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# PREDICTING MONTHLY AND SEASONAL RAINFALL, ONSET AND CESSATION OF THE RAINY SEASON IN WEST AFRICA USING ONLY SURFACE DATA

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## ABSTRACT

New empirical long-range schemes for the prediction of dates of onset and cessation and of the monthly and annual amounts of rainfall are developed for Kano, in the West African Sahel, using only surface synoptic data. They are based on variations in equivalent potential temperature, $\theta_e$, which occur as a result of the seasonal, monthly and daily variations of moisture in the summer monsoon flow over West Africa. Agricultural activities may begin about 72 days after the day the anomalies of $\theta_e$ (i.e. $\theta'$) first become positive for at least 15 days, essentially signifying the beginning of adequate moisture supply associated with a well established monsoon flow.

The new schemes ensure that both the cessation date and the annual amount of rainfall can be predicted *prior to* the onset of the rains, thus providing, in conjunction with the onset date, very important and useful information for reliable and effective planning of agricultural and water resource activities. Performance tests using an 11-year independent data set indicate that the schemes possess reliable skill.

Because the weather over Nigeria is very typical of the entire West African region, being affected by the same wind regime and weather phenomena, these prediction schemes will provide tremendous assistance for enhanced and sustainable agriculture, as well as for efficient water resources management, if extended to the whole area. Furthermore, the methods have the important advantage that, bearing in mind the fact that the majority of West African countries have very sparse, if indeed, any upper-air data, the surface synoptic data needed for their use are readily available in *all* of the countries. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: West Africa; equivalent potential temperature; rainfall onset; cessation and amounts

## 1. INTRODUCTION

West African precipitation is strongly dependent on the southwest monsoon flow, which has the unique characteristics of high seasonal, monthly and daily variability in its moisture content and (vertical) depth. These variabilities are particularly strong in the lowest 1 km of the atmosphere. The strength and direction of the variations generally determine the type, nature, extent and intensity of the resultant weather, particularly the thunderstorms and squall lines which are responsible for over 70% of the total annual precipitation over West Africa (Omotosho, 1985).

The most important problems associated with rainfall variability as a result of changes in moisture availability are:

(i) The highly variable dates of onset of the rainy season at one station and from one station to another. These variations could be up to 70 days from one year to another at a single station, as will be shown later.

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(ii) The temporal (monthly and annual) distribution of the precipitation at each station or over a small area.
(iii) The cessation and length of the rainy/growing season.

The onset dates are the most critical. Reliable prediction of onset time will greatly assist on-time preparation of farmlands, mobilisation of seeds/crops, manpower and equipment and will also reduce the risks involved in planting/sowing too early or too late.

Predicting the start of the rains in West Africa is a very challenging task because of the irregularities in the rainfall distribution, both in time and in space. Prediction methods have been proposed, some based on rainfall data alone (Ilesanmi, 1972; Obasi and Adefolalu, 1977; Stern *et al.*, 1982; Fasheun, 1983; Nnoli, 1996). These rainfall models cannot address the year-to-year variations in the onset dates. Other schemes are based on upper winds (e.g. Beer *et al.*, 1977; Omotosho, 1990, 1992). Omotosho's (1990) scheme, now in operational use at the African Centre of Meteorological Applications for Development (ACMAD), is capable of addressing the year-to-year variations in the atmospheric conditions and, hence, in precipitation. Omotosho (1992) also proposed a long-range onset prediction method based on upper wind direction changes alone.

However, even after crops/seeds have been planted/sown, they will still require favourable rainfall conditions during the early stages in order to eliminate crop failure. In addition, appropriate decisions with regard to irrigation needs and their timings, as well as water conservation strategies for dams and hydro-electric power utilisation, are all dependent on reliable estimates of monthly and seasonal precipitation prospects or amounts. Furthermore, a reasonable knowledge of the date of rainfall cessation enables the prediction of the length of the growing or rainy season, which is most useful for the selection of crop varieties, crop matching and cropping sequences (Kowal and Knabe, 1972). Therefore, in order to ensure maximum and sustainable agricultural productivity, as well as efficient water resource management practices, reliable predictions of the monthly and annual precipitation, the cessation date and the length of the rainy season are all equally very important.

Early methods for estimating annual precipitation were inter-tropical discontinuity (ITD)-rainfall models (e.g. Ilesanmi, 1972; Kowal and Knabe, 1972), which gave same rainfall estimates every year at each station or latitude. Omotosho (1992) proposed a scheme based on the accumulated moisture (specific humidity departures) within the boundary layer in the early stages of monsoon development. This method possesses the inherent ability to account for the annual variability in rainfall amounts. However, a major disadvantage of the schemes of Omotosho (1990, 1992) is the sparse network of the required upper-air data over the entire West African region. At present, there are also sea surface temperature (SST) models, which can predict rainfall amount (e.g. Lamb and Peppler, 1992; Eltahir and Gong, 1996; Fontaine and Janicot, 1996; Janicot *et al.*, 1998 and other models), but whose skills are still rather low (correlation coefficients of 0.3–0.4) and which only give estimates for the peak rainy season, i.e. July–September.

Similarly, all existing cessation models, except that of Omotosho (1992), are rainfall-based and give the same dates of cessation of rainfall every year, which is certainly far from reality. Omotosho's (1992) method, which is based on the vertical wind shear associated with the mid-tropospheric Africa easterly jet (AEJ), is also capable of treating each year independently; however, the sparse upper-air network again limits its application. In addition, the model can only be used several weeks after the onset of rainfall, by which time all planting and sowing have already been completed. Furthermore, the authors know of no method presently being used that gives estimates of monthly precipitation values or prospects. Obviously, there is a strong need for new and long-range schemes based on more readily available data and which will consequently have wider applicability. The present study is, therefore, an attempt to provide some solutions to the above critical problems.

Because West African precipitation is strongly dependent on the monsoon flow, its unique characteristics of seasonal, monthly and daily variability is, therefore, utilised to develop empirical prediction schemes for the onset, cessation, monthly and annual amount of rainfall over Kano in Nigeria. As the direction and intensity of these moisture and temperature variations of the flow over West Africa are adequately monitored by the equivalent potential temperature ($\theta_e$), a very conservative parameter with

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respect to both saturated and unsaturated (dry) atmospheric process, the parameter is employed in the simple schemes presented in this paper. Obasi (1964) and Adefolalu (1972) used the parameter to investigate rainfall variability over Lagos during the so-called 'little dry season' (July–August) of the coastal areas of West Africa. More recently, Omotosho (1989a) proposed the use of the anomalies of the parameter (i.e. $\theta'_e$) as predictors of the onset, persistence and clearance of dust haze over Kano. Later, using energetics analysis, Omotosho (1989b) further suggested that the observed negative anomalies ($\theta'_e < 0$) are essentially the result of the horizontal transport of drier and, to a lesser degree, colder air.

## 2. DATA AND ANALYSIS

### 2.1. The data

Daily mean values of surface pressure ($P$), temperature ($T$) and relative humidity ($RH$) for the months of March, April and May for about 26 years between 1966 and 1996 (15 years for developing and 10–11 years for testing the schemes) constitute the main data for this work. The 26 years are those for which continuous and consistent data are available, while the subdivision ensures that both good and bad rainfall years are in both the modelling and the validation periods. In addition, daily rainfall amounts for each of the chosen years were collected in order to determine the onset and cessation dates of rainfall, the dates of first precipitation (of 1.0 mm and 10.0 mm), and the monthly as well as the annual rainfall totals.

### 2.2. Equivalent and saturated equivalent potential temperatures

The equivalent potential temperatures were evaluated as follows. The saturation vapour pressures ($e_s = f(T)$ only) were computed from the integral of the Clausius–Clapeyron equation as

$$e_s = e_{so} \exp\,[M_v L_v (T - T_0)/R^* T_0 T], \tag{1}$$

where $e_{so} = 6.11$ hPa, $T_0 = 273.16$ K, $R^*$ is the universal gas constant, $L_v$ is the latent heat of vaporisation and $M_v$ is the molecular weight of water vapour. The saturation specific humidity $q_s$ was then evaluated from the relation:

$$q_s = \in_1 e_s/(P - \in_2 e_s), \tag{2}$$

where $\in_1 = 0.622$ and $\in_2 = 0.378$.

Next, the potential temperature, $\theta$, is evaluated from the Poisson equation as

$$\theta = T(1000/P)^{\kappa},$$

where $\kappa = R/C_p$, and $R$ and $C_p$ are the gas constant and specific heat for dry air at constant pressure, respectively.

Finally, the saturation equivalent potential temperature, $\theta_{es}$, was calculated from the expression

$$\theta_{es} = \theta \exp\,(L_c q_s/C_p T), \tag{3}$$

where $L_c$ is the latent heat of condensation. The actual air $\theta_e$ is similarly given by

$$\theta_e = \theta \exp\,(Lq/C_p T_v), \tag{4}$$

where $q$ is the specific humidity of the air and $T_v$ is its virtual temperature.

Long-term, large-scale averages of $\theta_e$ and $\theta_{es}$ (i.e. $\bar{\theta}_e$ and $\bar{\theta}_{es}$) were calculated using data of mean pressure ($\bar{P}$), temperature ($\bar{T}$) and relative humidity ($\overline{RH}$) taken from World Meteorological Organization (1996) (WMO) No. 847 of the 1996 Climatological Normals (Clino) for the period 1961–1990, and also from data supplied by the relevant countries, on request. The anomalies of equivalent potential temperature ($\theta_e$) were then computed for each day and averaged over 5-day periods to give time series of pentade values.

The West African atmosphere, like everywhere in the tropics, is inherently convectively and conditionally unstable. Convective instability is usually investigated through the use of equivalent potential temperature, $\theta_e$, whereas its saturation value, $\theta_{es}$, is used to study conditional instability. These are conservative parameters with respect to both saturated and unsaturated processes. Both parameters have been widely used to study the tropical atmosphere, particularly convection (Jordan, 1958; Obasi, 1964; Garstang *et al.*, 1967; Adefolalu, 1972). However, for a complete study of instability processes in the tropics, it is necessary to investigate the behaviour of both parameters together (A.K. Betts, personal communication, 1990). In West Africa, with its high daily, monthly and seasonal variations of moisture, these two variables would together serve to 'monitor' the relative warmness and moistness of the atmosphere over any location.

Now, $\theta_{es}$ represents the equivalent potential temperature of a hypothetically saturated atmosphere having the same temperature. Hence $(\theta_{es} - \theta_e)$ may be thought of as the '*moisture deficit*' of an unsaturated atmosphere, i.e. the additional amount of moisture required to bring it to saturation. Because $\theta_e$ is highly affected by variations in the moisture content, the anomalies of the parameters (i.e. $\theta'e$ and $\theta'_{es}$) are used in this study in order to provide more salient and interesting information. It must be noted, however, that although $\theta_{es} > \theta_e$, it is generally not the case for $\theta'_{es}$ and $\theta'_e$ Therefore, some insight is provided below into the possible meanings of $\theta'_e$ and $(\theta'_e - \theta'_{es})$.

Petterssen (1956) showed that at any level in the atmosphere,

$$C_p\theta_e = C_pT + Lq(1000/P)^k + gz, \tag{5}$$

where $T$ is the air temperature, $q$ is the specific humidity, $z$ is the height, $C_p$ is the specific heat at constant pressure and $g$ is the acceleration owing to gravity. Furthermore, Garstang *et al.* (1967) also showed that, because $q$ is large only in the lower atmosphere (in fact, below 900 hPa in West Africa), within limits of the accuracy of $q$, expression (5) may be approximated to

$$C_p\theta_e = C_pT + Lq + gz. \tag{6a}$$

But the moist static energy, $H_m$, at any level $z$ is given by

$$H_m = C_pT + gz + Lq. \tag{6b}$$

Hence

$$H_m = C_p\theta_e. \tag{7}$$

Thus, the moist static energy is proportional to the equivalent potential temperature.

Now

$$\theta'_e - \theta'_{es} = (\theta_e - \bar{\theta}_e) - (\theta_{es} - \bar{\theta}_{es}),$$

where $(\bar{\theta}_e)$ denotes long-term time averaging. Using the virtual temperature $T_v$ in $\theta_e$, applying (6a) and neglecting variations in $gz$, which are small in the tropics, it may be shown that

$$\theta'_{es} - \theta'_{es} = T'_v - T' + L\,(q' - q'_s)/C_p,$$

where $q_s$ is the saturation value of $q$, but $T_v = T(1 + 0.61q)$; so, neglecting variations $C_p$ (owing to $q$), the above expression becomes

$$\theta'_e - \theta'_{es} = 0.61\,(\bar{T}'q' + \bar{q}T' + T'q') + L(q' - q'_s)/C_p. \tag{8}$$

Typically in West Africa, $\bar{q} \sim q' \sim 10^{-2}$, $\bar{\mathrm{T}} \sim 300$ K and $\bar{\mathrm{T}}' \sim 10$ K. With $L \sim 10^6$ J/kg and $C_p \sim 10^3$ J/kg/K, expression (8) reduces to

$$\theta'_e - \theta'_{es} \sim L(q' - q'_s)/C_p. \tag{9}$$

Thus, the difference between the anomalies $\theta'_e$ and $\theta_{es}$ is just the difference between the anomalies $q'$ and $q'_s$.

Now for

$$q' > 0 \text{ and } q'_s > 0.$$

$$\theta'_e - \theta'_{es} > 0 \text{ if } q' > q'_s$$

or

$$\theta'_e - \theta'_{es} < 0 \text{ if } q' < q'_s.$$

But $q' > 0$ implies air that is moister than normal; $q'_s > 0$ means that the air would require more moisture than normal to bring it to saturation, i.e. it is drier than normal; in addition, $q' < 0$ denotes a drier than normal atmosphere and $q'_s < 0$ has opposite meaning to $q'_s > 0$. Thus, for an atmosphere with *pre-rainy season moisture build-up*, the only possibility is that

$$q' > 0,\ q'_s < 0, \text{ i.e. } q'_s < 0 < q'.$$

Here '*pre-rainy-season*' means the transition months of April and May, as the dust haze periods end in March.

In this case,

$$\theta'_e - \theta'_{es} > 0 \rightarrow \theta'_e > \theta'_{es}. \tag{10a}$$

With similar argument, the second situation where

$$\theta'_e - \theta'_{es} < 0 \rightarrow \theta'_e < \theta'_{es} \tag{10b}$$

is for an unusually drier than normal pre-season atmosphere This latter case provides some particularly interesting and important results and is discussed further in Section 3.3.3.

In the present study, six variants of $\theta'_e$ and its combination with $\theta'_{es}$ have been utilized as follows:

(i) the dates, $d$, when $\theta'_e > 0$ for at least three pentades, which indicates the beginning of abundant moisture supply, is used to predict the date of rainy season onset.
(ii) $\Sigma\theta'_e$ from March to May, which may be thought of as the '*accumulated excess moisture*', is used for annual/seasonal rainfall prediction. It is analogous to the method of Omotosho (1990).
(iii) The time that elapses after $\theta'_e > 0$ for 15 days before the first significant precipitation ($R \geq 1.0$ mm or 10.0 mm) falls provides a second method of estimating seasonal rainfall amount.
(iv) $\Sigma\,\Delta = \Sigma(\theta'_e - \theta'_{es})$ for the previous 2 months is used to forecast precipitation for the (following) third month. That is, March $\Delta$ + April $\Delta$ is used to predict May rainfall and so on.
(v) $\Sigma\,\Delta$ from March to June is a third method predicting seasonal rainfall.
(vi) The point of maximum separation between the $\theta'_e$ and $\theta'_{es}$ series, i.e. the date of the highest pre-season moisture build-up, is employed to predict the cessation date of the rainy season.

## 3. RESULTS AND DISCUSSION

### *3.1. Date of onset of the rainy season (OR)*

The date of onset of the rainy season was defined by Omotosho (1990), who also reviewed previous definitions. Table I shows significant variabilities in the date of onset of the rainy season for some West African stations. However, a re-analysis of rainfall data for Bamako (Mali), N'Djamena (Chad) and Niamey (Niger) to which the prediction scheme and onset definition of Omotosho (1990) have been applied since 1995 showed that the requirement for '. . . *the first three or four rainfalls of at least 10 mm with not more than 7 days between them*', which was used to obtain the results in Table I, is often difficult to meet, thus making model assessment difficult. Hence, it was deemed necessary to review the definition.

The first 20–28 days are the most critical for seed germination and crop establishment. It is thus important to have one or two initial heavy rainfalls ($\geq 10.0$ mm) to moisten and soften the soil sufficiently for seed germination and also to ensure crop survival in the following twenty days. It is for this reason that a modified definition has been proposed as follows: '*the beginning of the first two rains*

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Table I. Rainy season onset dates at three Sahelian stations

| | Bamako | Niamey | Kano |
|---|---|---|---|
| 1971 | 11 June | 9 July | 3 July |
| 1977 | 10 June | 26 June | 3 June |
| 1978 | *25 April* | 31 May | 29 May |
| 1983 | *8 July* | 11 June | *17 July* |
| 1984 | – | *9 May* | 1 June |
| 1987 | 11 June | *10 July* | 24 Junk |
| 1992 | 16 May | 6 June | *11 May* |
| 1994 | 27 May | 4 June | 5 June |
| 1995 | 10 May | 14 June | 8 June |
| 1996 | 16 May | 24 June | 3 June |
| 1997 | 25 May | 28 May | 23 May |

Dates in italics are for the *earliest* and *latest* onset.

*totalling 20 mm or more, within 7 days, followed by 2–3 weeks each with at least 50% of the weekly crop–water requirement*'. The 50% requirement (4 mm for Kano) was given by Kowal and Knabe (1972) and is also in use at AGRHMET, Niamey, Niger. This new definition is adopted in the present study. It has also been in use at ACMAD for all applications of the Omotosho (1990) scheme to stations in the West Africa Sahel since February 1998.

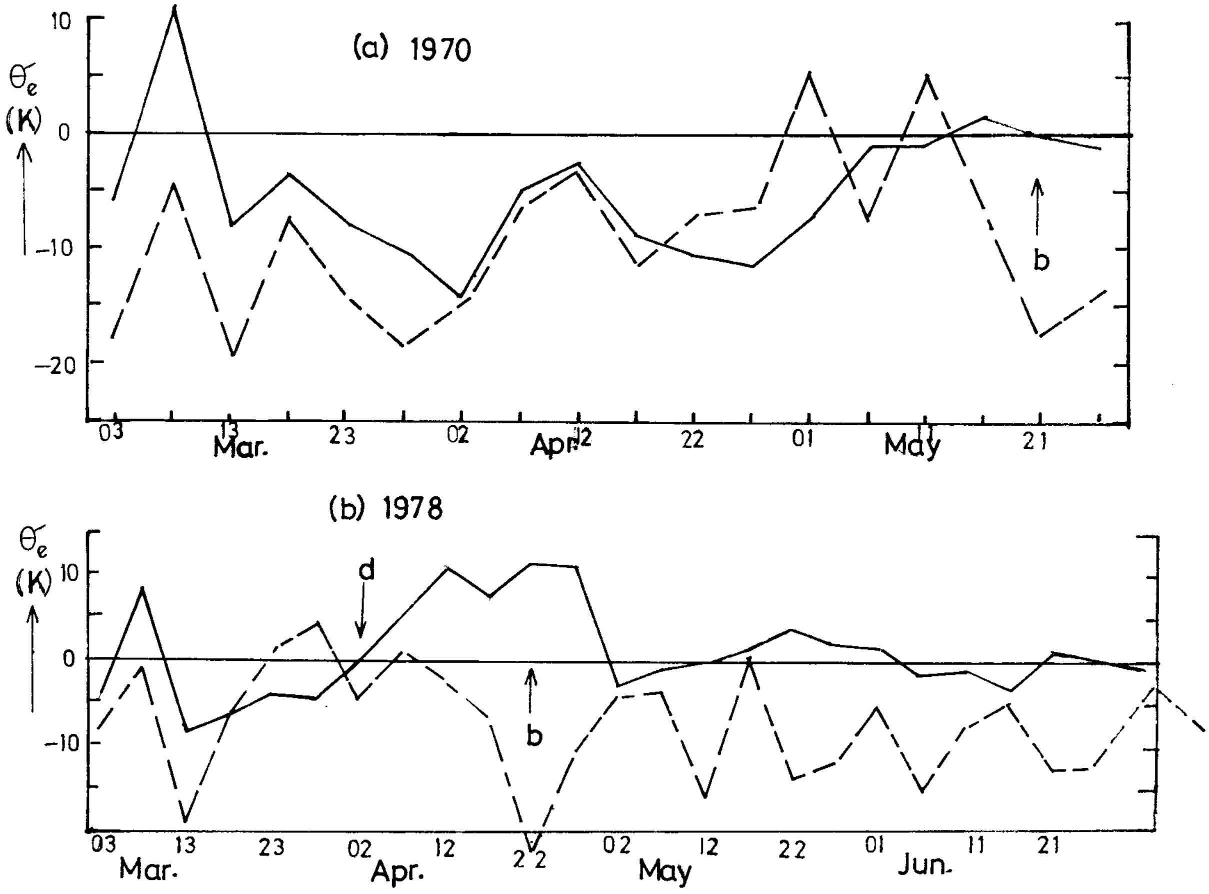

Figure 1. Pentade series of $\theta'_e$ and $\theta'_{es}$ at Kano

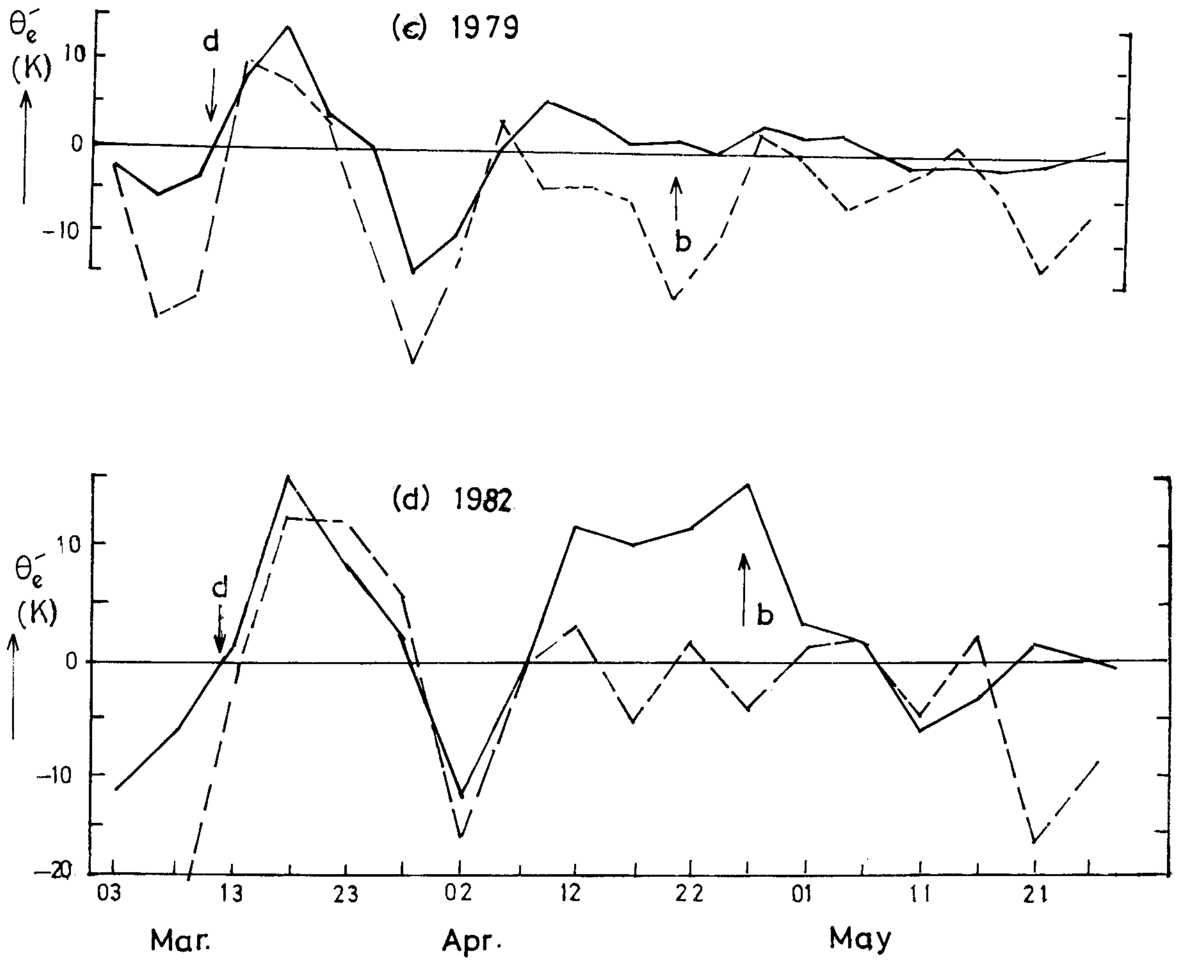

Figure 1 (*Continued*)

The time series in Figure 1 represent eight of the studied years. From these, the number of days '*D*' between the date *d* in Figure 1, when $\theta'_e$ first becomes positive (i.e. $\theta'_e > 0$) for at least three pentades (15 days), and the dates of rainfall onset (*OR*) for each year were noted and the mean determined for all 15 years. Because $\theta'_e$ is analogous to the specific humidity anomaly $q'$ (see Equation (9)), the date of $\theta'_e > 0$ signifies the beginning of proper moisture supply necessary to moisten the already very dry and often dusty atmosphere. The mean of *D* was 72 days. Thus, in any year, if the date *d* when $\theta'_e > 0$ for greater than or equal to three pentades is known, then *OR* for that year is given by

$$OR = d + 72 \text{ days.} \tag{11}$$

The method was tested using an independent data set (1965–1975). The results are depicted in Figure 2, and show good agreement between actual (*ORa*) and predicted (*ORp*) dates of onset of precipitation, except during three years. No prediction was made for 1970 because $\theta'_e > 0$ for 15 days was indeterminate (see Figure 1(a)). Based on decadal crop–water requirements, the predicted OR is taken as correct if it is within 10 days of the actual date of onset.

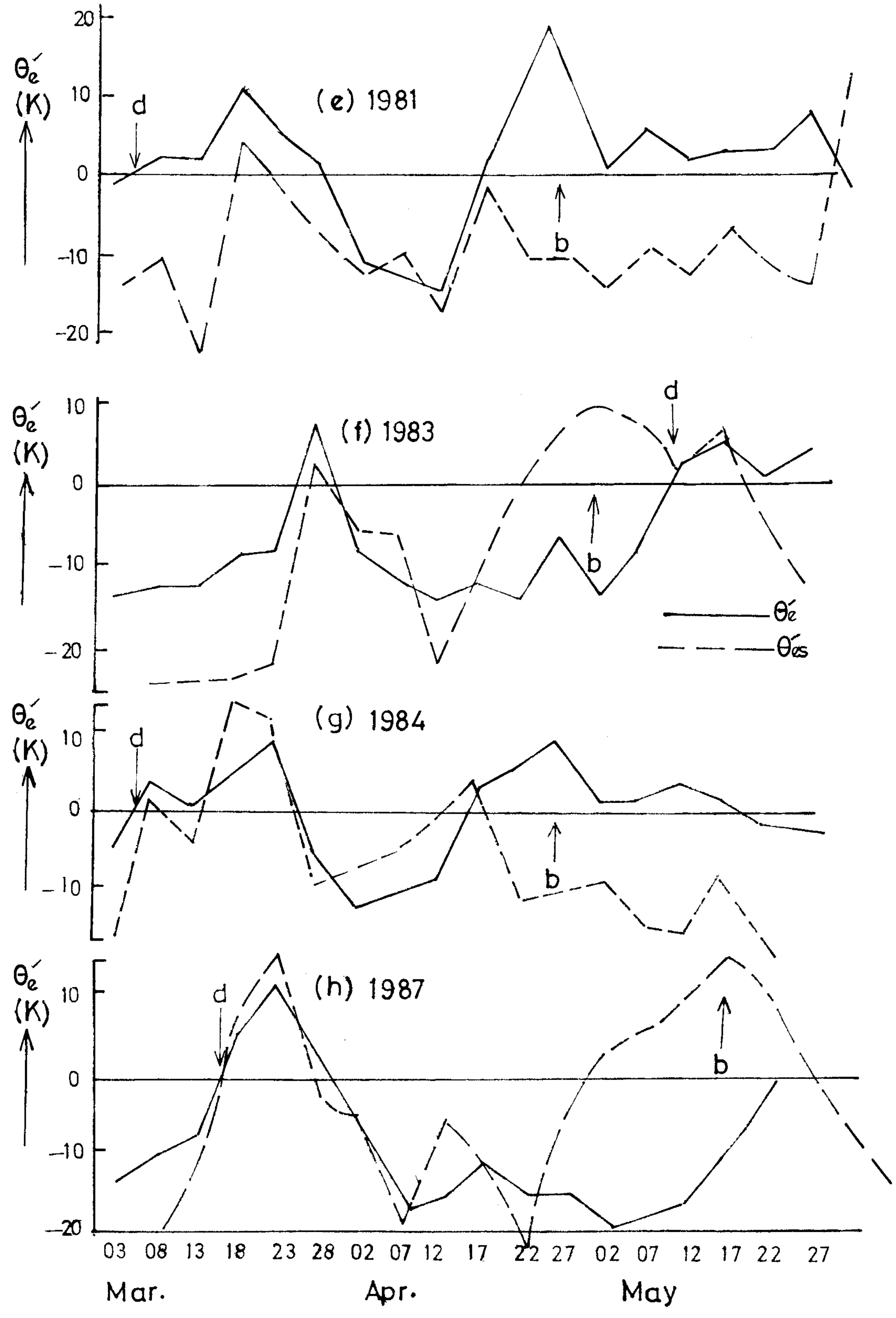

Figure 1 (*Continued*)

### *3.2. The cessation and length of the rainfall season*

In this method, the first step is to note the dates ($b$) of the points of maximum separation between $\theta'_e$ and $\theta'_{es}$ (Figure 1), which denote the pentades in which the maximum pre-season moisture build-ups occur. This is carried out for all 26 years.

Next, the dates of cessation of rainfall ($CR$), defined as 'any day from 1 September after which there are 21 or more consecutive days of rainfall less than 50% of the crop–water requirement', are also noted for each of the years. It may be noted that the only difference between this and the definition of Omotosho (1992) is the stipulation of 21 instead of 15 days of dry spell. Again, as was explained earlier, this slight modification is a result of detailed study of more than 50 years of rainfall data. Finally, the number of days between $CR$ and $b$ are determined for each of the 15 years. The mean is 149 days. Thus, once $b$ is known, the rainy season is expected to end on the day given by

$$CR_p = b + 149. \tag{12}$$

This is then applied to the data of 1965–1975. The results are given in Table II. The errors (in days) are within the variability range for the cessation of rainfall at Kano.

Furthermore, the length of the rainy or growing season (LRS/LGS) may be obtained using the following formula:

$$\mathrm{LRS/LGS} = CR_p - OR_p. \tag{13}$$

The results, also given in Table II, together with their errors, are very encouraging.

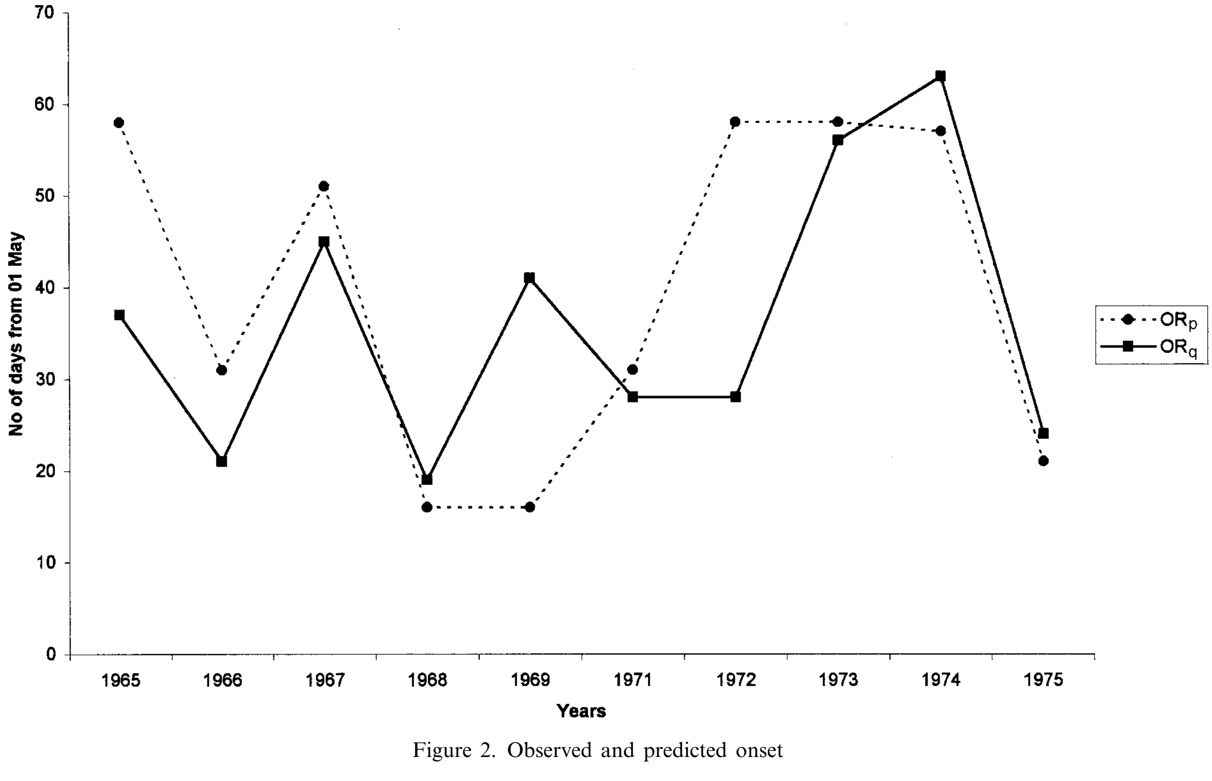

Figure 2. Observed and predicted onset

Table II. Actual and predicted onset, cessation and length of the rainy season at Kano

| | Cessation dates *CR* | | | Onset dates *OR* | | | Length of rainy/growing season (LRS/LGS) in days | | |
|---|---|---|---|---|---|---|---|---|---|
| | Actual | Predicted | Error (days) | Actual | Predicted | Error days | Actual | Predicted | Error (days) |
| 1965 | 7 October | 13 September | −24 | 6 June | 27 June | +21 | 123 | 78 | −45 |
| 1966 | 27 September | 23 September | −4 | 21 May | 31 May | +10 | 129 | 115 | −14 |
| 1967 | 28 September | 19 September | −9 | 14 June | 20 June | +6 | 106 | 91 | −15 |
| 1968 | 22 September | 20 September | −2 | 19 May | 16 May | −3 | 126 | 127 | +1 |
| 1969 | 16 October | 9 September | −37 | 10 June | 16 May | −15 | 128 | 116 | −12 |
| 1970 | 26 September | 5 September | −21 | 13 June | — | — | 105 | — | — |
| 1971 | 23 September | 28 September | +5 | 28 May | 31 May | +3 | 118 | 120 | +2 |
| 1972 | 3 October | 23 September | −10 | 28 May | 27 June | +30 | 128 | 88 | −40 |
| 1973 | 23 September | 3 October | +10 | 25 June | 27 June | +2 | 90 | 98 | +8 |
| 1974 | 2 October | 3 October | +1 | 2 July | 26 June | +6 | 92 | 99 | +7 |
| 1975 | 20 September | 23 September | +3 | 24 May | 21 June | −3 | 119 | 125 | +6 |

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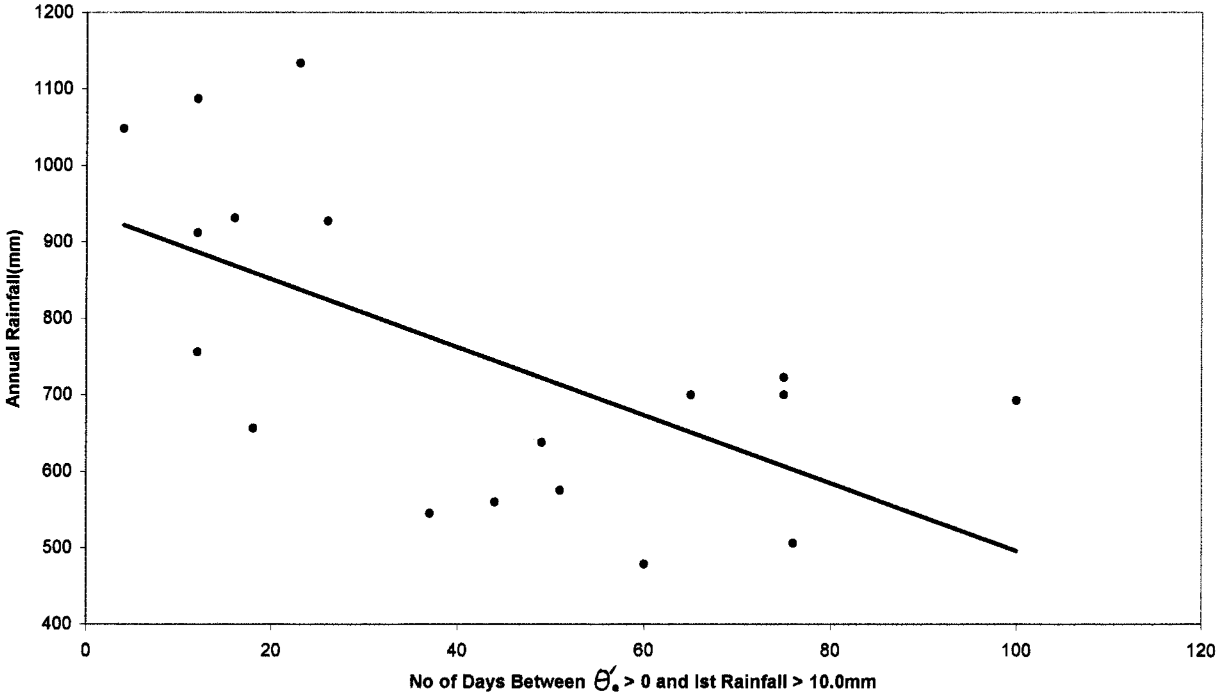

Figure 3. Seasonal rainfall prediction for Kano from first heavy rainfall method

*3.3. Seasonal rainfall amount*

Adefolalu (1973) showed that August precipitation in Lagos may be predicted from $\theta_e$ anomalies. In the present study, this same parameter is used to develop a scheme to estimate annual/seasonal rainfall. Three different methods are proposed.

*3.3.1. Precipitation amount from $\theta'_e > 0$ and first 10 mm rainfall.* In this case, the number of days *D2* between the date when $\theta'_e$ first becomes positive for at least three pentades and that of the first precipitation of either 1.0 mm or 10.0 mm is correlated with the seasonal rainfall. Because the minimum weekly crop–water requirement is about 8 mm, a 10-mm rainfall threshold, which satisfies this criterion and also ensures adequate initial wetting and softening of the soil, was used for the regression analyses. However, a threshold value of 1.0 mm could also be used.

The annual estimates can be obtained from Figure 3 or from the regression equation:

$$R\ (\text{mm}) = 945.4 - 5.44D2. \tag{14}$$

Seasonal rainfall estimates for ten other independent years, obtained from the equation, are given as $R_1$ in Table III.

*3.3.2. Rainfall from 'accumulated excess moisture', $\Sigma\ \theta'_e$.* The scatter plot and line of best fit are shown in Figure 4. The regression equation for the predicted precipitation (in mm) is

$$R = 738.2 + 1.4\ \Sigma\ \theta'_e, \tag{15}$$

where Σ is taken from March to May inclusive.

The observed (*Ro*) and the predicted (*R*) rainfall from Equation (15) for the 11 independent years are given in Table III as $R_2$. It can be seen that the scheme predicts rather better than does Equation (14) in many years but it does not predict extreme values well. Omotosho (1990) used an analogous method—the

Table III. Actual and predicted annual rainfall at Kano (with categories)

| Year | Precipitation (mm) | | | | Category using $+25\%\ \bar{R}$ | | | | Percentage error from observed *R*o | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Actual | Predicted | | | Actual | Predicted | | | | | |
| | *Ro* | $R_1$ | $R_2$ | $R_3$ | *Ro* | $R_1$ | $R_2$ | $R_3$ | $R_1$ | $R_2$ | $R_3$ |
| 1965 | 904 | 668 | 557 | 726 | N | N | B/N | N | −26 | −38.0 | −19.7 |
| 1966 | 776 | 750 | 675 | 842 | N | N | N | N | −3.4 | −13.1 | +8.5 |
| 1967 | 789 | 733 | 664 | 719 | N | N | N | N | +7.2 | −15.8 | −8.9 |
| 1968 | 611 | 701 | 682 | 892 | N | N | N | N | +14.7 | +11.6 | +46.0 |
| 1969 | 909 | 668 | 746 | 612 | N | N | N | N | −26.5 | −17.9 | −32.7 |
| 1970 | 922 | – | 613 | 707 | N | – | N | N | – | −33.5 | −23.3 |
| 1971 | 706 | 886 | 611 | 647 | N | N | N | N | +25.5 | −13.5 | −8.4 |
| 1972 | 669 | 875 | 706 | 768 | N | N | N | N | +30.8 | +5.5 | +14.8 |
| 1973 | 414 | 499 | 564 | 530 | B/N | B/N | B/N | B/N | +20.5 | +36.2 | +28.1 |
| 1974 | 661 | 842 | 638 | 617 | N | N | N | N | +27.4 | −3.5 | −6.7 |
| 1975 | | | 716 | 743 | N | N | N | N | 1.8 | <0.1 | +4.3 |
| From percentage errors, No. of predicted years within ±20% of observed *Ro* | | | | | | | | | 4 | 8 | 7 |

Index $R_1$: from first rainfall $R \geq 10.0$ mm; $R_2$: using $\Sigma\,\theta'_e$; $R_3$: using $\Sigma(\theta'_e - \theta'_{es})$; Normal, N: $R$ within $\bar{R} \pm 25\%$; Below normal, B/N: $R < \bar{R} - 25\%$ Above normal, A/N: $R > \bar{R} + 25\%$.

accumulated moisture (specific humidity anomalies, $q'$) within the boundary layer between April and the date of rainfall onset (end May/June)—to predict seasonal precipitation. However, unlike $\theta_e$ used here, specific humidity, $q$, is a non-conservative variable.

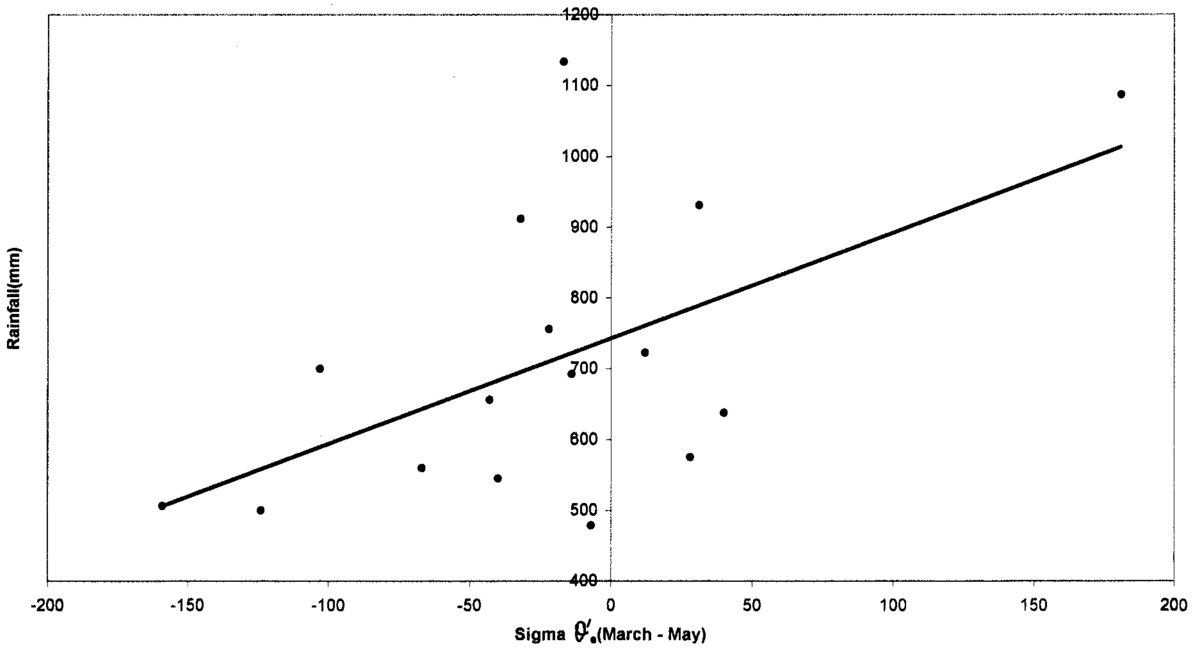

Figure 4. Seasonal rainfall prediction for Kano from accumulated excess moisture method

*3.3.3. Precipitation amount from* $\Sigma\,\Delta = \Sigma(\theta'_e - \theta'_{es})$. The regression equation from this method is of the form

$$R\ (\text{mm}) = 600.7 + 0.80\,\Sigma\,\Delta, \tag{16}$$

where $\Sigma\,\Delta$ is from March to June inclusive.

Equation (16) could serve as an update for Equations (14) and (15) as the summation is now taken up to June. Comparisons of the observed and the predicted rainfall and their percentage errors for the validation data are made in Table III, with the results from Equation (16) listed as $R_3$.

It is now interesting to discuss briefly the series for $\theta'_e$ and $\theta'_{es}$ shown in Figure 1 for some years. It can be seen that, in general, $\theta'_{es} < 0 < \theta'_e$ from the second half of April to mid or late May, except in 1983, 1987 and 1973 (not shown) where $\theta'_e < 0 < \theta'_{es}$. It should be recalled that these three years and 1984 were severe drought years with $R \lesssim 500$ mm. However, 1984 has series that are similar to those of normal or good rainfall years. Nevertheless, the behaviour of the series may provide an important signal for predicting low (bad) rainfall years.

In Table III, the rainfall results have also been classified into categories following Omotosho (1990, 1996) but here using $\pm 25\%$ $R$ limits for Bad/Normal/Good years. They are in good agreement with actual (observed) precipitation. Using values, however, the predicted rainfalls are within 20% of the observed ($Ro$) values in at least for seven out of 11 cases for $R_2$ and $R_3$, but the accuracy is low for $R_1$, although it tends to give better estimates for years of low rainfall.

### 3.4. *Monthly rainfall estimates*

Between latitudes 11°N and 14°N (Kano is ~12°N), rainfall during the months of May and June is extremely crucial for crop survival because of the high temperatures and evaporation rates. This is because the rainy season onset is usually within these 2 months and the first 20–30 days following sowing and planting are the most critical. Hence, knowledge of the expected rainfall in these months is very important for planning irrigation needs.

In the method proposed here, $\Sigma\,\Delta = \Sigma(\theta'_e - \theta'_{es})$ for March and April is used to estimate May precipitation, $\Sigma\,\Delta$ (April and May) is used for June rainfall, and so on. However, only May and June results, shown as rainfall departures from the long-term mean versus $\Sigma\,\Delta$, are presented in Figure 5 because the accuracy of the prediction decreases significantly after June. This is to be expected because, in the early rainy season (May and June), the moisture depth is shallow and the depth of the convectively unstable atmospheric layer is high (Obasi, 1964). In July, and particularly in August, the monsoon layer has become very deep, reaching up to 800 hPa (and even 700 hPa) and strongly reducing the instability.

Obasi (1964) also showed that, over Lagos in these 2 months which are known as the ‘little dry season’ period over the coastal parts of West Africa, convectively stable layers are often embedded in an otherwise convectively unstable atmosphere. He also found that, whereas the highest levels of convectively unstable layers occur in May and June, the lowest occur in July. Hence, other instability release mechanisms (e.g. transient easterly waves) are probably now more important.

The observed and the predicted May and June precipitation for the validation years 1965–1975 are given in Table IV. The regression equations are as follows:

$$\text{For May:}\quad R\ (\text{mm}) = 14.1 + 0.30\,\Sigma\,\Delta. \tag{17a}$$

$$\text{For June:}\quad R\ (\text{mm}) = 35.5 + 0.79\,\Sigma\,\Delta. \tag{17b}$$

In these, the rainfall anomalies ($R'$ from Figure 5) have been converted to actual values. In addition, Table IV provides a comparison of the predicted and the actual values for the low rainfall years (category below normal, B/N) in each month, which, as stated above, can have disastrous consequences for crop survival. The usefulness of the schemes is quite obvious.

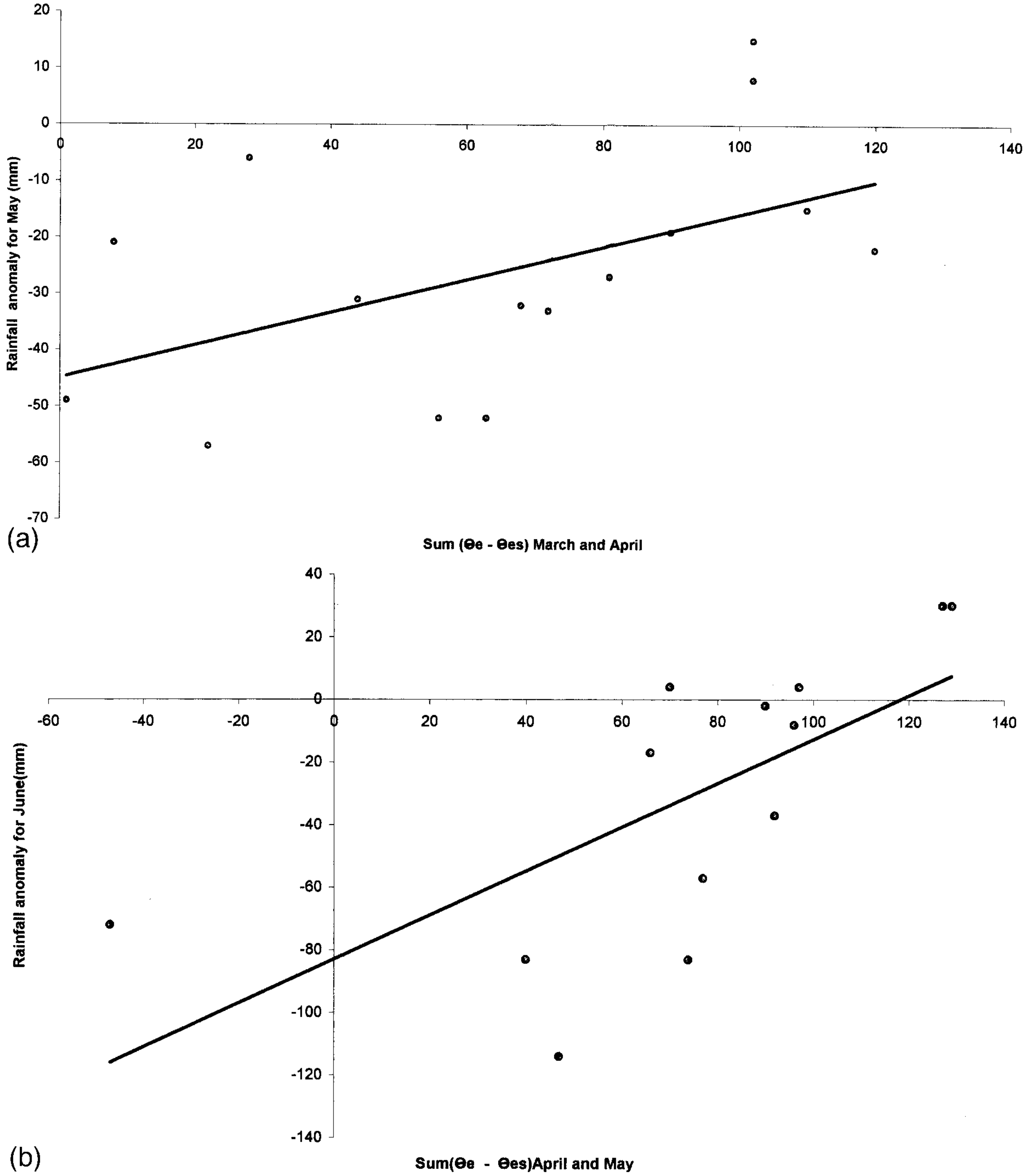

Figure 5. (a and b) Monthly rainfall prediction for Kano

However, because monthly precipitation forecasting for a single station or small area in West Africa is a completely new exercise and overlaps both medium- and long-range parts of the prediction spectrum, the results presented here should be used with caution. In this respect, the categorisation of expected monthly rainfall prospects would be more appropriate and reliable than actual monthly values.

Table IV. Actual and predicted May and June rainfall at Kano (with categories) using $\Sigma(\theta'_e - \theta'_{es})$

| Year | May | | | | June | | | |
|---|---|---|---|---|---|---|---|---|
| | Rainfall (mm) | | Category using $\pm 20\%$ $\bar{R}$ | | Rainfall (mm) | | Category using $\pm 20\%$ $\bar{R}$ | |
| | Observed *Ro* | Predicted *R* | Observed *Ro* | Predicted *R* | Observed *Ro* | Predicted *R* | Observed *Ro* | Predicted *R* |
| 1965 | 5 | 56 | B/N | N | 247 | 50 | A/N | B/N |
| 1966 | 112 | 61 | A/N | N | 93 | 156 | B/N | A/N |
| 1967 | 58 | 55 | N | N | 154 | 84 | A/N | B/N |
| 1968 | 42 | 66 | B/N | N | 147 | 212 | A/N | A/N |
| 1969 | 28 | 24 | B/N | B/N | 191 | 66 | A/N | B/N |
| 1970 | 17 | 31 | B/N | B/N | 53 | 80 | B/N | B/N |
| 1971 | 69 | 34 | N | B/N | 24 | 69 | B/N | B/N |
| 1972 | 100 | 45 | A/N | B/N | 133 | 104 | N | N |
| 1973 | 3 | 26 | B/N | B/N | 39 | 10 | B/N | B/N |
| 1974 | 42 | 36 | B/N | B/N | 43 | 92 | B/N | B/N |
| 1975 | 40 | 42 | B/N | B/N | 127 | 126 | N | N |
| Mean, $R$ (1935–1995) | 59 mm | | | | 119 mm | | | |
| No. of years predicted to be below $\bar{R}$ | 9 | | | | 8 | | | |
| Actual No. of years below $\bar{R}$ | 8 | | | | 5 | | | |
| No of years correctly predicted | 7 | | | | 4 | | | |

Index Normal, N: $R$ within $\bar{R} \pm 20\%$; Below normal, B/N: $R < \bar{R} - 20\%$; Above normal, A/N: $R > \bar{R} + 20\%$.

## 4. CONCLUSION

For the first time and using only surface data, reasonably reliable empirical methods have been developed for predicting the onset and cessation, and monthly and seasonal amounts of rainfall at Kano, a Sahelian station in Nigeria. These were based on the unique characteristics of the West African flow regime (the seasonal, monthly and daily variabilities of its moisture content) through the use of equivalent potential temperature, a parameter that is conserved for both dry and saturated processes. Because the variations in the parameter are based on the variabilities in the moisture of the monsoon flow affecting the whole of West Africa, which Nigeria adequately typifies, similar methods can be used for the entire region.

Because upper-air stations are few in number and not consistently operational in West Africa, these new and simple schemes have three important advantages over all other methods, where they exist:

(i) the surface data required for them are readily available at many stations in each country;
(ii) the annual variations in the dates of onset, cessation and rainfall amounts are accounted for through the variability of $\theta'_e$ resulting from either the seasonal or the monthly variations of moisture (of the monsoon flow);
(iii) it is now possible to predict the cessation and the annual amount of rainfall prior to the onset of the rains, thus allowing advance and effective planning of agricultural and water resources activities; and
(iv) prediction of rainfall for the first 2 months of the rainy season will greatly assist irrigation planning.

The schemes together will, therefore, provide welcome solutions to most of the rainfall prediction problems of the region.

It may, at first sight, seem rather surprising that it is possible to use only surface data to develop such apparently reliable schemes for an all-round rainfall prediction over West Africa. However, upon the realisation that, in the tropics and particularly over the highly heated continental West Africa, it is mostly the surface and near-surface air that ascends to form the clouds that produce the precipitation, it becomes obvious that the characteristics (heat and moisture properties) of this air would certainly determine rainfall and its variations over the sub-region. However, it is recognised that the use of only surface data has limitations, as can be seen particularly in Table IV for monthly rainfall prediction.

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