastic models [11]. The idea behind this classification is the level of physical realism incorporated into the model structure. The last type is the most widely used by Campbell (1990), Haylock et al. (2004), Semenov et al. (1997) and there are a variety of them WGEN, ClimGEN, STARDEX project, MCME and others [6, 9, 12-14]. The WGEN variety is the one incorporated under the GoldSim Simulation software and is the subject of our study.

The general objective of this work is to simulate the annual extreme daily rainfall and annual rainfall in the horizons 2031-2060 and 2071-2100 for the homogeneous climatic zones of Ivory Coast. Doing this prospective analysis will allow us to simulate future rains to see the impacts of climate change on them and to anticipate the measures to be taken in the context of the design of sanitation and drainage facilities in Ivory Coast.

2. Materials and Methods

2.1. Study Area Presentation

Ivory Coast is in West Africa, in the intertropical zone, between the equator and the tropic of cancer, precisely between latitudes 4°30 'and 10°30' North and longitudes 8°30 and 2°30 West (Figure 1). It covers an area of 322,462 km^2 (about 1% of the African continent) and borders with the Gulf of Guinea to the South, Ghana to the East, Liberia and Guinea to the West, Mali, and Burkina Faso in the North. Figure 1 shows the study area which is Ivory Coast.

In Ivory Coast, there are five major climatic zones (Figure 2) generated by Kouao et al. (2020): the tropical transition regime or Sudanese zone climate in the north (R4), the equatorial regime of attenuated transition or Baoulean zone climate in the center (R3), the equatorial transition regime or the Attiean climate (littoral R2 and Inside R1) in the South and the mountain regime or mountain climate in the West (R5). Two main types of plant landscapes are present on Ivorian territory: a forest landscape and a savannah landscape. The first covers the southern half of the country and belongs to the Guinean domain. The second occupies the northern half of Ivory Coast and is part of the Sudanese zone domain [15]. According to Brou (2005) the Guinean domain has a predominantly dense humid forest vegetation. Ivory Coast is characterized by a relief not high. Most of the land consists of trays and plains. The west of the country, mountainous region, however, presents some reliefs beyond a thousand meters (the mount Nimba culminates at 1,752 m). Apart from this region, altitudes generally vary between 100 and 500 meters, with most plateaus being around 300 to 400 meters. These have different aspects. The highest tops are rigid in their shapes as well as in their materials; those of intermediate levels quite often have blunt shapes; the lower ones have a certain rigidity but are made of loose materials. Huge and rigorously tabular and horizontal vertical expanses are sometimes present in the savanna regions, but also under the small snags of savannas included in the dense forest. The dominant element of these plates is constituted by a ferruginous armor visible on the surface in the form of rust-colored slabs, but sometimes veiled with sand [16].

2.2. Data

Data used for this study come from the national meteorological measurement network of Ivory Coast. The annual maximum daily rainfall data used covers the period 1931-2020 and comes from twenty-six (26) rainfall stations distributed throughout the country (Figure 3). They were made available to us by SODEXAM (Aeronautical, Airport and Meteorological Development and Exploitation Company). These stations have been classified in the main climatic zones of Ivory Coast (Table 1) according to Kouao et al. (2020) [15]. The choice of stations was guided by the availability and quality of chronological data (fewer gaps with a threshold of 5%).

Figure 1. *Presentation of the study area (Ivory Coast).*

Table 1. *Distribution of stations according to climatic zones.*

Zones	Weather	Stations
Zone R1	Attiean Inside zone	Aboisso, Agboville, Agnibilékro, Azaguié, Abengourou, Dimbokro, Gagnoa, Lamé, Tiassalé, Bouaflé, Daloa
Zone R2	Attiean Littoral zone	Abidjan, Grand-Lahou, Sassandra, Tabou
Zone R3	Baoulean zone	Bouaké, Bouna, Dabakala, Mankono, Séguéla, Ferkéssédougou
Zone R4	Sudanese zone	Boundiali, Odienné
Zone R5	Mountain's zone climate	Man, Toulepleu, Guiglo

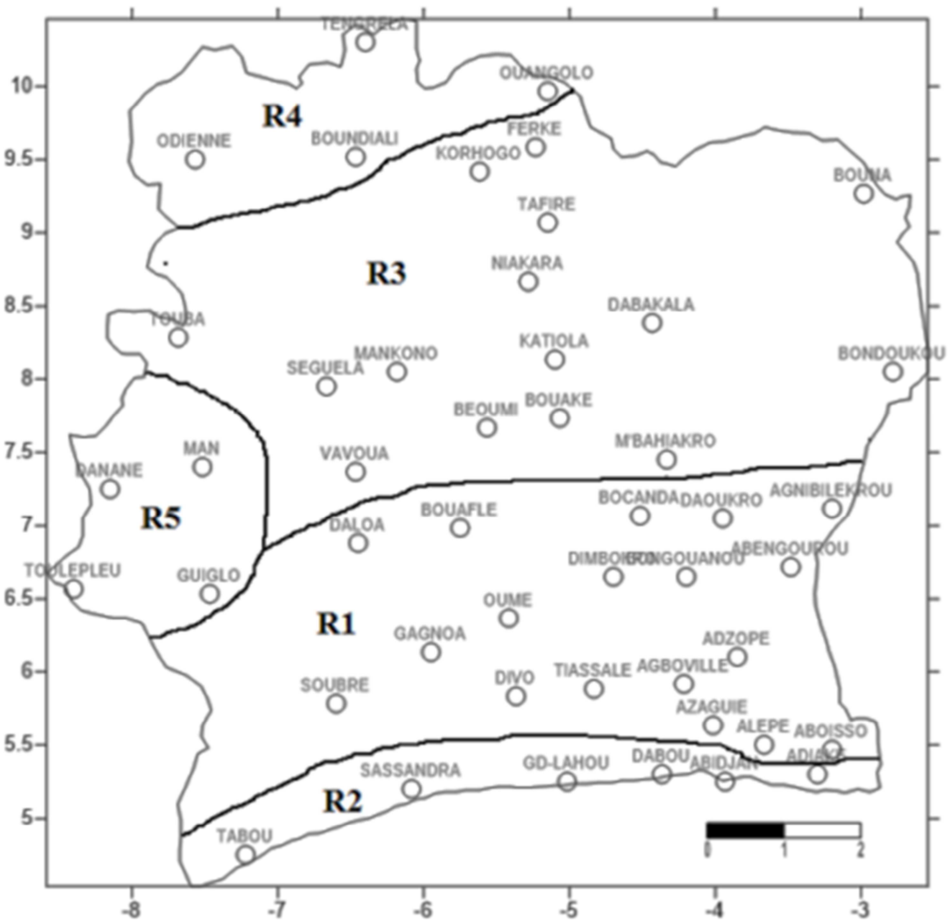


Figure 2. *Ivory Coast Main climatic zones [15].*

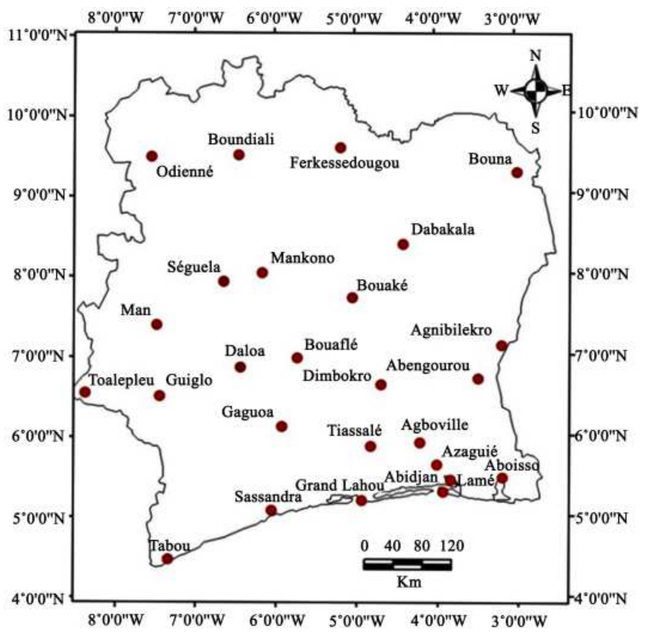


Figure 3. *Location of selected rainfall stations.*

The various data have undergone preprocessing. Indeed, the method of double cumulations and single residuals were applied to the data of extreme rainfall to identify any erroneous values. The regional vector method and linear regression made it possible to fill in the gaps and correct the values identified as erroneous.

The characteristics of the maximum daily rainfall are presented in Table 2. Maximum daily rains vary between 17 (Agboville) and 480 mm (Boundiali) with an average ranging from 73.61 (Agnibilékro) to 136.59 mm (Grand-Lahou). The values of the standard deviation of the different stations oscillate between 20.32 (Dimbokro) and 59.29 mm (Tabou) with an average of 38.02 mm. The values of the coefficient of variation are all greater than 25%. They vary from 26.76% (Dimbokro) to 58.52% (Boundiali). Thus, the heights of the annual maximum daily rainfall at the various stations are heterogeneous. These rainfall amounts are therefore dispersed in time and space.

As for the flattening coefficient, its values are all greater than zero with values ranging from 0.21 (Odienné) to 4.58 (Boundiali). This shows that the rainfall values of the different stations do not follow the law of normal distribution and have a less flat peak with thicker ends compared to the normal distribution. Asymmetry coefficients are generally positive. They are in proportion of 12% of negative values and 88% of positive values with values ranging from -0.56 (Mankono) to 30.47 (Boundiali); This reflects the fact that the distribution at the level of these data is spread to the right of their mean. As for the stations with negative values, the distribution of their data is spread to the left of their average.

Table 2. *Statistical characteristics of annual and extreme rainfall norms (1931-2020).*

Stations	Minimum	Average	Maximum	Standard deviation	CV (%)	Asymmetry coefficient	Kurtosis coefficient
Abengourou	29.82	83.45	234.5	37.13	44.49	1.77	3.99
Abidjan	38.6	136.44	311.6	45.95	33.67	0.8	1.58
Aboisso	42.9	132.77	327.1	55.68	41.94	1.04	1.17
Agboville	17	87.11	294.93	36.22	41.58	2.35	10.55
Agnibilékro	25.2	73.61	190.1	25.42	34.54	1.49	4.13
Azaguié	42	97.42	225.46	36.28	37.24	1.03	1.17
Bouaflé	31.08	80.22	223.2	30.87	38.48	1.77	5.16
Bouaké	24.43	74.4	196.68	29.23	39.29	1.35	3.19
Bouna	26.04	79.13	211.02	34.36	43.42	1.43	3.01
Dabakala	24.63	82.12	223.39	32.77	39.9	1.54	4.13
Boundiali	26.31	90.41	480	52.91	58.52	4.58	30.47
Daloa	28.2	86.12	193.5	32.22	37.41	1.22	1.92
Dimbokro	31.2	75.93	130	20.32	26.76	0.43	0.22
Ferkéssedougou	26.23	75.59	185.72	30.53	40.39	0.77	0.8
Gagnoa	37.5	81.57	246.9	30.96	37.95	2.5	9.96
Grand-Lahou	34.16	136.59	296	52.74	38.61	0.82	0.61
Guiglo	39.16	99.38	264.11	43.89	44.16	1.54	2.98
Lamé	39.97	125.4	293.88	44.65	35.6	1.34	2.6
Man	28.99	83.04	198.62	32.11	38.66	0.93	1.61
Mankono	30.93	83.01	157.3	32.67	39.35	0.47	-0.56
Sassandra	37	119.86	253	53.75	44.84	0.58	-0.37
Séguéla	27.16	78.68	230.94	35.52	45.15	1.21	2.77
Odienné	27.92	81.25	153.5	29.65	36.49	0.21	-0.48
Tiassalé	28.1	87.32	227.18	33.84	38.76	1.74	4.24
Tabou	38.25	136.48	345.7	59.29	43.44	0.43	0.57
Toulepleu	33.5	91.45	269.18	39.46	43.15	2.12	6.68
Maximum	29.82	83.45	234.5	37.13	44.49	1.77	3.99
Minimum	38.6	136.44	311.6	45.95	33.67	0.8	1.58
Mean	42.9	132.77	327.1	55.68	41.94	1.04	1.17

2.3. Design and Evaluation of the Markovian Model

2.3.1. Design of the Stochastic Model

Wilby et al. (2004) defined a stochastic weather generator or Weather Generator (WG) as a model that reproduces the statistical attributes (mean and variance) of a climatic variable considered at the local scale [17]. The output variable of this type of model is an artificial time series of very high temporal resolution meteorological data at the limit of computing resources. There are two types of stochastic generators. Richarson (1981, 1984) developed the “Richardson” type [8-9] or WGEN and the “serial” type or LARS-WG generated by Rasko et al. (1991), Semenov et al. (1998) [10, 18]. WGEN is characterized by the modeling of the considered variable using Markov chain which generally describes two states as dry or wet for precipitation. Modeling of the order 1 type of Markov chain considers the current state and the standby state of the variable considered. The generator used in this work is of the "Richardson" or WGEN (Weather Generator) type incorporated in the GoldSim Pro 12.1 software which gives practical ease. The main purpose of this stochastic model is to generate future rainfall data in the middle of the 21st century (2031-2060) and the end of the 21st century (2071-2100).

2.3.2. Precipitation Occurrence Model by Markov Chain

The daily rainfall data from the 26 stations in this study were used to simulate the sequences of occurrence of rainfall from the transition probability matrices derived from the Markov chains of order 1. The procedure followed for the generation of the rainfall is that recommended by Stern et al. (1984). It takes place in three (3) stages [19]:

1) Generation of data for fitting the Markov chain model;
2) Generation of transition probabilities;
3) Simulation of the rainfall series.

(i). Preparation of Rainfall Data

According to Dlamini et al. (2015) Markov chains make it possible to consider that the possibility of an event of given occurrence depends essentially on the state of the previous day (dry or wet) [20]. In this study, a Markov chain of order 1 with two (2) states to simulate the occurrence of rain. This model is characterized by four (4) possible situations respectively a dry day preceded by a dry day (ss), a dry day preceded by a rainy day (sh), a rainy day preceded by a dry day (hs) and a rainy day preceded by a rainy day (hh). Based on Konate (2018) study the preparation of rainfall data begins with the synthesis of the various information contained in the history data [21]. It involves counting these different eventualities as presented in Table 3.

Table 3. *Count of wet days and dry days in historical data during the study period (1931 to 2020).*

		Previous day (i)		
		Dry (d)	Wet (w)	Total
Current day (j)	Dry (d)	N_{dd}	N_{dw}	N_d
	Wet (w)	N_{wd}	N_{ww}	N_w

(ii). Generation of Transition Probabilities

The previous step is followed by the generation of the different transition probabilities resulting from the counts of the sequences of wet and dry days. These transition probabilities are distributed as follows [21]:

1) P-dd: probability of a dry day preceded by a dry day;
2) P-dw: probability of a dry day preceded by a wet day;
3) P-wd: probability of a wet day preceded by a dry day;
4) P-ww: probability of a wet day preceded by a wet day;
5) Pw: probability of a wet day.

The probabilities P-wd and P-ww are those which characterize rainy days. The probability Pw allows the estimation of the global probability, of first order of occurrence of the rains during a year. The average amount of rainfall per wet day is also estimated in this part. It allows the generation of rainfall data in the next step.

(iii). Simulation of Rainfall Amounts on Wet Days

Rainfall amounts are modeled after the generation of rainy states in terms of wet days (rainfall ≥ 1 mm). This simulation of rainfall amounts is done for the days that have been modeled as wet after fitting a probability distribution to the rainfall amounts of these rainy days. The probability distribution used for the fitting is the two (2) parameter gamma function represented by the relationship 1 [21].

$$P(x) = \left(\frac{k}{\mu}\right)^k x^{k-1} \frac{exp\left(\frac{kx}{\mu}\right)}{\Gamma(k)} \quad \mu > 0, k > 0, x > 0 \qquad (1)$$

The parameters μ and k are respectively the mean and the shape parameter. Γ(k) is the gamma function.

The parameters of the gamma function are estimated by the maximum likelihood method [21]. Obtaining probabilities adjusted to data from the Markov chain model makes it possible to obtain the average amount of rainfall per rainy day over the year. The average amount of rain per rainy day is estimated for wet days of the year, however, only one shape parameter is determined for the entire rainfall data coverage period. The rainfall threshold for days considered wet is 1 mm. Within the framework of this study, future data are estimated up to 2100. The modeling is carried out under the environment of the commercial software Goldsim Pro 12.1. The Markovian model will be calibrated over the period 1931-1990 (60 years) and validated over the period 1991-2020 (30 years).

2.3.3. Model Evaluation

The validation of the model is carried out by comparing the training values obtained and the observed values of the defined validation series. Numerical criteria and visual criteria (graphical representations) were used to judge the performance of the model.

To assess the predictive quality of the model developed in this study, the Nash-Sutcliffe criterion was used. For Kouassi (2007), Kouassi et al. (2012, 2018) this criterion is often used to best calibrate a hydrological model or assess its performance (22-24).

The Nash-Sutcliffe criterion is given by equation 2:

$$Nash = 100\left[1 - \frac{\sum_i (X_i - Y_i)^2}{\sum_i (X_i - \bar{X})^2}\right] \qquad (2)$$

Xi: observed values; Yi: simulated values and the mean of the observed values: $\bar{X}$

According to Kouassi et al. (2018) [24]:

1) Nash-Sutcliffe ≥ 90%: the model is excellent;
2) 80% ≤ Nash-Sutcliffe < 90%: the model is very satisfactory;
3) 60% ≤ Nash-Sutcliffe < 80%: the model is satisfactory;
4) Nash-Sutcliffe <60%: the model is bad.

2.3.4. Approaches to Correcting Markovian Model Outputs

To improve the climate models at the desired scales (from the regional scale to the local scale) and the accuracy (decrease in model biases), several correction approaches have been developed. The applicability of six daily and annual precipitation bias correction methods was tested in this study. These methods were chosen based on a review of the literature on their ability to significantly reduce data biases from statistical models. All the correction methods were calibrated over the period 1931-1990 (60 years) and validated over the period 1991-2020 (30 years).

The common method of correction known as disturbance (delta method) makes it possible to reduce the biases of the outputs of the climate models based on Wetterhall (2012) study. It is based on the application of a modification factor to the series of data simulated by climate models to make them more representative of the observed climate. This corrective factor is applied multiplicatively for the correction of the series. In the case of this study, we used the delta method (also called direct method) as formulated by [25].

$$P_{i,cor} = P_{i,sim} \times \frac{\overline{P_{obs}}}{\overline{P_{sim}}} \qquad (3)$$

and represent respectively the corrected and to be corrected (or simulated) value of the precipitation of day i, P_{obs} and P_{sim} designate the daily averages of precipitation observed for the calibration period and simulated by the Markov chains for the same period.

Lenderick et al. (2012) noticed that this method corrects the biases in the mean but not the coefficient of variation of the simulated values [26].

Other correction methods have been developed by some authors such as the scaling method which represents the delta method on a monthly scale. Also, we quote empirical quantile methods. Here, the basic assumption of a quantile-quantile fit is that model errors depend on the value of the simulated variable. Based on Gobiet (2015) this conception of the phenomenon of model uncertainty is a gross simplification of the characteristic errors of a model since model errors are not only influenced by the local value of the simulated variable [27]. Nevertheless, this simple principle is still powerful since it separates drizzles from heavy precipitation and is preferable for bias correction of complex regimes. Also, the application of quantile methods is much more flexible compared to previous methods which assume the stationarity.

Quantile methods consist of calculating quantile-by-quantile changes in the distribution functions of daily data. The empirical method uses the empirical distributions of the data series (precipitation, maximum and minimum) observed and simulated by the climate models to correct the biases of these projections, hence the name of the procedure. The classical formulation of this approach is given by:

$$y = F_{obs}^{-1}\left(F_{Sim}(x)\right). \quad (4)$$

Where x and y designate respectively the value to be corrected and the corrected value; F_{obs} and F_{sim} are respectively the distributions of values observed and simulated by the climate model. is the inverse of the distribution of observed values. Thus, in this formulation, the probability of observing at most x mm/day of rain in the series of the model is therefore assigned to the quantile of the distribution of observations. For N'Tcha (2018) this method can produce better bias corrections but depends on several degrees of freedom and may not be stationary due to extreme values [28]. The same authors have shown that such an empirical approach performs better in correcting extreme precipitation values than theoretical quantile methods. Gudmundsson et al. (2012) implementing several quantile methods on daily precipitation data, found that a non-parametric empirical approach is the most robust [29].

2.4. Analysis of Indicators of Past and Future Hydrological Standards

In this section, we will first focus on make descriptive statistics of past hydrological standards (annual rainfall normals, extreme rainfall normals) which consists in determining parameters such as the average, the minimum, the maximum, the coefficient of variation, the standard deviation, the coefficient of skewness and kurtosis coefficient. They allow to have an overall idea on the behavior of the series according to the size of the sample. Then, an analysis of the frequency distribution of extreme rainfall was made.

In addition, the normals (extreme and annual rainfall) of the homogeneous climatic zones of Ivory Cost (Mountain climate, Baoulean zone climate, Attiean Inside zone climate, littoral, and the Sudanese zone climate) were determined over the reference period (1931-2020).

Then, the future normals (extreme rainfall and annual rainfall) of the homogeneous climatic zones from the future periods (2031-2060; 2071-2100).

This final section of the study made it possible to evaluate future hydrological standards and to determine the biases between those calculated with the reference period of this study (1931-2020) and those of future periods (2031-2060 and 2071-2100).

The relative differences between the standards studied (annual rainfall normals, extreme rainfall normals) considering each time a standard as a reference value, were evaluated. For Kouassi et al. (2019) the relative deviations represent the difference between the standard considered and the reference standard [30]. The relative deviations are expressed as a percentage. The formulation of the relative deviations of the standards is as follows (Equation 5) [30]:

$$\Delta X_{i/réf} = 100 \times \frac{X_i - X_{réf}}{X_{réf}} \quad (5)$$

With:

- $\Delta X_{i/r?f}$: absolute relative deviation;
- X_i : standard of period i;
- $X_{r?f}$: reference standard;

-i: period (year).

3. Results and Discussion

3.1. Results

3.1.1. Evaluation of the Markovian Model

Tables 4 and 5 highlight the results of the numerical criteria used to evaluate the performance of the Markovian model designed for maximum daily rainfall and annual rainfall in homogeneous climatic zones.

Regarding the annual maximum daily rainfall, it is found that the Nash-Stucliffe values range between 94.56% (Attiean Inside zone) and 97.36% (Sudanese zone), while the Markovian model at the annual scale was very conclusive with very satisfactory performances ranging from 97.15% (Baoulean zone) to 98.83% (Mountain's zone). These values are all greater than 60% and are very close to 100%, thus reflecting a good match between the observed values and the simulated values. In other words, the observed values and the model are consistent. These very satisfactory results make it possible to certify the performance of the designed model.

Table 4. *Performance in the validation phase of the Markovian model for maximum daily rainfall.*

Stations	Nash–Stucliffe (%)
Mountain's zone	95.43
Baoulean zone	96.1
Attiean Inside zone	94.56
Attiean Littoral zone	97.04
Sudanese zone	97.36

Table 5. *Performance in the validation phase of the Markovian model for annual rainfall.*

Stations	Nash–Stucliffe (%)
Mountain's zone	98.83
Baoulean zone	97.15
Attiean Inside zone	98.17
Attiean Littoral zone	98.07
Sudanese zone	98.63

Figures 4 to 7 highlight the comparison of annual and maximum daily rainfall as well as observed and simulated annual rainfall over the validation period (1991-2020). Indeed, the observed and simulated values are less dispersed around the line Y = X. The points of the graph are very close to the line. This result reflects the fact that the model tends to faithfully represent the observed values. Nevertheless, it is noted that for the climatic regime of the Attiean Littoral zone, part of the simulated rainfall values is underestimated by the model. This observation can be explained by the fact that the area is very wet, thus giving relatively high observed values (up to 164.3 mm as annual maximum daily rainfall).

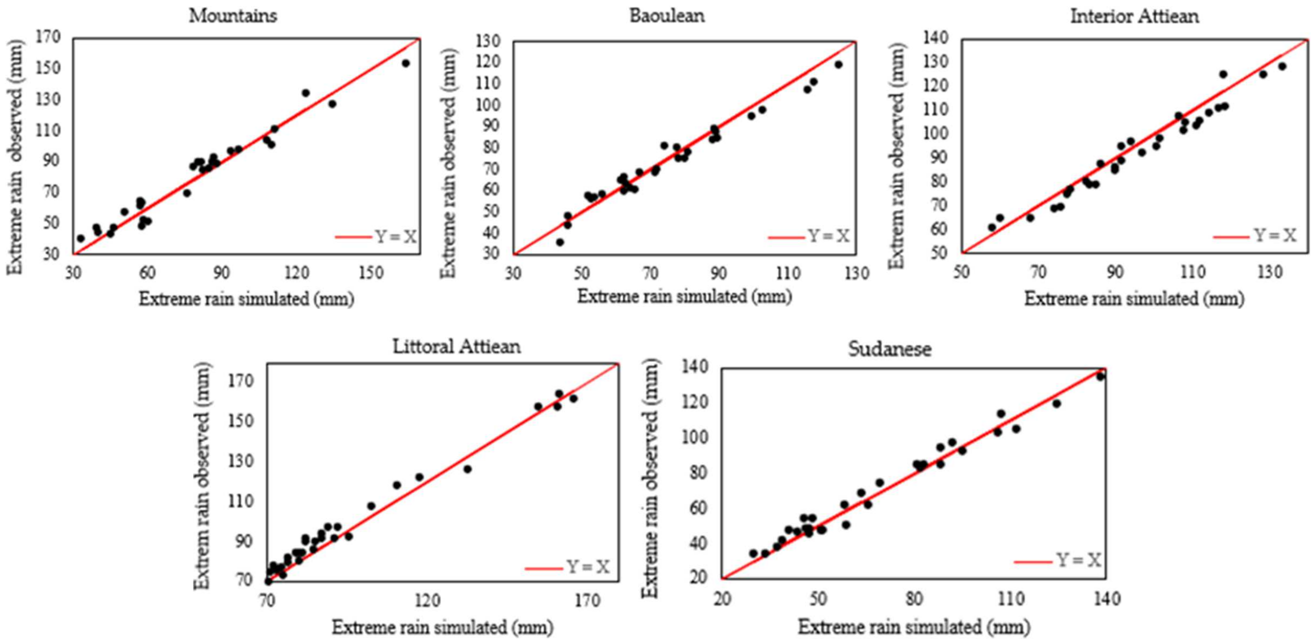


Figure 4. *Observed and simulated maximum daily rainfall in the different climatic regions of Ivory Cost.*

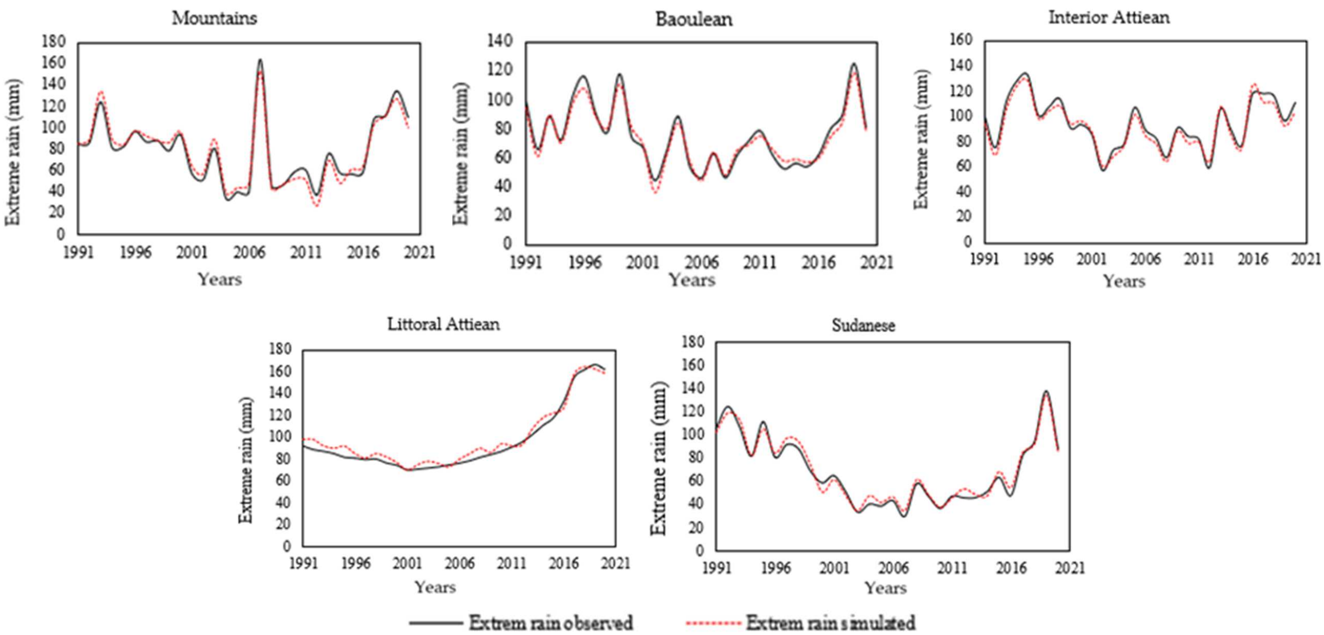
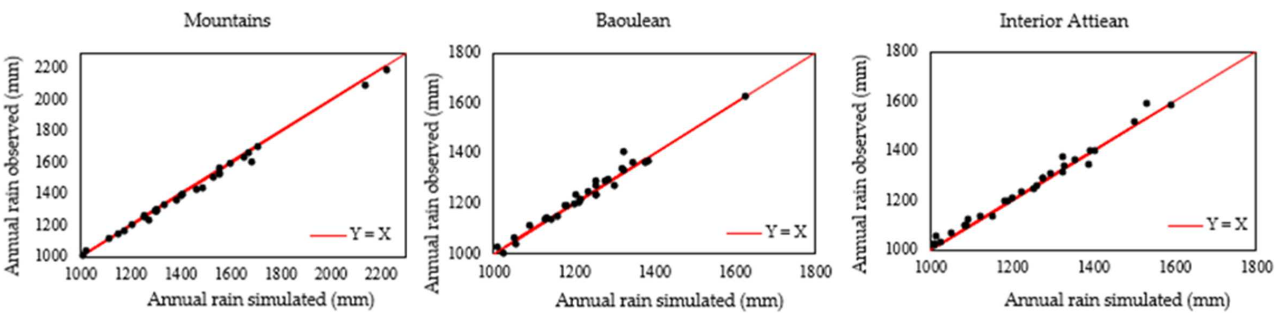


Figure 5. *Curves of maximum daily rainfall observed and simulated in the different climatic regions of Ivory Cost.*



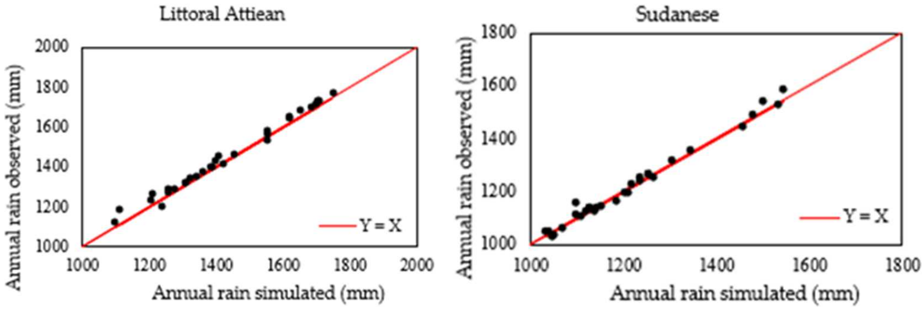


Figure 6. *Annual rainfall observed and simulated in the different climatic regions of Ivory Coast.*

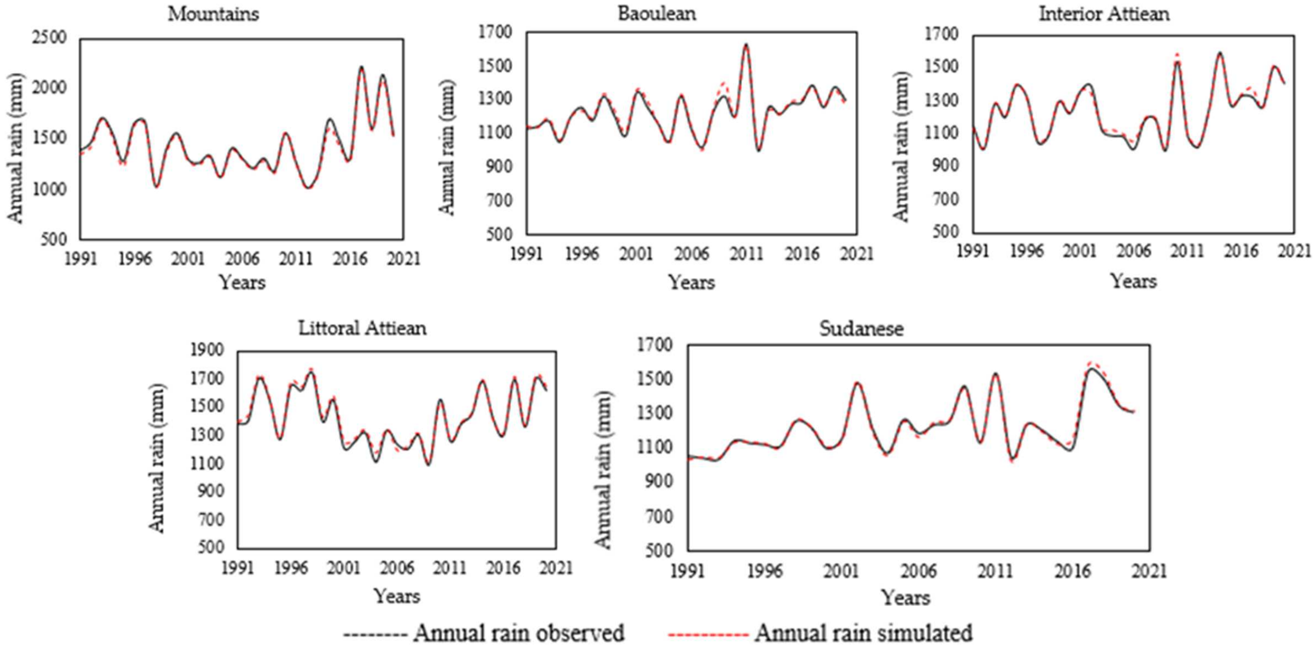


Figure 7. *Curves of annual rainfall observed and simulated at the level of the different climatic regions of Ivory Coast.*

In view of the observations made, the visual criteria allow us to verify the conclusions envisaged from the numerical performance indicators.

We can therefore conclude that the model is efficient and can reasonably simulate the extreme rainfall of the periods 2031-2060 and 2071-2100. Nevertheless, correction methods were applied considering the differences observed between the observed and simulated values for the 1991-2020 validation period.

3.1.2. Analysis of Predicted Extreme Rainfall Normals

The predicted daily rainfall amounts vary between 52.95 mm (Baoulean zone) and 244.10 mm (Attiean Littoral zone) with averages ranging from 69.41 mm (Baoulean zone) to 160.78 mm (Attiean Littoral zone) for the period 2031-2060. The values of the standard deviations oscillate between 18.74 mm (Sudanese zone) and 39.18 mm (Attiean Littoral zone). As for the coefficient of variation (CV) of the data from the different regions, it is less than 25% for all the zones. This reflects the homogeneity of the values at the level of the zones and a low dispersion of the annual maximum daily rainfall forecast for the period 2031-2060. For the period 2071-2100, the heights of simulated extreme rainfall vary between 44.46 mm (Baoulean zone) and 222.9 mm (Attiean Littoral zone) with averages ranging from 70.85 mm (Baoulean zone) and 222.9 mm (Attiean Littoral zone) and deviations -types of 14.21 mm (Baoulean zone) and 43.41 mm (Attiean Littoral zone). The coefficients of variation of this series range from 20.05% (Baoulean zone) to 30.80% (Attiean Littoral zone). This last coefficient being higher than 25%, it can be concluded that the heights of extreme rains will know a dispersion in time during the period 2071-2100 in the Attiean Littoral zone. 05% (Baoulean zone) to 30.80% (Attiean Littoral zone). This last coefficient being higher than 25%, it can be concluded that the amounts of extreme rains will know a dispersion in time during the period 2071-2100 in the Attiean of the coast. 05% (Baoulean zone) to 30.80% (Attiean Littoral zone). This last coefficient being higher than 25%, it can be concluded that the heights of extreme rains will know a dispersion in time during the period 2071-2100 in the Attiean Littoral zone.

Table 6 highlights the different biases between the past annual maximum daily rainfall (1931-2020) and that of the middle of the 21st century (2031-2060) and that of the end of the 21st century (2071-2100). These bias values for the period 2031-2060 vary from -16.56% (Attiean of the Inside) to +36.74% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -34.13% (Mountain's zone) and +37.89% (Attiéen du littoral). These biases are significant and reflect an increase in extreme rainfall to come. The years 2031-2060 will then experience an increase in extreme daily rainfall in the areas of Attiean Littoral zone, Sudanese zone from the middle of the 21st century (2031-2060) to the end of the 21st century (2071-2100).

Table 6. *Extreme rainfall bias for the periods 2031-2060 and 2071-2100.*

Stations	Bias (2031-2060 / 1931-2020)	Bias (2071-2100 / 1931-2020)
Attiean Littoral zone	+36.74%	+37.89%
Attiean Inside zone	-16.56%	-14.83%
Sudanese zone	+39.18%	+22.02%
Mountain's zone	-16.03%	-24.13%
Baoulean zone	+7.24%	+5.12%

3.1.3. Analysis of Forecasted Annual Rainfall Normals

The predicted annual rainfalls vary between 1,003 mm (Sudanese zone) and 1,155.84 mm (Attiean of the coast) with averages ranging from 1240.51 mm (Sudanese zone) to 1630.21 mm (Mountain's zone) for the period 2031-2060. The values of the standard deviations oscillate between 196.64 mm (Baoulean zone) and 259.33 mm (Mountain's zone). As for the coefficient of variation (CV) of the annual rains of the different regions, it is less than 25% for all the zones (varying between 15.87% for Attiean Littoral zone and 17.51% for Attiean Inside zone). This reflects a good homogeneity of the values at the level of the zones and a low dispersion of the annual maximum daily rainfall forecast for the period 2031-2060. For the period 2071-2100, the simulated annual rainfall amounts vary between 1,007 mm (Attiean Inside zone) and 2,179.66 mm (Attiean Littoral zone) with averages ranging from 1,214.07 mm (Baoulean zone) to 1,570.35 mm (Attiean Littoral zone) and standard deviations from 161.58 mm (Baoulean zone) to 275.48 mm (Attiean Littoral zone). The coefficients of variation of this series range from 13.31% (Baoulean zone) to 17.54% (Attiean Littoral zone). These coefficients being less than 25%, therefore the heights of extreme rainfall will experience a homogeneous distribution over time during the period 2071-2100. Table 7 highlights the different biases between past annual rainfall 1931-2020 and that of the middle of the 21st century (2031-2060) and that of the end of the 21st century (2071-2100). These bias values for the period 2031-2060 vary from -10.72% (Attiean Inside zone) to +1.22% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -12.08% (Attiean Inside zone) and -0.24% (Attiean of the coast). The years 2031-2060 will then experience a drop in annual rainfall except for the Attiean area of the coast which will record a slight increase in annual rainfall, while in the period 2071-2100, there will be a more pronounced drop in these annual rainfall over the entire Ivorian territory. These bias values for the period 2031-2060 vary from -10.72% (Attiean Inside zone) to +1.22% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -12.08% (Attiean of the Inside) and -0.24% (Attiean of the coast). The years 2031-2060 will then experience a drop in annual rainfall except for Attiean Littoral zone which will record a slight increase in annual rainfall, while in the period 2071-2100, there will be a more pronounced drop in these annual rainfall over the entire Ivorian territory. These bias values for the period 2031-2060 vary from -10.72% (Attiean Inside zone) to +1.22% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -12.08% (Attiean Inside zone) and -0.24% (Attiean Littoral zone). The years 2031-2060 will then experience a drop in annual rainfall except for the Attiean area of the coast which will record a slight increase in annual rainfall, while in the period 2071-2100, there will be a more pronounced drop in these annual rainfall over the entire Ivorian territory.

Table 7. *Annual rainfall bias for the periods 2031-2060 and 2071-2100.*

Stations	Bias (2031-2060 / 1931-2020)	Bias (2071-2100 / 1931-2020)
Attiean Littoral zone	+1.22%	-0.24%
Attiean Inside zone	-10.72%	-12.08%
Sudanese zone	-4.45%	-7.52%
Mountain's zone	-5.60%	-9.44%
Baoulean zone	-7.39%	-8.20%

3.2. Discussions

The Markovian model for the simulation of the annual maximum daily rainfall gives Nash-Stucliffe coefficients oscillating between 94.56% (Attiean Inside) and 97.36% (Sudanese zone), while the Markovian model at the annual scale was very concluding with very satisfactory performance ranging from 97.15% (Baoulean zone) to 98.83% (Mountain's zone). These values thus reflect the great capacity of the model to simulate rainfall. The Markovian model therefore made it possible to simulate the daily rainfall for the future periods 2031-2060 and 2071-2100.

In this study, the Markov chain model was decisive. Its use only required the adjustment of historical data unlike other studies which are based on climate scenarios, sometimes requiring a downscaling on the region of interest. Markov chains have long been used to generate many time series of meteorological data, although the difficulty lies in the choice of order [21]. The choice of order for this study is based on previous studies. Considering the dependence inside the time series leads to the use in most cases, of Markov chains of order 1, for modeling as recommended by Shukla et al. (1984) [31]. So, a wide variety of simulation models of several authors as Mearns et al. (1984). have produced data, from Markov chains, for the study and prevention of certain hydroclimatic natural disasters. Some authors used long synthetic weather series of temperatures to examine the impact of severe droughts on crop behavior in the central United States [32], while some authors as Favis-Morlock et al. (1997) study the long-term rates of soil erosion in the UK and find a significant impact [33]. Moreover, numerous studies have demonstrated that the Markov chain model is in general suitable for synthetic precipitation time series. One work carried out in Malaysia on rainfall data in relation to rice production, supports the use of Markov chains for the simulation of future rainfall data [20]. Indeed, the WGEN stochastic meteorological generator model, based on Markov Chains, showed that order 1 better described the characteristics of rainfall, after comparing statistical parameters, simulated rainfall, and historical rainfall over the same years of coverage.

In the same ideas order, in Israel, Gabriel et al. (1962) has been noted, that the occurrences of daily precipitation in the city of Tel Aviv in Israel, successfully fit the model of Markov chains of order 1 [34]. In addition, some research as Kottegoda et al. (2004) study reported that the first-order Markov chain model was the best fit to historical rainfall data in Italy [35]. In Africa, in Nigeria, forecasting studies on rainfall and its impact on agricultural production have been carried out from Markov chains of order 1 by Abubakar et al. (2014) [36]. These authors indicated a downward trend in rainfall in the Minna region. The Markov Chains model is mainly based on the assumption that there is a dependence between the occurrence of daily rains to those of the day before. The most interesting features of Markov chain models relate to their ability to readily identify seasonality in daily precipitation [19]. In most cases, the first-order Markov chain model can describe the daily occurrence of precipitation. The maximum daily rainfall amounts recorded during the period 1931-2020 vary between 29.83 (Sudanese zone region) and 230.45 mm (Mountain's region) with averages ranging from 81.59 mm to 115.52 mm. The extreme rainfall forecast varies between 52.95 mm (Baoulean zone) and 244.10 mm (Attiéen du littoral) with averages ranging from 69.41 mm (Baoulean zone) to 160.78 mm (Attiéen du littoral) for the period 2031-2060. For the period 2071-2100, the heights of simulated extreme rainfall vary between 44.46 mm (Baoulean zone) and 222.9 mm (Attiéen du littoral) with averages ranging from 70.85 mm (Baoulean zone) and 222.9 mm (Attiéen du littoral). The biases between the past annual maximum daily rainfall 1931-2020 and those in the middle 21st century (2031-2060) vary from -16.56% (Attiean Inside zone) to +36.74% (Attiean Littoral zone). Those from the end of 21st century (2071-2100) fluctuates between -34.13% (Mountain's zone) and +37.89% (Attiean Littoral zone). These biases are significant and reflect an increase in extreme rainfall to come. The years 2031-2060 will then see an increase in extreme daily rainfall in Attiean Littoral zone areas, Sudanese zone in the middle of the 21st century (2031-2060) at the end of 21st century (2071-2100), while decreases in extreme rainfall will be recorded at the level of the Attiean of the Inside and the mountain range.

Past annual rainfall amounts (1931-2020) vary between 1,022.75 mm (Baoulean zone) and 2,058.28 mm (Mountain's zone) with averages ranging from 1,339.51 mm (Sudanese zone) to 1,698.11 mm (Attiéen du littoral). The predicted rainfall amounts vary between 1,003 mm (Sudanese zone) and 1,155.84 mm (Attiean Littoral zone) with averages ranging from 1,240.51 mm (Sudanese zone) to 1,630.21 mm (Mountain's zone) for the period 2031-2060. For the period 2071-2100, the simulated annual rainfall amounts vary between 1,007 mm (Attiean of the Inside) and 2,179.66 mm (Attiean Littoral zone) with averages ranging from 1,214.07 mm (Baoulean zone) to 1,570.35 mm (Attiean Littoral zone). The different biases between the past annual rains 1931-2020 and those of the middle of the 21st century (2031-2060) and those of the end of the 21st century (2071-2100) vary from -10.72% (Attiean Inside zone) to +1.22% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -12.08% (Attiean Inside zone) and -0.24% (Attiean Littoral zone). The years 2031-2060 will then experience a drop in annual rainfall except for Attiean Littoral zone area which will record a slight increase in annual rainfall, while in the period 2071-2100, there will be a more pronounced drop in these annual rainfall over the entire Ivorian territory.

Through a study of precipitation projections in five West African countries (Gambia, Mali, Sierra Leone, Chad, and Togo), the authors show that the projections resulting from regional climate modeling experiments and are highly variable, and often show no consensus as to the direction, let alone the magnitude, of potential changes in precipitation. Among the set of results from the global models described in the IPCC AR5 (2009), significant increases and decreases are expected for much of the region. This is also the case for regional climate model projections in some areas of the five project countries, although in other areas there is also consensus on increases or decreases in precipitation [37].

Some data have been simulated by Danumah (2016), for the District of Abidjan, from the LARS-WG model, rainfall data spanning from 2011 to 2100 [38]. These generated data highlight an increase in rainfall from 4% to 10% and an upward trend in extreme rainfall indices such as consecutive wet days and rains greater than 10 mm, which could increase the number of floods. However, another author Oga et al. (2016) predict, using the same LARS-WG climate model, a drop in rainfall by 2050 in the Ivorian coastal zone in the south-east of Ivory Coast [39]. Rainfall projections for forecasting have also been studied in Africa. In this sense, Bayoko et al. (2003) from the MAGICC-SENGEN model, would indicate a decrease in rainfall during the years 2025 to 2100 in Mali [40]. Besides, some research coming from Chen et al. (2012) notes a decrease in rainfall in Sudan but an increasing trend for South Sudan from the LARS-WG model, by 2100, which will have a negative impact respectively on agricultural production (risk of famine) and on the environment (floods, landslides) [41]. In the United States, in the State of Texas, the Headlines de Brazos basin will experience large decreases in precipitation of up to 5.2% and 6.8% in the years 2055 and 2090, respectively according to simulation data of the LARS-WG model obtained by Awal et al. (2016) [42]. While in Brazil, Favis-Mortlock et al. (1999) notes an increase in rainfall in future years, after using the same model. This increase will result in significant erosion and an impact on agriculture in these regions [43].

4. Conclusion

This study was devoted to simulating annual and maximum daily rainfall using Markov Chain Model, more precisely in Ivory Coast. Regarding the annual maximum daily rainfall, it is found that the Nash-Stucliffe values range between 94.56% (Attiean Inside zone) and 97.36% (Sudanese zone), while the Markovian model at the annual scale was very conclusive with very satisfactory performances ranging from 97.15% (Baoulean zone) to 98.83% (Mountain's zone). These values are all greater than 60% and are very close to 100%, thus reflecting a good match between the observed values and the simulated values. These very satisfactory results make it possible to certify the performance of the designed model.

The predicted daily extreme rainfall amounts vary between 52.95 mm (Baoulean zone) and 244.10 mm (Attiean Littoral zone) with averages ranging from 69.41 mm (Baoulean zone) to 160.78 mm (Attiean Littoral zone) for the period 2031-2060. For the period 2071-2100, the heights of simulated extreme rainfall vary between 44.46 mm (Baoulean zone) and 222.9 mm (Attiean Littoral zone) with averages ranging from 70.85 mm (Baoulean zone) and 222.9 mm (Attiean Littoral zone).

The different biases between the past annual maximum daily rainfall (1931-2020) and that of the middle of the 21st century (2031-2060) and that of the end of the 21st century (2071-2100) have been calculated. These bias values for the period 2031-2060 vary from -16.56% (Attiean Inside zone) to +36.74% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -34.13% (Mountain's zone) and +37.89% (Attiean Littoral zone). These biases are significant and reflect an increase in extreme rainfall to come. The years 2031-2060 will then experience an increase in extreme daily rainfall in the areas of Attiean Littoral zone, Sudanese zone from the middle of the 21st century (2031-2060) to the end of the 21st century (2071-2100).

The forecasted annual rainfall heights range between 1,003 mm (Sudanese zone) and 1,155.84 mm (Attiean of the coast) with averages ranging from 1,240.51 mm (Sudanese zone) to 1,630.21 mm (Mountain's zone) for the period 2031-2060. The values of the standard deviations oscillate between 196.64 mm (Baoulean zone) and 259.33 mm (Mountain's zone). For the period 2071-2100, the simulated annual rainfall amounts vary between 1,007 mm (Attiean Inside zone) and 2,179.66 mm (Attiean Littoral zone) with averages ranging from 1,214.07 mm (Baoulean zone) to 1,570.35 mm (Attiean Littoral zone).

These bias values for the period 2031-2060 vary from -10.72% (Attiean Inside zone) to +1.22% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -12.08% (Attiean Inside zone) and -0.24% (Attiean Littoral zone). The years 2031-2060 will then experience a drop in annual rainfall except for Attiean Littoral zone which will record a slight increase in annual rainfall, while in the period 2071-2100, there will be a more pronounced drop in these annual rainfall over the entire Ivorian territory. These bias values for the period 2031-2060 vary from -10.72% (Attiean Inside zone) to +1.22% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -12.08% (Attiean Inside zone) and -0.24% (Attiean Littoral zone). The years 2031-2060 will then experience a drop in annual rainfall except for Attiean Littoral zone which will record a slight increase in annual rainfall, while in the period 2071-2100, there will be a more pronounced drop in these annual rainfall over the entire Ivorian territory. These bias values for the period 2031-2060 vary from -10.72% (Attiean Inside zone) to +1.22% (Attiean Littoral zone). Those of the period 2071-2100 fluctuate between -12.08% (Attiean Inside zone) and -0.24% (Attiean Littoral zone). The years 2031-2060 will then experience a drop in annual rainfall except for the Attiean Littoral zone area which will record a slight increase in annual rainfall, while in the period 2071-2100, there will be a more pronounced drop in these annual rainfall over the entire Ivorian territory.

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