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CLIMATE VARIABILITY AND IMPLICATIONS FOR MAIZE PRODUCTION IN BENIN: A STOCHASTIC RAINFALL ANALYSIS

E.K. AGBOSSOU, C. TOUKON, P.B.I. AKPONIKPÈ[1] and A. AFOUDA[2]
Faculté des Sciences Agronomiques (FSA), Université d'Abomey-Calavi (UAC), Laboratory of Hydraulics and Water Management (LHME), BP 526 Cotonou, Benin
[1]Faculté d'Agronomie (FA), Université de Parakou (UP), Environmental Soil Physics and Hydraulics Unit (PSHE), 03 BP 351 Parakou-Université, Bénin
[2]Faculté des Sciences et Techniques (FAST), Université d'Abomey-Calavi (UAC), Laboratory of Modeling and Applied Hydrodynamics (LAMHYA), BP 526 Cotonou, Benin
Corresponding author: akponikpe@yahoo.com

ABSTRACT

To better assess the occurrence of climate variability and change and related effects on crop production for improved adaptation in Benin, we analysed the stochastic dependence of dry and wet dekads (i.e. ten days), for two periods (1951-70 compared to 1971-1990) at 36 meteorological stations, based on Markov chains. The implications on maize (*Zea mays* L.) production, the main staple food in the country, was assessed by comparing drought probabilities with crop stage, water requirement and water stress. We found (i) a slight increase in the marginal probability of dry spells P(D) during the 1971-1990 period compared to the 1951-70 one, (ii) that the second period 1971-1990 was characterised by a general increase in the succession of dry states, a higher transition probability from a dry dekad to the next dry P(D|D) than all other transition probabilities and a significantly higher probability of transition from two subsequent dry dekads to a third dekad dry P(D|DD) than P (D|D) at most stations, (iii) an increase in the length of dry spells and, therefore, dry periods on the sub-period 1971-1990, and (iv) that maize crop during its development in Benin is more likely to be subject to dry dekads successions than wet ones, resulting in poor yield, especially after 1970. This study shows that the frequent maize yield decline in Benin is partly explained by an increased occurrence of the succession of dry dekads (i.e. increase in the length of dry spells).

Key Words: Dekads, Markov chains, rainfall, *Zea mays*

RÉSUMÉ

Afin de mieux évaluer l'avènement de la variabilité et des changements climatiques ainsi que des effets connexes sur la production agricole au Bénin, une analyse de la dépendance stochastique des décades sèches et humides (10 jours) a été faite pour deux périodes (1951-70 en comparaison à 1971-1990) dans 36 stations météorologiques sur base des chaines de Markov. Les implications sur la production de maïs (*Zea mays* L.), la principale culture vivrère du pays, ont été évaluées en comparant les probabilités de la sécheresse avec les stades de croissance, les besoins en eau et le stress hydrique. Les résultats révèlent que (i) une légère augmentation de la probabilité marginale de la sécheresse P(D) au cours de la période 1971-1990 par rapport à 1951-70, (ii) la seconde période 1971-1990 était caractérisée par une augmentation générale dans la succession des périodes sèches, une probabilité élevée de transition de la décade sèche à la suivante sèche P (D|D) par rapport à toutes les autres probabilités de transition et, une probabilité de transition significativement élevée de deux décades sèches subséquentes à la troisième décade sèche P(D/D) dans la plupart des stations, (iii) une augmentation de la longueur de la sécheresse et, par conséquent, des périodes sèches au cours de 1971-1990, et enfin (iv) au cours de son stade de développement, la culture du maïs au Benin est plus exposée à la succession de décades sèches que celles humides, avec pour conséquence la réduction du rendement, notamment après 1970. Cette étude montre que la baisse fréquente du rendement du maïs au Benin est en partie liée à l'augmentation de la fréquence des successions de décades sèches (c'est-à-dire l'augmentation de la longueur de la sécheresse).

Mots Clés: Décades, chaînes de Markov, pluviométrie, *Zea mays*

INTRODUCTION

Several studies have analysed the rainfall variability of West Africa and have revealed an abrupt decreasing trend occurring in the 1970ies that was clearly shown for the Sahel (Carbonnel and Hubert, 1987; Paturel *et al*., 1995; Le Barbé *et al*., 1997). Contrary to the Sahel, in the southern parts of the sub-Saharan Africa, while the temperature trend is widely reported to be increasing, annual rainfall is reportedly highly variable on inter-annual and inter-decadal time-scales, and no long term trend was identified (McSweeney *et al*., 2010). Meanwhile, it is important to better understand the occurrence of this high observed climate variability and its effect on crop production for better adaptation in Sub-Saharan West Africa (Kandji *et al*., 2006).

The analysis of the effects of climate variability on crop may be done through three approaches (i) long term agricultural experiments, (ii) dynamic soil-water-crop modelling and/or (iii) dry spell occurrence probability analysis in relation to crop water requirement satisfaction. In the context of Benin and Sub-Saharan West Africa, long term experimental data are seldom available and existing ones cover just few years. The use of crop models implies many parameterisation data (soil, crop, etc) which are not always available. Dry spell probability analysis may represent a cheaper and less-time consuming alternative option for these environments.

The analysis of the erratic occurrence of dry spells within a year or season, calls on sophisticated methods that can account for the nature of dependence between wet and dry spells. The mathematical tools available to explore such dependencies are the Markov chains, Poisson processes, renewal processes and auto-regressive models such as ARMA and ARIMA (Afouda, 1985). However, most of these tools do not show sufficient flexibility, and thus effort is currently geared towards finding simple methods for analysing dependencies within sequences. The Markov chains method provides a relative simplicity and offers possibilities of generalisation to Markov processes, which are solutions of stochastic differential equations (Afouda, 1985; 1988 and 1989; Lawin and Afouda, 2002). The Markovian properties of rainfall data were previously analysed in Benin for the six synoptic stations based on annual rainfall (Afouda and Adisso, 1997), and daily rainfall (Afouda,1985; Le Barbé and Lebel, 1997; Afouda *et al*., 2002). But annual time step is too long to relate to crop performance and a daily step is often the best option considered in agronomy. But analysing the dependence of wet and dry days in the tropics, Jackson (1981) showed that contrary to higher latitudes (where the state of only one previous day is enough), at least two previous days and even three in some seasons are important. Taking these facts into consideration, a dekadal (ten days) time step appears to be better than annual and daily dry spell probability analysis in connection to crop performance in Sub-Saharan West Africa. The objective of this study was to analyse, based on Markovian structure, the stochastic dependence of dry and wet dekads, using the case of maize production. Maize is the main staple food crop in the country.

MATERIALS AND METHODS

Biophysical features of Benin. The Republic of Benin (6°30-12°30 N, 1°0-3°40 E) has an area of 112,622 km² and is approximately 700 km long, from the Atlantic Ocean to the Niger River. The rainfall seasons of Benin are controlled by the movement of the tropical rain belt known as the Inter-Tropical Conversion Zone, ITCZ, which oscillates between the northern and southern tropics over the course of the year. In northern Benin (Sudanian climate), there is a single wet season occurring between May and November, when the ITCZ is in its northern position and the prevailing wind is south-westerly; and a dry season between December and March when the 'Harmattan' wind blows north-easterly (McSweeney *et al*., 2010). The southern regions of the country have two wet seasons (Guinean climate). The major rainy season occurs from March to July; and the shorter one from September to November, corresponding to the northern and southern passages of the ITCZ across the region. The seasonal rainfall in this region varies considerably on inter-annual and inter-dekadal timescales, due in part to variations in the movements and intensity of the ITCZ, and variations in timing and intensity of the West African Monsoon. Maize crop is grown during wet seasons twice in the south (Guinean) and once in the northern part (Sudanian) (Akponikpe, 1999).

Data collection. Rainfall data of 36 meteorological and 6 synoptic stations were collected from the National Meteorological Service (SNM-Benin/ ASECNA) (Fig. 1). To enable fairly accurate analysis of the dependence of stochastic spatio-temporal variability of rainfall, the selected rainfall

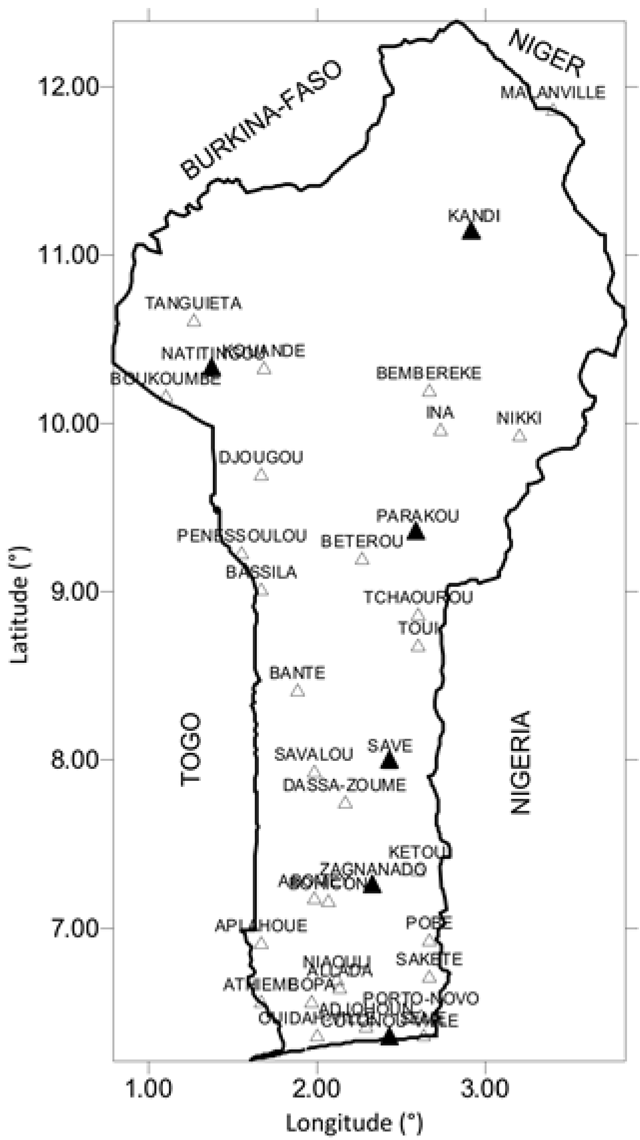

Figure 1. Rainfall (△) and synoptic (▲) stations of Benin.

stations and data period in this study contained the most complete information as possible. The duration under analysis covers a period of 40 years, from 1951 to 1990.

Stochastic rainfall analysis based on Markov chains. Based on the Markov chains method, we considered two random variables to describe the temporal rainfall structure (Afouda, 1985). The first was the amount of rainfall events within a given time interval; the second was the state (wet or dry) of the given interval. The characterisation of rainfall events depends on the time scale. In the literature, both discrete and continuous time scales are reported. In this study, rainfall events are considered at discrete time scales represented by dekadal value at a given site.

For the discrete time scale and let:

$\{Y_t, t \varepsilon T\}; (T=1,2,....)$ (1)

be the discrete variable defining the rainfall amount at dekad t and

$\{X_t, t \varepsilon T\}; (T=1,2,....)$ (2)

be the discrete variable defining the state of the t^{th} dekad such as

$X_t = 1$ if $Y_t >$ ho, indicating a wet state (sufficient rainy events within dekad)

$X_t = 0$ if $Y_t \leq$ ho, indicating a dry state (no or insufficient rainfall within dekad)

h_0 being a well defined threshold. For the present study, $h_0 = 3.4$ mm.

We are interested in the probability that the dekad t is wet or dry, given that the previous ones X_{t-1} , X_{t-2} , ….., X_{t-r} are wet or dry. This probability is named the r^{th} order Markov probability. For the 1^{st} order, it reads :

$\Pr(X_t = j \mid X_{t-1} = i) = \beta_{ij} =$ i, j are the states (0 or 1) (3)

This relationship expresses the conditional probability of transition from the state i of the previous dekad t-1 to the state j of the current dekad t. It clearly indicates that the state of the dekad t depends only on the condition of the previous dekad t-1 for 1^{st} order Markov chains. As a dekad can be characterised in terms of rainfall by only two states (wet or dry), the matrix for the conditional probabilities of Markov transition is shown in Table 1.

The sum of the conditional probabilities on each row equals 1, i.e:

$\beta_{01} = 1 - \beta_{oo}$ and $\beta_{10} = 1 - \beta_{11}$

In practice, calculations are made considering a finite number of dekads. Taking into account the notation adopted for the dry and wet states, we can identify N_{ij} pairs of dekads such as:

$N_0 = N_{00} + N_{01}$ (4)

$N_1 = N_{10} + N_{11}$ (5)

$N = N_0 + N_1$ (6)

Where N_0, N_1 and N are, respectively, the number of dry, wet and total number of dekads under study. N_{01} and N_{10} are the number of dekads changing from the dry state to the wet, and the number of those changing from wet to dry, respectively. The marginal and transition probabilities read:

$F_0 = N_0/N$; $1 - F_0 = N_1/N$; $\beta_{ij} = N_{ij}/Ni.$ (7)

The marginal probability of a dry dekad is:

$F_0 = \beta_{01} / (1 - \beta_{00} + \beta_{10})$ (8)

The knowledge of the marginal and transition probabilities allows us to calculate the characteristics of the spells.

TABLE 1. Matrix for the conditional probabilities of Markov transition

		Dekad t	
		0	1
Dekad t-1	0	β_{00}	β_{01}
	1	β_{10}	β_{11}

Let's consider now the event of observing a sequence (spell) of exactly n dry dekads. It is realised if we have the succession of states as follows:

1.00 … 01 (n times)

The variable defining the duration reads:

$$d_0 = \min \{ n ; x_i = 0\} \quad (9)$$

Then :

$$P_r \{ d_0 = n\} = P_r(1)\, P_r(0|1)\, P_r^{\,n-1}(0|0)\, P_r(1|0) \quad (10)$$

With the above notations, it reads

$$P_r\{ d_0 = n\} = (1 – F_0)\, \beta_{10} \cdot \beta_{00}^{\,n-1}\, \beta_{10} \quad (11)$$

After some algebraic calculus, it follows after Thirriot (1983) that the expected value (mean or first moment) of dry spells is:

$$m_1 (d_0) = 1/ (1 - \beta_{oo}) \quad (12)$$

Other parameters of the dry spells (second moment, standard deviation and coefficient of variation):

$$m_2 (d_0) = (1 + \beta_{oo}) / (1 - \beta_{oo})^2 \quad (13)$$

$$\sigma (d_0) = [\beta_{oo}/ (1 - \beta_{oo})^2]^{1/2} \quad (14)$$

$$C_v (d_0) = (\beta_{oo})^{1/2} \quad (15)$$

The cumulative distribution function (CDF)

$$P_r \{ d_0 < n\} = 1- (\beta_{oo})^n \quad (16)$$

The same calculations were made for the rainy spells. They led to similar results by replacing the indices of dry spells by those characterising the rainy spell.

It generally appears that the Markov transition probabilities are a function, not only of initial and final states, but also the moment of transition. But we have assumed in this case that for our case study, they are independent of time, that is to say they are stationary. The process is then simply determined by the data of Equation (3) above and the value of the probability of X_0 at the initial time t = 0.

As abrupt changes in climate were reported to start in the 70ies and rainfall data recording started around 1950 on most of the meterorolgical stations, we studied the stochastic dependence of wet and dry spells for two sub – periods (1951-70 and 1971-90) and for the whole period (1951-90) to have comparable sub-period duration. We thus computed for each station:

(i) the Markovian probability of having a wet dekad if the previous was wet (β_{11}) denoted as P (W|W);
(ii) the Markovian probability of having a dry dekad if the previous was dry (β_{00}) denoted as P (D|D);
(iii) the Markovian probability of having a dry dekad followed by wet P (W|D) and *vice versa* P (D|W).
  - the marginal probabilities F_0 and F_1 (equations 7 and 8)
  - the average length $m(d_0)$, standard deviation (d_0) and coefficient of variation $Cv(d_0)$ of dry spells.

We also considered the transition probabilities of order two. The transition matrix of the Markov chain of order two is shown in Table 2; where b_{ijk} represents the conditional probability of obtaining a couple of states (j, k) subsequent to a couple of state (i, j) such that :

$$b_{ijk} = N_{ijk} / N_{ij} \quad ; \quad \sum_{k=0}^{j} \beta_{ijk} = 1 \quad (17)$$

Contrary to the first order, some zero appear here because of the uncertain occurrence of some couple of states. For each station, we computed the matrix of transition focusing more on dry spells.

Relations with maize cropping. The stochastic rainfall analysis was compared with maize water requirement and response to water stress from literature to draw implications for maize crop in the country.

RESULTS AND DISCUSSIONS

Marginal probabilities. The marginal probability maps showed that the probability of dry spells P(D) was maximum in Cotonou (0.667) for the period 1951-70 and (0.669) for 1971-90; while the minima occurred at Bohicon (0.586) for the first period and in Save (0.619) for the second period (Fig. 2). There was a slight increase in the probability P(D) during the second, 1971-1990, compared to the first period of 1951-70. This increase varied from 0.2% (in Cotonou) to 1.8% (at Bohicon). Furthermore, this increase became higher from south to north. Regarding the marginal probability of wet dekads P(W), (not shown), it was lower in the northern part of the country for the two sub-periods and decreased systematically on all stations during the second sub-periods (1971-1990).

The stochastic dependence of wet and dry spells

The analysis of the stochastic dependence of the internal structure of the succession of dry and wet spells showed a general increase in the succession of dry states in the 1971-90 period compared to the first one 1951-70. In addition, the probability of transition from a dry dekad to the next dry P(D|D) was higher than all other transitions' probabilities, and increased from sub-period 1951-70 to 1971-1990 (Fig. 3). P(D|D) was maximum in the north (0.718 in Kandi; 0.675 in Natitingou to and 0.670 in Parakou). Furthermore, P(D|D) increased gradually from the south (0.554 in Cotonou) to the north (0.718 in Kandi). This resulted in the decrease in the probability of transition from a wet dekad to the next wet (P (W|W), following the same pattern.

Regarding the succession of wet and dry dekads, the probability of transition from a wet

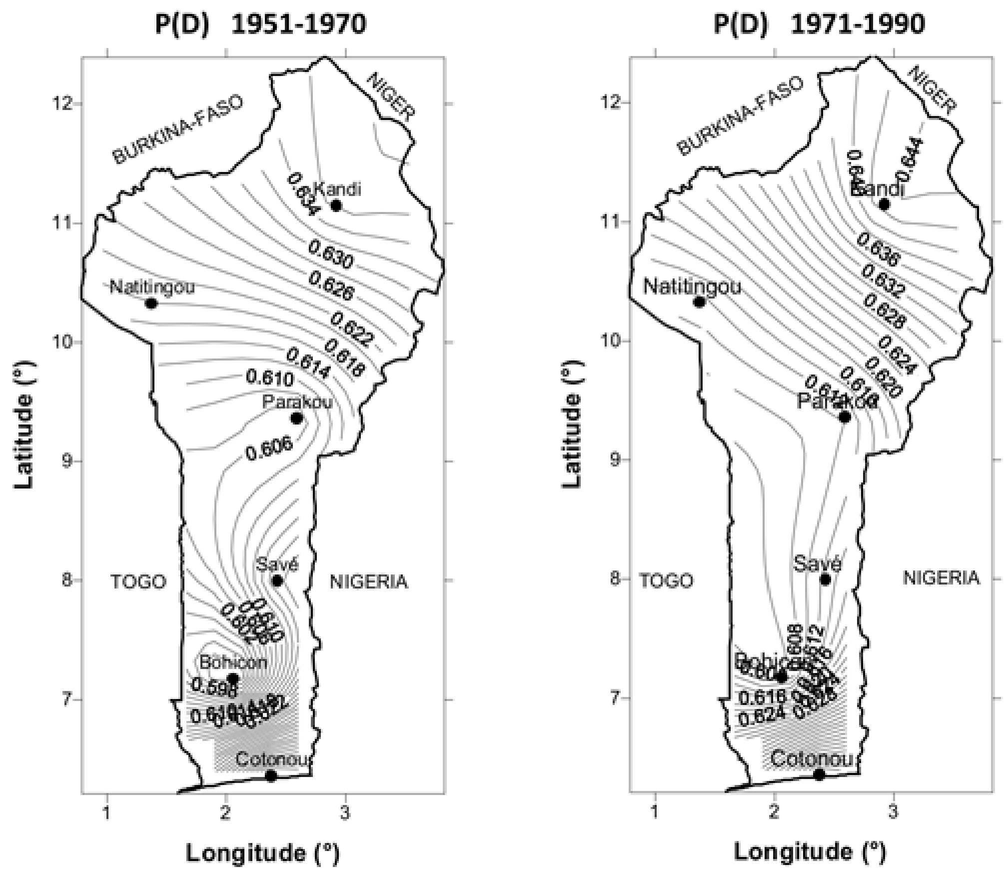

Figure 2. Probability of dry spells in Benin.

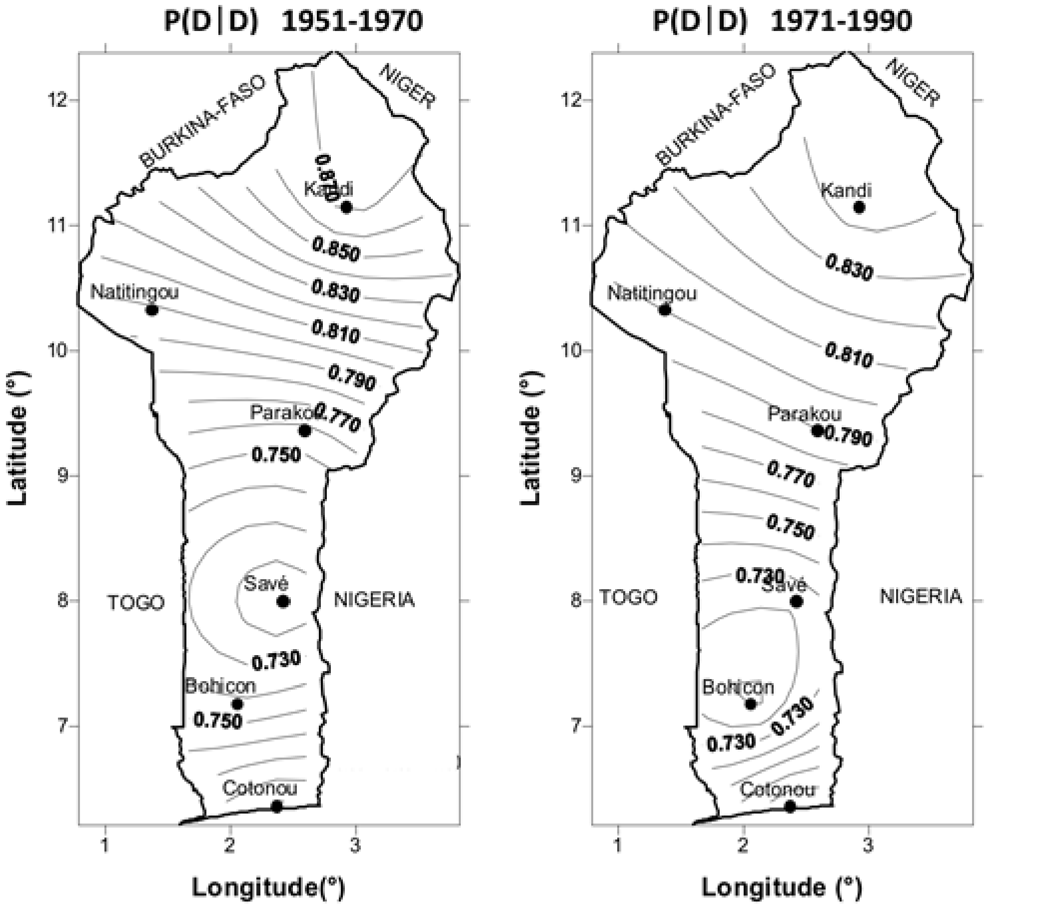

Figure 3. Probability map of transition from a dry dekad to another dry over two periods in Benin.

dekad to the next dry (P (D|W) was higher than the inverse transition probability (P (W|D) on all the stations studied. The probability P(D|W) increased from 2% (Cotonou) to 6% (Kandi) shifting from the sub-period 1951-70 to 1971-90, with higher absolute values generally in the south of the country. P(D|W) showed an increase in the north-south direction over the two sub-periods of study. It was noticed that P(D|W) was maximum in the south (Bohicon and Cotonou), in agreement with several previous observations within the Dahomey gap inserted in southern Ghana-Togo-Benin (Afouda and Adisso, 1997). The most important finding at the 2nd order of the Markov chain (Fig. 4) was that the probability of transition from two subsequent dry dekads to a third dekad dry P(D|DD) was significantly higher than P (D|D). Furthermore, P(D|DD) increased in general on all stations, with the maximum values (between 0.888 and 0.914) in the north when we shift from the sub-period 1951-70 to 1971-90. However, P(D|DD) changed very little at some stations in the centre of the country. Likewise P(W|WW) significantly decreased in the second sub-period 1971-90 compared to the first.

The statistical parameters of dry spells calculated for synoptic stations (Table 3) reflect an increase in the length of dry spells and therefore dry periods on the sub-period 1971-1990. Our results are consistent with those of Afouda and Adisso (1997) and Lawin (2001) confirming the general increasing trend of dry spells. Furthermore, we find that the north, especially the Natitingou region which is the “water tower” of the country also struck by drought.

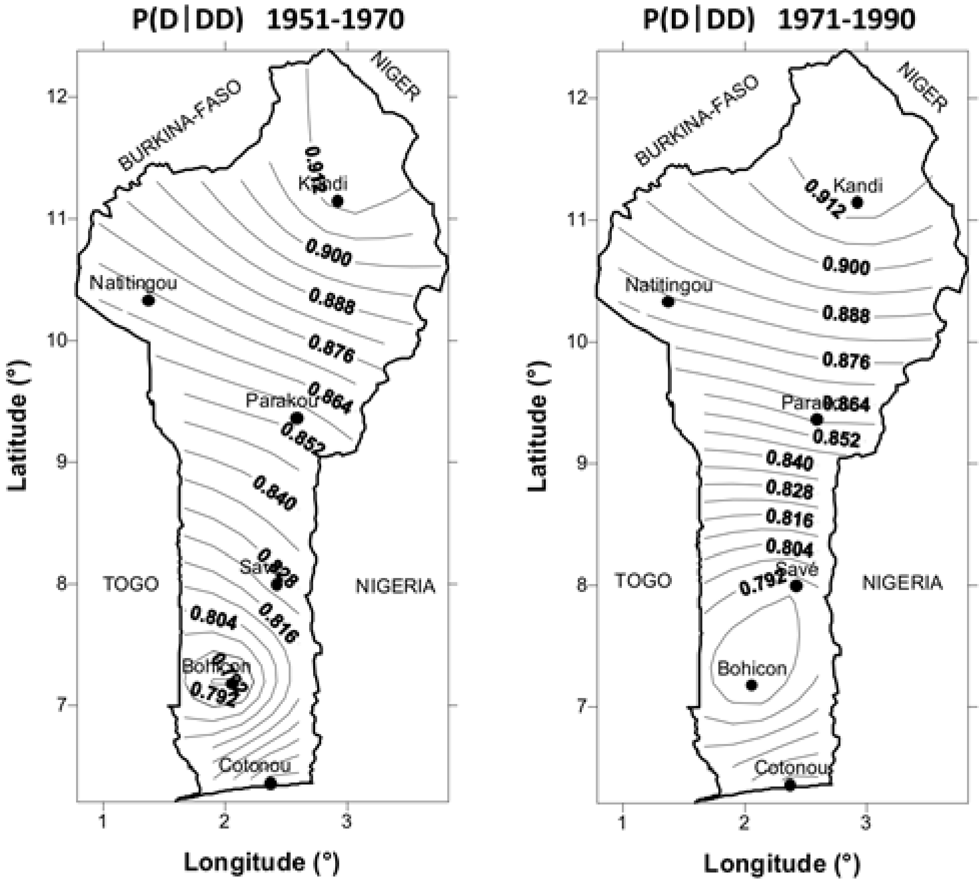

Figure 4. Probability map of transition from two subsequent dry dekads to another dry dekad over two periods in Benin.

TABLE 2. The transition matrix of the Markov chain of order two. β_{ijk} represents the conditional probability of obtaining a couple of states (j, k) subsequent to a couple of state (i, j)

		t-1 and t			
		00	01	10	11
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}

Implications for maize production. These mathematical results will be compared with maize crop water requirement and response to water deficit to infer the impact of rainfall variability and change on the production of maize in Benin. Several studies have highlighted the sensitivity of maize to water deficit during the period from stage 10 to 12 leaves and ending at the dough grain stage (Sobrado, 1986; Mansouri-Far *et al*., 2010). During this period, any water deficit adversely affects maize performance. In fact, maize water requirement increases to its maximum around the third or fourth dekad (Allen *et al*., 1977). Flowering starts around 15 to 20 days after

TABLE 3. Average (m_1 [dekad]), standard deviation (σ[dekad]) and coefficient of variation (C_v [-]) of dry spells (s_0) during two periods for Benin synoptic stations

	1951-1970			1971-1990		
	m_1 (s_0)	σ (s_0)	C_v (s_0)	m_1 (s_0)	σ (s_0)	C_v (s_0)
Cotonou	2.041	1.457	0.714	2.232	1.659	0.743
Bohicon	3.571	3.041	0.849	3.448	2.913	0.843
Savè	3.448	2.913	0.843	3.636	3.086	0.851
Parakou	4.167	3.639	0.872	4.762	4.240	0.889
Natitingou	4.444	3.901	0.880	5.000	4.453	0.894
Kandi	5.000	4.453	0.894	6.667	6.150	0.922

sowing (DAS) and is followed by the critical period of grain formation and filling between the third and fourth or sixth dekad.

Water deficit in these periods severely affects number of grains per ear, ear number and individual grain weight leading to lower yield (Algans and Desvignes, 1983). Maize yield will consequently depend on water adequacy determined by the probability of state transition during this sensitive period. For optimum water satisfaction, one would expect (i) the marginal wet dekad occurrence probability P(W) to be high, (ii) the transition probabilities from wet to the next wet P (W|W) to be high and (iii) P (W|WW) to be high as well. But our results showed a low level of these probabilities, which yet decreased during the second sub-period (1971-1990). This is evidenced by the general increase in the succession of dry states (P(D), P (D|D), P (D|DD)) pronounced from the northern parts of the country to the latitude of Bohicon. In Benin and generally in the Sub-Saharan West Africa, farmers tend to sow maize after the first main rainfall (>20 mm) occurring at the start of the rainy season period (Akponikpè *et al*., 2010). Considering that the sowing dekad is wet, the next two dekads are more likely to be dry (P(D|W), P(D|DW)). After sowing, germination may occur but the plants will face dry dekads around the third and fourth dekads shown to be highly sensitive to water stress. Consequently, maize crops in Benin are more likely to be subject to dry dekads successions than wet ones; thus resulting in poor yield, especially after 1970.

Our finding corroborate with those of other works on the adverse effect of climate change on maize production in Benin. Akponikpè (1999) using a water-balance crop modeling approach, reported a decrease in maize yield in south of Benin from the West to East between 40 to 250 kg ha^{-1} during 1971-1990 compared to 1950-1970. Fakorede and Akinyemiju (2001) also showed similar drought increase trend and adverse effect on maize production in Ile-Ife rainforest area of Nigeria.

CONCLUSION

This study showed that there is a slight increase in the marginal probability of dry spell P(D) during the 1971-1990 compared to 1951-1970. Furthermore, there is a general increase in the succession of dry states in the 1971-90 period compared to the first one 1951-1970. The probability of transition from a dry dekad to the next dry P(D|D) is higher than all other transition probabilities, and increased from sub-period 1951-70 to 1971-1990. The probability of transition from two subsequent dry dekads to a third dekad dry P(D|DD) is significantly higher than P (D|D) at most stations.

This study also showed that the often maize yield decline in Benin is partly explained by an increased occurrence of the succession of dry dekads (i.e. increase in the length of dry spells). The study highlights the need to seek effective adaptation measures addressing drought risk management for maize in Benin.

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