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M. V. K. SIVAKUMAR

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center, Niamey, Niger

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ABSTRACT

Recurring droughts and decreased agricultural productivity during the last two decades in West Africa point to the need for a clearer understanding of the length of dry spells, their frequencies, and their probabilities. The simplest calculations of dry spells for general applications involve computation of the probabilities of maximum and conditional dry spells exceeding a user-specified threshold value from a given calendar date. For more precise applications in agriculture, it is important to consider the different periods after sowing a crop, since sowing dates in the semiarid West African regions vary from year to year. Using the specific definition of onset of rains in each year as the sowing date, the length of dry spells was calculated from the historical rainfall data. Probability distribution of time to the next wet day and the percentage frequencies of dry spells were computed for successive days after sowing (DAS) a crop. Dry-spell analysis showed a pronounced drop in the drought risk for cereal crops from the panicle initiation phase (20 DAS) to the flowering phase (60 DAS). The relationships between mean annual rainfall and average frequency of dry spells for the selected locations in West Africa showed distinct patterns and permit the prediction of the frequency of dry spells from annual rainfall totals. Applications of the dry-spell analysis for the choice of a crop/variety, supplemental irrigation, and crop water requirements have been described with examples.

1. Introduction

The recent 17-year drought in the West African Sahel has been the longest and perhaps the most severe this century (Payne et al. 1987). Since subsistence agriculture is the main mode of employment in rural West Africa, the main effect of droughts has been reduced agricultural productivity. Successive crop failures have led to food scarcity, resulting in malnutrition, unchecked disease, decimation of livestock herds, and, ultimately, famine, with a staggering loss of human life (Morse 1987). The consequences of drought are often woven into the economic and social fabric of a region; these are referred to by Glantz (1987) as second- and third-order effects, for example, price increases, increased food imports, surges in rural-to-urban migration rates, etc.

Recurrence of droughts and associated famines in Africa over the past two decades have led to the realization that occurrence of droughts will be a continuing phenomenon in Africa and that droughts could persist for some length of time. Two major symposia have addressed the problems of drought in West Africa: the 1973 symposium on "Drought in Africa" (Dalby and Church 1973), and the colloquium on "Drought and Hunger in Africa: Denying Famine a Future" (Glantz 1987). Proceedings of these meetings highlighted the need for the analysis of historical weather data for understanding the length of dry spells, their frequencies, and their probabilities.

Nicholson (1980, 1981, 1983) described the occurrence of droughts in West Africa mainly in terms of a large spatial scale of departure. Nicholson (1983) also used the distribution of runs of consecutive dry years to distinguish between the Sahelian and southern African rainfall regimes. More recently, Rasmusson (1987) assessed droughts in West Africa by using normalized departures from average rainfall over the various lengths of the record.

Mutsaers (1979) calculated the dry-spell occurrences in Cameroon and pointed out that for agricultural applications of precipitation probabilities, both the amount and distribution of rainfall in a given period should be considered. Simple empirical analysis of long-term rainfall data for dry spells could provide information useful for agricultural applications, but very few studies of this nature for West Africa have previously been made. For example, dry-spell lengths could be employed as a guide in breeding varieties of various maturity durations for different locations. Information on dry-spell lengths could also be used in decision making with respect to supplementary irrigation and field operations such as harvesting.

The objective of this paper is to describe an empirical analysis of probabilities, lengths, and frequencies of dry spells in West Africa with suitable examples showing how these data could provide a basis for developing long-term cropping strategies.

Corresponding author address: M. V. K. Sivakumar, ICRISAT—Centre Sahelien, B.P. 12404, Niamey, Niger (via Paris).

TABLE 1. Probability (%) of maximum and conditional dry spells exceeding indicated lengths within 30 days after a starting date at Niamey, Niger.

	Maximum dry spell (days)			Conditional dry spell[a] (days)		
Starting date	>7	>10	>15	>7	>10	>15
1 May	100	100	83	100	93	57
11 May	97	93	70	93	80	50
21 May	97	83	60	87	70	50
1 June	87	67	53	80	43	23
11 June	70	43	23	63	27	7
21 June	53	27	10	50	13	0
1 July	53	20	7	43	13	3
11 July	43	10	3	33	10	3
21 July	33	17	3	23	7	0
1 August	30	7	0	27	7	0
11 August	47	10	0	43	3	0
21 August	57	13	0	57	13	0
1 September	80	23	13	77	20	13
11 September	97	70	43	97	67	40
21 September	100	93	70	100	90	63
1 October	100	97	97	97	97	93

[a] Calculation of dry-spell conditional on the day before the start of the period under consideration being rainy.

2. Methods

In this study, the analysis of dry spells has been carried out using daily rainfall data for selected locations in West Africa. The data were examined for continuity and missing records. Years with missing days of data were not included in the analysis.

The simplest calculations of dry spells involved transformations of the columns of rainfall data to give dry-spell lengths using the INSTAT climatic guide (Stern et al. 1989). The spell lengths were processed further to give maximum dry spells in 30-day periods starting from the first day of each decade. The term "decade" here refers to the 10-day averaging periods of each month that are commonly used in the Francophone West African countries. Each month is divided into three decades starting from the 1st, 11th, and 21st day of the month. The last decade of the month, which includes all the days up to the end of the month, could have either 10 or 11 days, depending on the month (with the exception of February).

Probabilities of maximum dry-spell lengths exceeding 7, 10, and 15 days over the next 30 days starting from the first day of each decade were then calculated. The choice of these spell lengths reflects the need to consider shorter spell lengths for drought-sensitive crops such as corn, as opposed to drought-hardy crops such as millet, which can withstand longer dry spells of even 15 days. Also, for a given crop, certain growth stages are more sensitive to droughts and have a higher water requirement. For example, most grain crops are sensitive to drought at the time of flowering and grain filling.

In addition to the maximum dry spell, conditional dry spells were also calculated. These are the lengths of dry spells conditional on the day prior to the beginning of a spell being rainy. These data enable the user to assess if a break in dry spells due to rain has a significant impact on the subsequent spell length.

The aforementioned calendar-based computations have only a limited value for specific applications to crop planning in West Africa, since the sowing dates and crop phenology change with rainfall distribution each year. To overcome this problem, the specific definition of "onset of rains" in each year (Sivakumar 1988) was used as the sowing date. The date of onset of rains was defined as that date after 1 May when rainfall accumulated over 3 consecutive days is at least 20 mm and when no dry spell within the next 30 days exceeds 7 days. The length of dry spells (or days until the next day with rainfall greater than a threshold value)

TABLE 2. Maximum length of dry spell (days) at three probability levels for different days after sowing at Niamey, Niger. Data are presented under each of the five rainfall thresholds used for dry-spell computations.

Days after sowing	Mean rainfall (mm)	1 mm			5 mm			10 mm			20 mm			25 mm		
		90%	50%	10%	90%	50%	10%	90%	50%	10%	90%	50%	10%	90%	50%	10%
10	37.9	4.8	1.4	0.2	7.3	1.4	0.2	18.5	5.6.	0.8	24.1	7.3	1.1	30.3	11.5	2.8
20	35.3	7.4	2.2	0.3	11.8	3.6	0.5	18.5	7.0	1.7	27.1	11.7	3.7	31.3	13.5	4.3
30	36.3	5.9	1.8	0.3	10.0	3.8	0.9	15.0	5.7	1.4	21.4	9.3	2.9	27.8	12.0	3.8
40	46.2	5.0	1.5	0.2	6.6	2.5	0.6	11.1	4.2	1.0	16.4	4.9	1.0	24.7	9.4	2.3
50	48.7	5.1	1.5	0.2	5.3	1.6	0.2	10.3	3.9	1.0	19.3	5.8	1.0	25.6	9.7	2.4
60	48.7	5.6	1.7	0.3	7.0	2.1	0.3	10.3	3.1	0.5	19.9	6.0	0.9	25.9	9.8	2.4
70	63.1	5.1	1.5	0.2	5.5	1.5	0.2	10.5	1.8	0.2	25.2	7.6	1.1	25.2	7.6	1.1
80	51.3	13.6	2.3	0.1	16.2	2.7	0.1	16.2	2.7	0.1	27.9	8.4	1.3	32.2	12.2	3.0
90	39.3	13.0	2.2	0.1	14.1	2.4	0.1	24.8	7.5	1.1	30.1	11.4	2.8	39.5	18.6	6.9
100	33.3	19.1	3.2	0.1	19.1	3.2	0.1	31.3	9.4	1.4	35.4	15.3	4.8	39.5	19.9	8.2
110	22.0	20.6	3.5	0.2	30.6	9.2	1.4	33.9	12.9	3.1	36.5	17.2	6.4	40.8	21.6	9.6
120	12.9	30.1	9.1	1.4	31.6	12.0	2.9	38.6	18.2	6.7	39.5	22.4	11.2	39.5	25.1	15.0
130	8.6	32.6	12.4	3.0	36.5	17.2	6.4	39.6	22.5	11.2	40.3	24.6	13.7	40.7	27.7	17.8
140	2.8	41.1	20.8	8.5	41.6	25.4	14.2	41.6	27.4	18.6	41.6	27.4	18.6	41.6	27.4	18.6

was computed at different probability levels following the procedures given by Hills and Morgan (1981). Rainfall thresholds used for this purpose were 1, 5, 10, 20, and 25 mm. The minimum rainfall threshold of 1 mm is an insignificant amount for crop use, but it does signify the ending of a dry spell. The other four threshold values have been so chosen as to give the user an idea of the waiting times for satisfying a proportion of the water requirement of the crop. The length of dry spells was calculated at the probability levels of 90%, 50%, and 10%.

Frequencies (F) of dry spells were computed as

$$F(D < x) = \frac{N(D_i)}{M} \times 100,$$

where $N(D_i)$ is the number of years a dry spell of length $< x$ started in a prescribed 10-day period i and M is the number of years of data.

3. Results and discussion

a. Probabilities of dry spells computed on calendar-day basis

The probabilities of dry spells exceeding 7, 10, and 15 days within the 30 days after the first day of each decade of the year at Niamey, Niger, are presented in Table 1. Dates are presented from the beginning of May to the beginning of October, which is the period during which rains are received at Niamey. These data provide a quick overview of the drought risks during the year. Up to the beginning of June, the probability of maximum dry-spell lengths exceeding 7 and 10 days is more than 80%. Conditional dry-spell probabilities also show that even if the dry spell is broken due to rain, the risk of a long dry spell before 1 June is still quite high and exceeds 70%. These data show that sowing field crops with first rains before 1 June is fraught with considerable risk, while the period after 1 June is more favorable since the probabilities of dry spells decrease rapidly, indicating significantly reduced risk to the emergence and subsequent growth of crops. The probabilities of both the maximum and conditional dry spells exceeding 10 days are above 70% from the middle of September, which suggests that standing crops after that time will face increasingly greater risks of water shortage.

According to Farmer and Wigley (1985), it is difficult to determine the specific causes of drought on a regional scale in West Africa. They explained that the probable causes of long dry spells, such as those before 1 June at Niamey, relate to the position of the intertropical convergence zone (ITCZ), sea surface temperatures, land surface boundary conditions (albedo or moisture level), atmospheric humidity, location and intensity of Hadley-type and Walker-type vertical circulations, and/or upper-airflow patterns and associated atmospheric energetics. Among the possible explanations for lack of moisture over the Sahel at the beginning of the rainy season, as given by Rasool (1982), are the displacement of ITCZ and changes in global east-to-west air circulation patterns caused, in part, by changing conditions over distant oceans (Indian, Atlantic, and Pacific). A detailed discussion of the physical processes that can cause droughts is beyond the scope of this paper, but an up-to-date review is given by Rasool (1984) covering both global and regional scales.

b. Length and frequencies of dry spells computed on sowing-day basis

The length of dry spells for consecutive 10-day periods after sowing was determined for each of the five

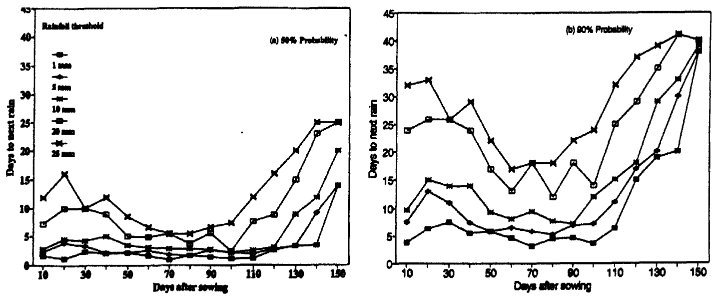


FIG. 1. Number of days until next rainfall greater than the threshold values at (a) 50% probability and (b) 90% probability at Ouagadougou, Burkina Faso.

rainfall thresholds at three probability levels (90%, 50%, and 10%). The choice of these probability levels reflects the degree of certainty with which the user would like to determine the dry-spell length. An example of the computed values for Niamey, Niger, is shown in Table 2. For consecutive 10-day periods after sowing, the results show the mean rainfall and the dry-spell length at different probability levels. Since the analysis was based on the onset of rains for each year of the database, mean rainfall data provide a good idea of the average rainfall pattern during the crop cycle at Niamey. Assuming that a pearl millet variety of a 90-day maturity duration comes to the panicle initiation stage within 20 days after sowing (DAS) and to the flowering stage by 50–60 DAS, mean rainfall from sowing to panicle initiation stays around 35 mm/10 days and increases to 49 mm/10 days by the time of flowering.

Data under the 90% probability columns show that, starting a given 10-day period after sowing, 90% of the dry spells will end within the number of days given. For example, at 50 DAS, for the 10-mm rainfall threshold, 90% of the dry spells will end in 10.3 days or less, while 50% of the dry spells will end in 3.9 days or less.

A plot of the dry-spell lengths at different rainfall thresholds and two probability levels for Ouagadougou, Burkina Faso, is shown in Fig. 1. Mean annual rainfall at Ouagadougou is 792 mm, and hence the waiting period at all rainfall thresholds is much less than that observed for Niamey (Table 1), where the mean annual rainfall is 560 mm. One significant feature that emerges from the data in Fig. 1 is the pronounced drop in the drought risk (or the waiting period for rainfall) from 20 DAS to 60 DAS. This is more evident at the 90% probability level (Fig. 1b) than at the 50% probability level (Fig. 1a). In terms of crop phenology the implication is that dry spells from the stage of emergence to panicle initiation (up to 20 DAS) last longer than those during panicle initiation to flowering (20–60 DAS). The length of dry spells increases with time after 100 DAS.

The underlying physical mechanism for the observed lower drought risks from 20 to 60 DAS could be attributed to the more or less regular positioning, by this time, of the ITCZ, backed by the moist southwesterly monsoon, which has embedded easterly waves with associated cloud clusters and squall (or disturbance) lines (Farmer and Wigley 1985).

Frequencies of dry spells have been computed at three rainfall thresholds of 1, 10, and 20 mm for dry spells of <5, 5–10, 10–15, 15–20, and >20 days. The percentage frequency of dry spells at Kaya, Burkina Faso, is shown in Table 3. Mean annual rainfall at Kaya is 696 mm. The data show that at the lower rainfall threshold of 1 mm, the frequency of dry spells of <5 days is by far much higher in comparison to other dry-spell ranges. As the rainfall threshold is increased from 1 to 20 mm, the percentage frequency of dry spells of <5 days decreases and the frequency for the other ranges increases.

At lower rainfall locations, the shift in percentage frequencies from one rainfall threshold to another is more pronounced than for the higher rainfall locations. An example of this feature is shown in Fig. 2 for Mopti, Mali (mean annual rainfall 696 mm), and in Fig. 3 for Kedougou, Senegal (mean annual rainfall 1288 mm). At Kedougou the percentage frequency is highest for dry spells < 5 days (Fig. 3) at all three rainfall thresholds. At the lowest rainfall threshold of 1 mm,

TABLE 3. Percentage frequency of dry spells for indicated rainfall thresholds at Kaya, Burkina Faso.

Days after sowing	Rainfall threshold (mm)	Dry spells (days)				
		<5	5–10	10–15	15–20	>20
10	1	82	18	0	0	0
	10	60	18	12	2	8
	20	34	14	14	14	24
20	1	69	20	8	3	1
	10	42	23	11	12	12
	20	23	25	5	15	32
30	1	80	15	2	3	1
	10	48	31	6	6	9
	20	28	26	17	6	23
40	1	75	20	5	0	0
	10	57	22	14	5	2
	20	42	15	14	14	15
50	1	86	12	0	2	0
	10	55	31	11	3	0
	20	37	34	15	6	8
60	1	89	11	0	0	0
	10	71	23	6	0	0
	20	55	22	12	8	3
70	1	92	8	0	0	0
	10	82	12	3	3	1
	20	60	22	6	5	7
80	1	89	11	0	0	0
	10	75	12	5	3	5
	20	51	26	9	3	11
90	1	89	9	0	0	2
	10	69	20	3	2	6
	20	57	26	3	3	11
100	1	86	9	2	0	3
	10	71	17	3	0	9
	20	45	22	5	6	22
110	1	78	6	3	2	11
	10	55	18	3	0	24
	20	34	15	12	5	34
120	1	68	12	6	0	14
	10	45	17	8	2	28
	20	34	18	5	3	40
130	1	63	8	3	5	21
	10	34	9	11	8	38
	20	18	8	8	8	58
140	1	49	11	9	0	31
	10	23	12	8	5	52
	20	11	11	3	0	75
150	1	38	11	5	3	43
	10	17	11	2	3	67
	20	5	5	2	3	85

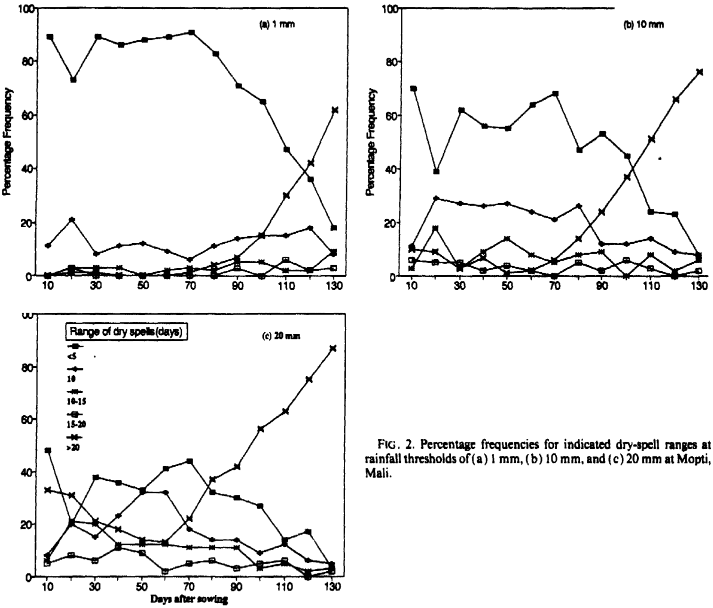


FIG. 2. Percentage frequencies for indicated dry-spell ranges at rainfall thresholds of (a) 1 mm, (b) 10 mm, and (c) 20 mm at Mopti, Mali.

the frequency spread for dry spells > 10 days is very small, but as the rainfall threshold is increased to 20 mm, the separation of frequencies for dry spells > 10 days is more apparent. At all three rainfall thresholds the percentage frequency for dry spells of <5 days shows a decrease from 120 DAS with a simultaneous increase in the frequencies for the dry-spell range of 5–10 days.

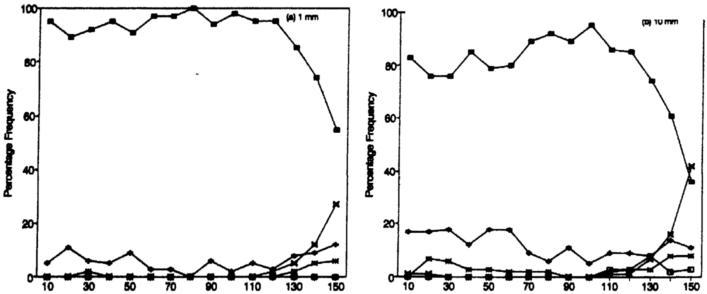
In view of the differing pattern of the drought frequencies with mean annual rainfall that emerged from Figs. 2 and 3, calculations were made of the dry-spell frequencies for 150 locations in West Africa to examine if there is any particular trend to this pattern across all locations. The average frequency of dry spells of <5, 10–15, and >20 days was calculated at the 10-mm rainfall threshold. The relationship between mean annual rainfall and the average frequency for dry-spell ranges (Fig. 4) shows distinct patterns. Frequencies of the lowest dry-spell range of <5 days increase asymptotically with increasing annual rainfall (Fig. 4a). For the intermediate dry-spell range of 10–15 days, frequencies are low (3%–12%) and change little as annual rainfall increases (Fig. 4b). With dry spells exceeding 20 days (Fig. 4c), the frequencies decrease sharply with increasing mean annual rainfall. The relationships in Fig. 4 are well defined by the fitted equations and permit the prediction of the frequency of dry spells from annual rainfall totals. These relationships will be valid only in locations with a monomodal rainfall distribution pattern that is so common in the Sahel.

From the discussion on dry-spell lengths and frequencies for West Africa, the following conclusions can be drawn.

(i) Drought risks in West Africa are very much related to the mean annual rainfall. With increasing annual rainfall, the percentage frequencies of short dry spells increased, while the frequencies of long dry spells decreased.

(ii) In general, dry spells around panicle initiation phase are longer than those during the flowering phase, particularly for the low-rainfall locations.

(iii) Dry spells become progressively longer at some



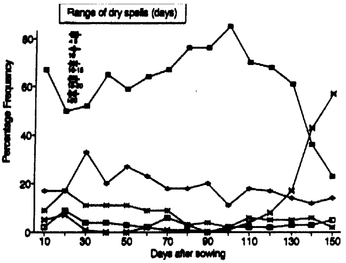


FIG. 3. Percentage frequencies for indicated dry-spell ranges at rainfall thresholds of (a) 1 mm, (b) 10 mm, and (c) 20 mm at Kedougou, Senegal.

point during the grain-filling phase. At low-rainfall locations, this point occurs much earlier in the growing season in comparison to the higher rainfall locations.

4. Application of the analysis

In the arid and semiarid regions, where moisture is available for a relatively short period during the year, it is essential to match the crop phenology with the dry-spell lengths to meet the crop water requirements at the sensitive stages of crop growth. Information on the length of dry spells could be used as a guide for the choice of a particular crop or variety. For instance, at Niamey beyond 90 DAS the dry spells are longer, and it would be prudent to limit the choice of crop varieties to those that mature in 80–90 days.

With the increasing interest in exploring alternatives to the present cropping patterns in West Africa for greater productivity, dry-spell analysis could provide information on probable mismatches of phenology of a new crop and rainfall regime before expensive field trials are conducted.

Data on dry-spell lengths could also be used as a guide for breeding varieties of various maturity durations for different locations. An example of this application is shown in Fig. 5 for Niamey, Niger (mean annual rainfall 560 mm); Kaolack, Senegal (800 mm); Ouagadougou, Burkina Faso (830 mm); and Bougouni, Mali (1260 mm). At Niamey the length of dry spells increases with time after 90 DAS. Kaolack and Ouagadougou, with nearly similar mean annual rainfall, show some differences in the lengths of dry spells. Dry spells become progressively longer after 90 DAS at Kaolack and after 120 DAS at Ouagadougou. Breeding strategies should be oriented toward maturity in 80 days for Niamey, 90 days for Kaolack, 110 days for Ouagadougou, and 140 days for Bougouni.

Information on dry-spell lengths could also be used in decision making with respect to supplementary irrigation and field operations such as harvesting. For high-value crops, dry-spell lengths at 90% probability level could be used as a guide to schedule supplementary irrigations, since it is almost certain that the dry spells will end before the period computed. In regions

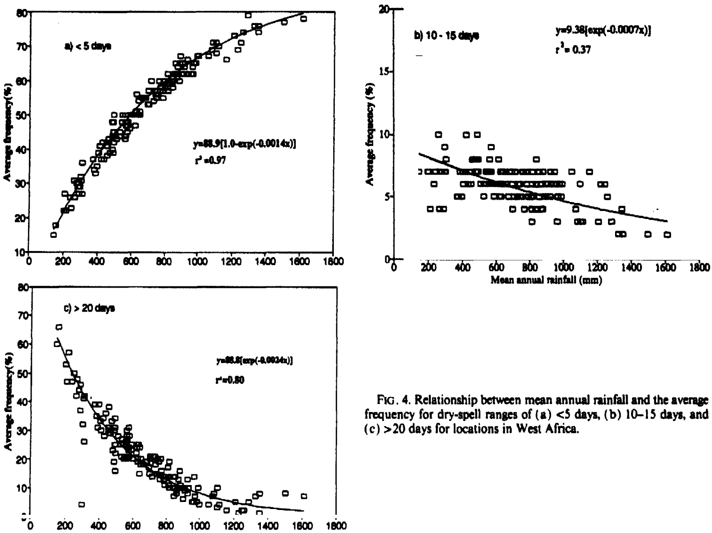


FIG. 4. Relationship between mean annual rainfall and the average frequency for dry-spell ranges of (a) <5 days, (b) 10–15 days, and (c) >20 days for locations in West Africa.

where groundnut is grown, it is important to schedule harvest operations before the soil becomes too hard due to long spells of dryness.

Using the data on dry-spell frequencies, one can provide answers to questions such as: At 60 days after sowing the crop, when at least half of the crop water requirement of 40 mm over the next 10 days must be met, what is the probability that sufficient rain will occur within 10 days? At Kaya, Burkina Faso (Table 3), the answer to this question would be that there is a 78% probability for the occurrence of this event (look for the value under the "<5" and "5–10" dry-spell columns for 60 DAS and the 20-mm rainfall threshold). Dry-spell frequency data could also be used in the design of, and in interpreting results from, multilocation tests in plant-breeding programs.

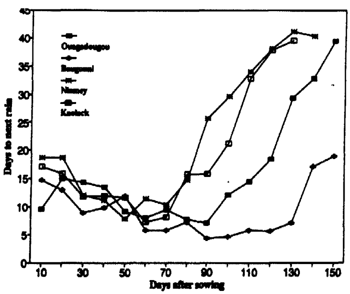


FIG. 5. Length of dry spells for 10-mm rainfall threshold at 90% probability for four locations in West Africa.

5. Conclusions

Data presented in this paper show that historical rainfall data could be effectively employed for a simple, empirical analysis of dry spells to provide information on the length of dry spells and their frequencies and probabilities. For agricultural applications, it is important to note that the nature of dry spells varies with the crop growth phases and that dry spells during the flowering phase of cereal crops are much shorter in West Africa. This contrasts significantly with the nature of dry spells in some parts of the semiarid tropical region of Asia, where dry spells in the middle of the rainy season (coinciding with the flowering phase) are considered to be more important. Simple analysis of dry spells illustrated here could clarify important research issues for agronomy and plant-breeding applications in West Africa.

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