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Study of the Probabilistic Decadal Rainfall Regimes in the Agro-Pastoral Zone of Cotton Production

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Abstract - *The study of probabilistic regimes of decadal rainfall in Banikoara commune revealed the existence of stochastic dependence, which was analyzed on the basis of Markov chains applied to two sub-periods (1971-1990) compared to (1991-2010). The results revealed (i) low rainfall variability characterized by a 5% increase in rainfall heights from the first sub-period to the second, a weak distribution of rainfall heights in the two sub-periods, and a lengthening of the wet period by 6 more decades from 1921 to 1973, (ii) the marginal probability of dry decades (58%) is higher than the marginal probability of wet decades (42%) for both sub-periods, leading to a succession of dry states from the first sub-period to the second, without lengthening the dry period; (iii) the drought is recurrent for two or even three decades in a row (93%); the probability of having one wet decade after another wet decade and the probability of having a wet decade after two successive wet decades are high, i.e. 95%; the probability of transition from one dry to another wet decade (6%) and the probability of the opposite transition (4%) are both low. In addition, there is a lengthening of the wet period, a weak distribution of rainfall heights and an alternation of deficit, average and surplus years that are modified by the annual rainfall regime. This expression of climate change is not without consequences on agricultural activities in agro-pastoral zones, particularly on agricultural calendars, sowing periods and therefore on agricultural yields. Thus, it is important to conduct research in relation to the integration of climate change adaptation measures and to develop new agricultural calendars for the use of farmers so that optimal sowing periods for the crops being developed can be determined.*

Keywords - *Probabilistic regimes, Decadal rains, Markov chain, Dry decades, Agro-pastoral zone.*

I. INTRODUCTION

Global climate change is reflected locally in several changes that modify production conditions. These include shifts in climatic calendars (notably delayed arrival of rainfall); changes in the amount of water received annually, with, in many regions, more pronounced and/or more frequent periods of drought; increased frequency of paroxysmal phenomena and abnormal events (cyclones, frosts, abnormally high temperatures); and finally, and everywhere, very high temporal and spatial variability at the local level ([1]). These extreme weather and climate conditions often considerably compromise sustainable agricultural development ([2]), and their impact is all the greater as farmers are also subject to other changes in their environment: degradation of fertility; deforestation and erosion of biodiversity; integration into the market economy and liberalization, with its demands for competitiveness; disadvantaged position in terms of access to resources (water, land in particular), but also financing problems.

In Africa, climate change represents a major threat to growth and sustainable development, as well as to the achievement of the Millennium Development Goals (MDGs) ([3]). The high temporal, spatial and quantitative variability of rainfall makes agricultural production systems vulnerable and constitutes a major constraint to the objectives of food self-sufficiency that West African countries have set ([4]). Benin, a West African country, is not spared from this phenomenon.

The present study is part of this context. The aim is to diagnose the probabilistic rainfall regime in order to identify periods of absence or scarcity of rainfall (drought) in the commune of Banikoara.

II. MATERIALS AND METHODS

A. Study area

The municipality of Banikoara is located in the northwestern part of the department of Alibori. It covers an area of 4,383 square kilometres, of which 2,148 square kilometres (49%) are cultivable land, and 2,235 square kilometres are occupied by the W Park. It is located between 10°50' and 11°30' north latitude and between 2° and 2°40' east longitude. It is bordered to the North by the Municipality of Karimama, to the South by the Municipalities of Gogounou and Kèrou, to the East by the Municipality of Kandi and to the West by the Republic of Burkina Faso. Banikoara is composed of ten (10) districts (Founougo, Goumori, Gomparou, Kokey, Kokiborou, Ounet, Sompérékou, Soroko, and Toura) and sixty-nine (69) villages and city districts.

The climate is of the Sudanian type, evolving towards the Sahelian type with a single rainy season from May to October and a dry season from November to April. This distribution of rainfall is not static; it varies in the number of days that the different seasons begin overtime. According to data from ([5]), the average annual rainfall varies between 792.184 mm to 1188.276 mm. As for the temperature, the annual average of minima varies between 19.77°C and 22.6°C and those of maxima between 33.35° and 35.85° ([3]). The Commune of Bankoara benefits from the tributaries of the Niger River, namely the Mékrou (410 km) to the northwest and the Alibori (338) to the southeast.

The commune enjoys a dry season from November to April and a single rainy season from May to October, the maximum intensity of which is generally in August. The average rainfall varies between 1000 and 1200mm.

B. Data collection and processing methods

For this study, we based ourselves only on factors of a purely climatic nature: rainfall and potential evapotranspiration. Thus, the rainfall and PTE data for the study area were collected from ASECNA. The study covered the period from 1971 to 2010, a period of 40 years. This period was subdivided into two sub-periods of 20 years each as follows: from 1971 to 1990 and from 1991 to 2010. The rainfall data for the study area was calculated by decade for each sub-period using Excel 2007 software.

C. Analysis method

We analyzed the occurrence of rainfall, which is governed by the Markov chain, and the rainfall height, which follows a gamma distribution, to characterize the probabilistic rainfall regime ([9]). The Minitab version 14 software was used for the different analyses. The analysis methodology used is presented in two steps.

Step 1: Analysis of rainfall occurrence

After calculating the rainfall per decade for each sub-period, we identified the dry and wet decades. The threshold of rainfall height to pass from a dry decade to a wet decade used in this study is that proposed by ([4]) (ho = 3.4 mm). Without going into the definition of the theory of Markov chains, well detailed in ([6], [10]), we thought it useful to give some definition for the clarity of our work. Thus, the basic Markov model corresponds to a simple state graph with a probabilistic transition function. At each time step, the model undergoes a transition that will potentially modify its state. This transition thus allows the modelled system to evolve according to a law known in advance. Nevertheless, this transition law is probabilistic. Indeed, the evolution of the system can be uncertain or simply not well known. This probabilistic function allows us to simply express the evolution law of the model in the form of a probability matrix. This opens the door to a very large number of uses where the evolution of a system is only known through statistics.

A process $\{X(t), t \in [0, T]\}$ forms a Markov chain if for $t \in [0,T]=0,1,2, \dots$ and for all possible values of the random variable X(t), we have :

$$\Pr\left\{\begin{matrix} X(t) = j/X(0) = i_0, X(1) = i_1, \dots, \\ X(t-1) = i_{t-1} \end{matrix}\right\} = \Pr\{X(t) = j/X(t-1) = i_{t-1}\}$$

where: t: time; Pr: probability; X(t): random variable.

If the realization of each draw depends on the realization of r previous draws and these only, then we say that the associated random variable forms a Markov chain of order r ($0 \le r \le T$). Thus the previous equation becomes:

$$\Pr\{X(t) = j \,/\, X(0) = i\_0, X(1) = i\_1, \dots\dots, X(t-1) = i\_(t-1)\} = \Pr\{X(t) = j \,/\, (X(t-r) = i\_(t-r), \dots, X(t-1) = i\_(t-1))\}$$

In the case where the draws are independent for any time $t \in [0, T]$ and for all possible values of the random variable$\{X(t), t \in [0, T]\}$, we have:

$$\Pr\{X(t) = i/X(0) = j_0, X(1) = j_1, \dots\dots, X(t-1) = j_{t-1}\}$$

with i, the realization of the draw at time t

The independent draw thus considered is assimilated to a Markov chain of order 0.

A Markov chain of order 1 is characterized by a marginal probability distribution $\Pr\{X(t_0) \le x\} = P_0(x)$ and the conditional probabilities $\Pr\{X(t) = j/X(t-1) = i\}$ Also called transition probability.

When the transition probability is independent of time, we speak of a homogeneous Markov chain, and for the Markov chain of order 1, for example, we have:

$\Pr\{X(t) = j/X(t-1) = i\} = \alpha_{ij}$, with α_{ij}, the transition probability from state i to state j.

Several random variables naturally enter into the description of rainfall events over time: (i) a first random variable is the one that counts the number of rain events within various time intervals; (ii) a second random variable is the one that describes the transition from a state Ei to a state Ej; (iii) a third variable is the one that associates a certain amount of rain (height, volume,) with rain events.

The Markov chain model is a stochastic, iterative model. Thus, the state of the decade t depends only on the state of the decade t-1 for the first-order Markov process and depends on the states t-1 and t-2 for the second-order Markov process ([11]). The stochastic matrix of first-order transition probabilities is represented by the table below ([4]):

TABLE I. Matrix of probabilities of first-order transitions

		Decade t	
		0	1
Decade t-1	0	α_{00}	α_{01}
	1	α_{10}	α_{11}

with $\alpha_{ij} > 0$ et $\sum \alpha_{ij} = 1$

The state pair count method was used to characterize the decades. Thus, Table 2 summarizes the state pairs where N_{01} and N_{10} represent the number of decades of transition from dry to wet and from wet to dry, respectively. The same reasoning leads to the count of possible states and the transition probability matrix for the homogeneous Markov chain of order 2 ([6]). Table 2 gives the distribution of the number of possible states and the transition probabilities. The real β_{ijk} represent the probability of having an (i, k) doublet succeeding an (i, j) doublet; with the properties:

$$\beta_{ijk} = \frac{N_{ijk}}{N_{ij}} \quad \text{and} \quad \sum_K \beta_{ijk} = 1.$$

TABLE II. A number of possible states and second-order Markov transition probability.

		Decade t-1 and t				
		00	01	10	11	
Decade t-2 and t-1	00	β_{000}	β_{001}	0	0	
	01	0	0	β_{010}	β_{011}	
	10	β_{100}		β_{101}	0	0
	11	0		0	β_{110}	β_{111}

After some algebraic calculations, it follows from ([10]) that the expected value (mean or first moment) of dry spells is: $m_1 (d_0) = 1 / (1 - \beta_{00})$.

Other parameters of dry spells (second moment, standard deviation and coefficient of variation): $m_2 (d_0) = (1 + \beta_{00}) / (1 - \beta_{00})^2$, $\sigma (d_0) = [\beta_{00} / (1 - \beta_{00})^2]^{1/2}$; $Cv (d_0) = (\beta_{00})^{1/2}$

The cumulative distribution function (CDF), $\Pr \{d_0 < n\} = 1 - (\beta_{00})^n$.

The same calculations were performed for the rainy season. They led to similar results by replacing the dry period indices with those characterizing the rainy season.

The parameters to be analyzed in this phase are (a) the probability of transition from one wet dekad to the next wet dekad P(H/H); (b) the probability of transition from one wet dekad to the next dry dekad P(S/H); (c) the probability of transition from one dry dekad to the next wet dekad P(H/S); (d) the probability of transition from one dry dekad to the next dry dekad P(S/S); (e) the marginal probability of dry dekads P(S) ; (f) the marginal probability of wet decades P(H); (g) the transition probability from two dry decades to the third dry decade P(S/SS); (h) the transition probability from two wet decades to the third wet decade P(H/HH); (i) the transition probability from two wet decades to the third dry decade P(S/HH); (j) the transition probability from two dry decades to the third wet decade P(H/SS).

Step 2: Rainfall analysis

To establish the distribution of decadal rainfall by period, all decadal rainfall heights were grouped into rainfall classes of 4 mm amplitude and histograms were constructed with the centres of rainfall classes as abscissa. The established distributions were fitted to the Gamma distribution ([9]), which is characterized by a high degree of flexibility in that it can be fitted to different forms of distribution ranging from highly asymmetric to symmetric like the normal distribution ([13]). Its probability density function is:

$f(x, \alpha, \beta) = \frac{1}{\beta^{\alpha}\, \gamma(\alpha)} x^{\alpha-1} e^{\frac{-\alpha}{\beta}}$ With α = shape parameter and β = scale parameter related to the observed distribution.

The decadal rainfall height data were used to estimate the parameters α and β using the maximum likelihood method ([12]). The decadal rainfall amounts also allowed us to plot the evolution of annual rainfall amounts in the commune of Banikoara and the annual cumulative rainfall during the period 1971-2010.

III . RESULTS AND DISCUSSION

A. *Probabilites d'apparition des pluies*

a) Probabilités marginales

The m.arginal probability of dry decades P(S) for the 1971-1990 subperiod yielded the same result as that calculated for the 1991-2010 subperiod, i.e. 0.58. The marginal probability of wet decades P(H) for both subperiods was 0.42. The analysis of these results shows, firstly, that the transition of the marginal probability of wet decades P(H) is lower than the marginal probability of dry decades; secondly, there is no significant difference between the two sub-periods (1971-1990 and 1991-2010).

The marginal probability map presented by ([14]) in their work on "Climatic Variability and Implications for Maize Production in Benin: A

Stochastic Analysis of Rainfall" gave as probability P(S) for the 1971-1990 sub-period a value that varies between 0.62 and 0.64 with respect to the Banikoara area. The probability P(S) calculated in this study (0.58) is, therefore, lower than that found by ([4]). Nevertheless, these results confirm those of ([4]) who suggest that the marginal probability of wet decades P(H) is lower in the northern part of the country for the 1971-1990 sub-period.

b) Stochastic dependence of wet and dry periods

Table 3 presents the transition matrix of conditional probabilities of the first-order Markov chain for the 1971-1990 subperiod. Note that the matrix gave the same results for the 1991-2010 subperiod.

TABLE III. Conditional probability matrix of the first-order Markov chain for the sub-period 1971-1990.

		Decade t	
		S	H
Decade t-1	S	14/15	1/15
	H	1/21	20/21

The analysis of the stochastic dependence of the internal structure of the succession of dry and wet periods for the two sub-periods (Table 3) shows that the probability of transition from one dry decade to the next dry decade [P (S/S) = 0.93] and that of transition from one wet decade to the next wet decade [P (H/H) = 0.95] are highly superior to the other probabilities. With respect to the succession of wet and dry decades, the probability of transition from dry to wet decade [P (H/S) = 0.06] is slightly higher than the reverse transition probability [P(S/H) = 0.04], contrary to the results of ([4]) according to which P (H/S) is lower than P (S/H) for the 1971-1990 subperiod.

With respect to the transition matrix of conditional probabilities of the Markov Chain of order 2 (Table 4), it emerges that the transition probability of two dry decades following a third dry decade P(S/SS), substantially equal to P(S/S), is high; that is 0.93. As a result, there are practically no rainfall events with a height exceeding the threshold (ho = 3.4 mm) during the dry period. Similarly, to have a wet decade after two successive wet decades, the probability P (H/HH) is significant. The high probabilities P (H/H) and P (H/HH) show that there is an occurrence of rainfall within the wet season. This also corroborates the report of ([13]) that the probability of rainfall occurrence is higher in the north. However, only the analysis of rainfall amounts within the decades will be able to attest to their sufficiency or insufficiency for crops.

Furthermore, the probability of having a dry decade after a succession of a dry and a wet decade P (S/HS) and that of having a wet decade after a succession of a wet and a dry decade P (H/HS) are zero. This is due to the fact that the dry and wet decades do not alternate.

([4]) found that the length of the dry period increased from the 1951-1970 sub-period to the 1971-1990 sub-period, confirming the general trend of increasing dry period discussed by ([8]). For this study, the statistical parameters of dry periods and rainy periods calculated (Tables 4, 5 and 6) for the 1971-1990 and 1991-2010 sub-periods are without significant difference. Thus, there is little climate variability from the 1971-1990 sub-period to the 1991-2010 sub-period. Therefore, it can be said that there is no state change.

TABLE IV. Transition matrix of the conditional probabilities of the Markov chain of second order for the sub-period 1971-1990.

		Decade t-1 and t			
		SS	SH	HS	HH
Decade t-2 and t-1	SS	13/14	1/14	-	-
	SH	-	-	0	1
	HS	1	0	-	-
	HH	-	-	1/20	19/20

TABLE V. Mean (m1 [decade]), standard deviation (σ [decade]) and coefficient of variation (Cv [decade]) of drought periods (s0) during the subperiod 1971-1990.

	m_1 (s_1)	σ (s_1)	Cv (s_1)
Banikoara	21	20,493	0,975

TABLE VI. Mean (m1 [decade]), standard deviation (σ [decade]) and coefficient of variation (Cv [decade]) of rainy periods (s1) during the sub-period 1971-1990.

	m_1 (s_1)	σ (s_1)	Cv (s_1)
Banikoara	21	20,493	0,975

B. Rainfall amounts

a) Distribution of decadal rainfall amounts from 1971 to 2010

Figure 4 shows the distribution of decadal rainfall amounts for the 1971-1990 subperiod (a) and for the 1991-2010 subperiod (b). For all 36 decades analyzed, rainfall amounts range from 0 to 96 mm. We note that the first sub-period (1971-1990) was marked by a high rate of rainfall of low rainfall amounts, i.e. 45%, while the high rainfall amounts in the series are of the order of less than 10%. The rainfall amounts between 16 and 52 mm remained below 5%. For the second sub-period (1991-2010), the highest rainfall rates were for rainfall amounts between 0 and 4 mm, or 42%. On the other hand, the highest rainfall heights achieved (84 to 96 mm) are low rates, less than 5%. Only the rainfall amounts of 34, 50, 58, and 70 mm showed a small change in rate during the last sub-period. Figure 2 reveals that the decadal rainfall amounts are weakly distributed during the two sub-periods (1971-1990 and 1991-2010) in that the highest percentages were recorded for the lowest rainfall amounts. And the highest rainfall amounts are distributed in small proportions. There is no significant difference between the two sub-periods. Nevertheless, there is a slight increase in rainfall amounts from the first sub-period to the second.

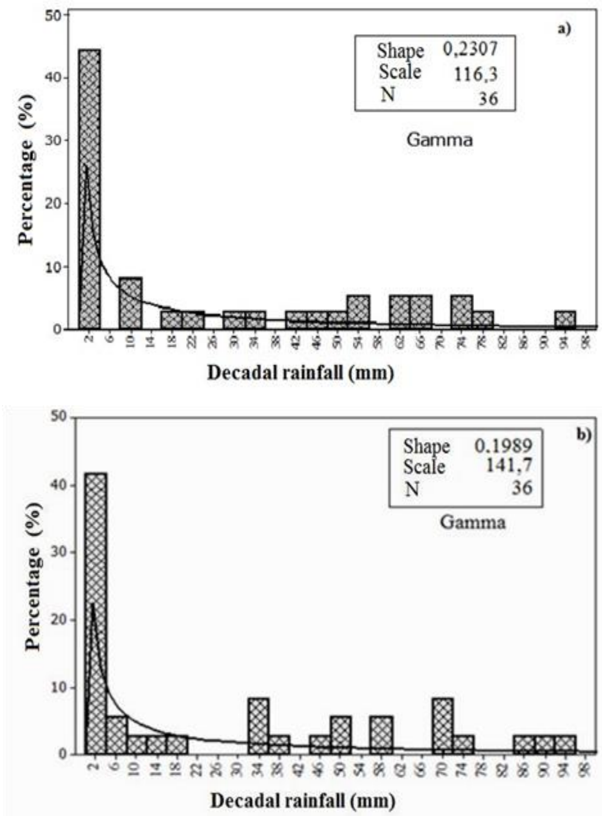

Fig 1. Distribution of decadal rainfall amounts. a) Subperiod 1971-1990; b) Sub-period 1991-2010.

Our results confirm ([20]) assertion that climatic conditions are characterized by a very high irregularity and poor distribution of rainfall in time and space. In addition, rainfall variability is effective in West Africa, and several studies have revealed a sharp downward trend occurring in the 1970s ([17], [18], [19]). However, the low rainfall rates recorded do not in themselves attest to the insufficiency or absence of rainfall during the rainy season. The interpretation of the phenomenon could be that it rains heavily on only two or three days during a decade, with the other days remaining dry, given that the temperature is high in the study area. The publication by ([20]) showed that in the savannah environment of West Africa, the risk of prolonged periods of drought during the plant growth period always exists, which can considerably affect yields. This could be linked to heavy and spaced rains or light but frequent rains within the decade ([15]); and secondly, to the type of showers encountered in Benin (thundershowers, monsoon rains and drizzle), each of which has its own particularities ([15]). For ([16]), the decrease in relatively high rainfall levels imposes agronomic constraints and induces changes in endogenous land use techniques.

b) Variability of rainfall patterns from 1971 to 2010

Figure 2 shows the shape of the decadal rainfall curves for the two sub-periods 1971-1990 and 1991-2010. The decadal rainfall curves over the course of the year show a regular rainfall pattern, first increasing until the maximum and then decreasing afterwards; this is because they result from a series of observations over 40 years. But in a single year, the rainfall is much more irregular.

Analysis of these two curves shows that the rainfall regime in the study area is unimodal with a marked maximum ([15], [21]). The commune of Banikoara is characterized by a rainy season from May to October, with June, July, August and September being the wettest months in the two sub-periods considered. These months are the wettest of the year and account for more than 60% of seasonal rainfall ([21]). The rainfall peak is observed in August for both sub-periods, as shown by ([7], [15], [20]), for the Sudano-Sahelian strip of West Africa.

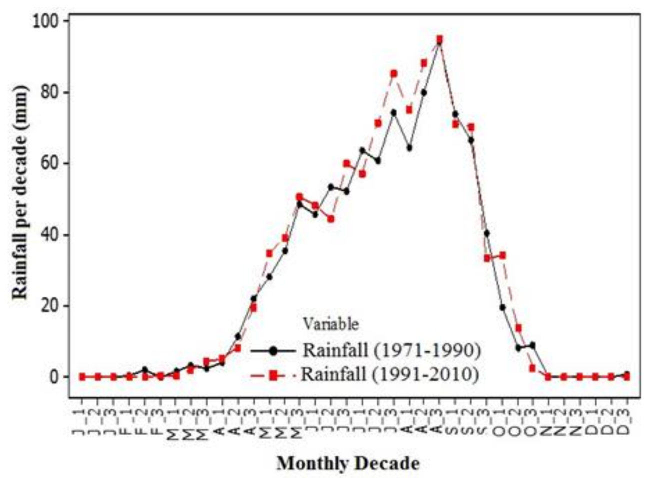

Fig 2. Decadal rainfall for the 1971-1990 and 1991-2010 sub-periods (Source: ([5]))

However, over the course of the year, the dekads of May, June, July, August, September and October become wetter for the 1991-2010 sub-period than for the 1971-1990 sub-period, except for the second dekad of June, the first dekad of July, and the first and third dekads of September, for which rainfall amounts go down a bit. These could be pockets of dryness during the rainy season, as mentioned by ([3]). The months of October and November see a drop in rainfall amounts due to the fact that the ITCZ retreats faster than it migrates north ([21]).

The dry season extends from October-November to March-April. During this period, the entire study area is under the influence of the dry northeasterly flow

(Harmattan) and rainfall averages only 25 mm ([21]). The months of November, December, and January have become drier and have an equal trend for both sub-periods. Similarly, from February to April, some decades are drier than others.

There is no significant difference between the two subperiods, but there is a slight increase in rainfall amounts during the rainy season from the first sub-period (1971-1990) to the second (1991-2010). Furthermore, the dry season and the rainy season share the lowest rainfall amounts, while the highest rainfall amounts are only distributed during the rainy season.

c) Annual rainfall totals

The evolution of annual rainfall over the period 1971-2010 has made it possible to identify surplus (wet), average (stable), and deficit (dry) years by means of the lower arithmetic mean (792.184 mm) and the upper arithmetic means (1188.276 mm). Thus, since 1971, the commune of Banikoara has experienced rainfall variations marked by alternating deficit and surplus years. The said commune is subject to a two-phase evolution of rainfall amounts: a regressive phase during the 1971-1990 sub-period and then a progressive phase during the 1991-2010 sub-period. This confirms the work of authors such as ([7]), [15], [16], [20], [23]) who report a reduction in the average annual amplitude of total rainfall since the end of the 1960s, particularly in the 1970s and 1980s. The average annual rainfall for the study area is 990.23 mm compared to 978 mm found in the central part of the Niger basin for the period 1955-1992 ([21]). According to ([20], [21]), the determining factors in the spatial variation of rainfall are latitude and altitude (orography).

Groups of deficit years alternate with groups of surplus years and groups of average years (Table 7). The analysis of Table 7 shows that 7.5% of the years are surplus, 80% of the years are average, and 12.5% of the years are deficit over the period from 1971 to 2010. During surplus years, crops are vulnerable to flooding and during deficit years, they suffer from water deficit ([22], [23], [25]), which causes the decrease in crop yields. ([15]) showed in his research the overall interannual variations in agricultural production in the face of rainfall variations, which was confirmed by the work of ([7], [16], [20]).

TABLE 7. Decadal rainfall for the sub-periods 19711990 and 1991-2010 (Source: ([5])).

Deficit years	Average years	Excessive years
1973, 1983, 1988, 1990, 1993	1971, 1974, 1975, 1976, 1977, 1979, 1980, 1981, 1982, 1984, 1985, 1986, 1987, 1989, 1991, 1992, 1994, 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010	1972, 1978, 1998

IV. CONCLUSION

At the end of this study, it was found that Banikoara commune is confronted with backlash from rainfall variability, as are the other agropastoral communes. From the results relating to the probabilistic decadal rainfall patterns over the period 1971-2010, it can be seen that there is little climatic variability from the 1971-1990 sub-period to the 1991-2010 sub-period, characterized by a dry situation. In addition, there is a lengthening of the wet period, a low distribution of rainfall and an alternation of deficit, average and surplus years that modify the annual rainfall regime. This expression of climate change is not without consequences for agricultural activities, in particular for agricultural calendars, sowing periods, and therefore for agricultural yields and even for livestock activities. Research efforts on adaptation strategies are therefore essential to help improve the already precarious living conditions of the local population.

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