Some Characteristics of the Rainfall Regime at Douala, Cameroun

By

Samuel Mbele-Mbong

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Colorado State University

Department of Atmospheric Science

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SAMUEL MBELE - MBONG

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ABSTRACT

Thirty-four years (1936-1969) of daily rainfall occurrence and total amounts for Douala, Cameroun (4° 04N, 9° 41E) have been analyzed by means of four different techniques, namely: simple Markov chain, depth-duration-frequency, Gumbel extreme value, and variance spectrum.

In the simple Markov chain model, the probability of rainfall occurrence on any day depends on whether or not rain fell the preceeding day. The model produced theoretical probabilities that fit the observed frequencies and thereby suggest first-order persistence of atmospheric conditions favorable to rainfall occurrence at this tropical station. The depth-duration-frequency analysis showed that major storms at Douala have a modal duration of 1-3 days, while periods of this length were indicated by the variance spectrum method to contain most of the variance.

Although the statistical significance of the spectral peaks remains to be tested and the analysis extended to more stations in the study area, the above characteristics of the rainfall regime at Douala seem to indicate predominant forcing of the daily rainfall process by synoptic-scale atmospheric phenomena. The nature of this forcing needs to be explored.

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LIST OF SYMBOLS

C_j Amplitude

D(K) Smoothing function in the lag domain

EDF Equivalent number of degrees of freedom

E[f(x)] Expected value of f(x)

f_j Ordinary frequency

f(x) Function of x

$F(X) = P(X \leq x)$ Probability that $X \leq x$

$f_c(\tau)$ Covariance function

g(f) Sample estimate of $\gamma(f)$

g(f) Unbiased estimate of g(f)

g_x Average annual number of independent daily values

i Time unit of observation; index

j Index in the Fourier summation

K Lag

ln Natural logarithm

m Maximum number of lags

m_τ Mean

n_iN Length of record

Pn Probability of rainfall occurrence in n-1 days

P_1 Probability of any day being wet

r_k Serial correlation coefficient

S_n Reduced standard deviation

S Standard deviation

S(f) Smoothing function in the frequency domain

t Time

t_{α}, $t(\alpha)$ Student t statistic

T_r Return period (recurrence interval)

X, $X_{i\tau}$, $\{X_t\}$ Observed value of variable X

$\overline{X}$ Mean of X

X_f Mode of X

y Reduced variate or linearizing variable

$\overline{y}$ Mean of y

α Confidence level

$\gamma(\lambda)$ Variance density function (spectral density of the unit variance density)

ε_i Deviation from the mean

θ_j Phase

λ_j Angular frequency

μ_x Mean

ν_{λ} Variance density spectrum

$\nu(\lambda)$ Variance density function

ρ_1 Conditional probability of a day being wet given that the previous day was dry

$\rho(\tau)$ Auto correlation function

σ_x Standard deviation

σ_x^2 Variance (var (x), var x)

τ Lag, duration

τ_1 Conditional probability of any day being wet given that the previous day was wet

χ^2 Chi-square distribution

LIST OF SYMBOLS (CONTINUED)

$\psi(\lambda)$ Spectral density function (variance density spectrum)

ω Period

I. INTRODUCTION

The research on "Water Resources Development in Africa, the Cases of Cameroun and Ghana", has three major objectives, the relevance and timeliness of which are made manifest by the proposed GARP Atlantic Tropical Experiment (GATE) and Continental Africa Project (CAP): (1) to describe the hydroclimatology of this region and in so doing (2) to contribute basic information that may be later used for planning the development and management of water resources there; possibly to develop useful principles for such planning; (3) to contribute to the improvement of the present state of knowledge of the meteorology of Africa. The research was to be carried out in three separate steps, namely data collection, data analysis and rainfall model design.

In the case of Cameroun, the first step, to date, has consisted in the search for climatological data. Thus annual, monthly and daily rainfall records for 29 stations in Cameroun and many more stations in Central Africa (Chad, Central African Republic, Congo, and Gabon) have been obtained through the Inter-Library Loan Service, from the Atmospheric Sciences Library, Silver Springs, Maryland. The length of record varies from station to station, 34 years for Douala, Cameroun being the maximum. Table I shows data on the rainfall stations in the study area.

To fill the gaps in some records, correspondence was initiated with the Cameroun Meteorological Service. Unfortunately no positive result to data has been forthcoming.

The monthly data were checked for homogeneity and independence. In the case of homogeneity, monthly fluctuations for 29 Cameroun stations were plotted; an example can be seen in Figure 1. Figure 1a shows monthly means. Visual examination of monthly rainfall anomalies, (Figure 2) failed to disclose any noticeable trends or jumps.

To test for independence, the correlogram, rk, for various lags k (k = 1, 2, ... 12 months) was computed for the variable

$$\varepsilon_i = X_{i\tau} - m_\tau$$

where τ is the month, and m_τ the monthly mean. By definition (Yevjevich, 1972, p.34) the correlogram or serial correlation is given by the expression:

$$r_k = \frac{\text{Cov}\ (X_i,\ X_i{+}k)}{(\text{Var}\ X_i\ \text{Var}\ X_i{+}k)^{\frac{1}{2}}}$$

$$r_k = \frac{\frac{1}{N-k}\sum_{i=1}^{N-k} X_i X_i{+}k - \frac{1}{(N-k)^2}\sum_{i=1}^{N-k} X_i \sum_{i=1}^{N-k} X_i{+}k}{\left[\frac{1}{N-k}\sum_{i=1}^{N-k} X_i^{\,2} - \frac{1}{(N-k)^2}\left(\sum_{i=1}^{N-k} X_i\right)^2\right]^{\frac{1}{2}} \left[\frac{1}{N-k}\sum_{i=1}^{N-k} X_i^{\,2}{+}k - \frac{1}{(N-k)^2}\left(\sum_{i=1}^{N-k} X_i{+}k\right)^2\right]^{\frac{1}{2}}}$$

with tolerance limits computed from:

$$r_k\ (5\%) = \frac{-1 \pm 1.645\sqrt{N-k-1}}{N-k}$$

The results for Douala are shown in Figure 3. Because for the 95 percent level of tolerance limits about 5 percent of the rk values should be outside these limits, and none was outside the limits, it may be assumed that in this case, the series of monthly rainfall anomalies is not distinguishable from an independent series provided the autocorrelation coefficients, rk, are mutually uncorrelated. This result means that monthly rainfall deficits or surplus with respect to the monthly mean is independent of the previous month, i.e., factors influencing monthly rainfall other than the annual periodicity represented by the annual mean, have a period less than one month.

From the foregoing, it was concluded that, for Douala, the data show no noticeable inhomogeneity, i.e., no transient components (trends, jumps, of slippages) superimposed on the rainfall series.

Step II, namely the analysis is still underway. Several analysis techniques, including frequency-depth-duration, extreme value, Markov chain and variance spectrum, have been adapted to date. The application of these methods to the data for Douala constitutes the remainder of this report.

II. SOME CHARACTERISTICS OF THE RAINFALL REGIME AT DOUALA

1. Depth-Duration-Frequency Analysis

This method is applicable to point or station rainfall analysis and normally uses the output of a recording rain gauge. From this continuous record, the rainfall mass curves for all large storms measured at the station are plotted. Next standard intervals of time are selected, e.g., 30 min., 1 to 24 hours, and the rainfall above a chosen crossing level for each selected interval is read from the mass curve. The partial series so generated for each duration is submitted to a frequency analysis by the Gumbel method (described below) to obtain a depth-duration-frequency (return period) graph.

A storm was taken as an uninterrupted sequence of one or more days with rainfall greater than or equal to 1 millimeter. This truncation level was arbitrary. A better threshold value (to be used later) is the mean value for a particular month of the year. Storms with a cumulative amount equal to or greater than 50mm were used for the frequency analysis. The storms by duration are given in Table II. Figure 4 shows the number of storms with yields equal to or greater than 50mm. Figure 5 shows the result of the Gumbel analysis for the partial series of Table II. Computations of the 95% confidence limits suggested that probable values for return periods less than 2 years or greater than 10 years are not reliable. Similarly for durations greater than 5 days. Consequently, only durations of 1 to 5 days and return periods of 2 to 10 years are shown in Table III and Figure 6. Table IV shows mean rainfall yields for "storms" of various durations and the dispersion about the mean.

The following results are thought to be important:

a. Rainfall episodes yielding 50mm or more defined as major "storms", have durations ranging from 1 to 31 days, with 3 days as the mode.

b. For a given duration (τ = 1 to 5 days), the probable extreme rainfall amount corresponding to a return period of 3 years has the smallest 95% confidence interval.

c. The yields for major "storms" of all durations are very variable.

2. Extreme Value Analysis

Twenty-four hour periods with rainfall larger than 100mm ($\sim$4 in.) were selected for each year for the period 1936-1969. The 100 values of the partial series so generated are given in Table V.

The Gumbel extreme value analysis to be presently described was applied to this series.

a. Review of the Theory. -- Consider the daily values of a hydro-meteorological element (WMO, 1969). Let g_x be the average annual number of independent daily values. Then the probability that a daily value exceeds x is g_x/n; while the probability that a daily value is less than x is $1-(g_x/n)$.

The probability F(x) that the annual maximum (or the largest of values above an arbitrary base) is less than or equal to x is then given by

$$F(x) = P(X \leq x) = 1 - \frac{g_x}{n} \qquad (2.1)$$

Now the limiting value of $(1-\frac{t}{n})^n$ for large n is e^{-t}. So to a close approximation, one may write

$$F(x) = P(X \leq x) = e^{-g_x} \quad (2.2)$$

If we define $y = -\log g_x = a(x-x_f)$, then the probability F(x) that the maximum is less than or equal to x can be written

$$F(x) = P(X \leq x) = e^{-e^{-y}} \quad (2.3)$$

y is called the reducing variate or linearizing function. For a given record, $y = a(x-x_f)$, where $x_f = \bar{x} - 0.45005\sigma_x$ is the mode, a measure of the central tendency, and $a = \frac{\pi}{6\,\sigma_x}$ is the dispersion parameter. $\bar{x}$ is the mean of the series and σ_x the standard deviation which measures the dispersion of the data about the mean.

But

$$P(X \leq x) = \frac{1}{1 - T_r} \quad (2.4)$$

where T_r is the recurrence interval or return period, defined as the average number of years between events of equal or greater magnitude. Therefore:

$$1 - \frac{1}{T_r} = e^{-e^{-y}} \quad (2.5)$$

Taking the logarithm of both sides and rearranging:

$$X(T_r) = X_f + \frac{1}{a} \ln\left[-\ln\left(1-\frac{1}{T_r}\right)\right]$$

$$= X_f + \frac{1}{a}\left(\ln T_r - \frac{1}{2T_r} - \frac{5}{24T_r^2} - \frac{1}{8T_r^3}\right) \quad (2.6)$$

or

$$X(T_r) \approx X_f + \frac{1}{a} \ln T_r$$

Given the mean and standard deviation of a hydrometeorological series, in this case the partial series of daily rainfall, equation 2.6 may be used to estimate extreme values, $X(T_r)$, for selected return periods T_r.

Then the accuracy of the computed values $X(T_r)$ may be evaluated as follows: (1) select a confidence level, α, e.g., 95%; (2) from a Table obtain $t(\alpha)$; (3) compute $S_e = \beta(T_r)$, where $\beta(T_r) = (1 + 1.14K + 1.1K^2)^{\frac{1}{2}}$ and $K = \frac{y(T_r) - \bar{y}_n}{S_n}$; where $y(T_r)$ is the reduced variate expressed as a function of return period, $\bar{y}_n$ and S_n are the reduced mean and standard deviation, respectively. The values of $\bar{y}_n$ and S_n are functions only of the sample size, and can be obtained from Tables. K is known as frequency factor. (4) compute the confidence interval $\pm t(\alpha)S_e$ within the limits of which, with the given confidence level, α, one may expect to find the true rainfall value $x(T_r)$.

b. Results. -- The results are shown in Table VI.

By way of interpretation, Table VI predicts, for example, that the probable 34-year largest 24-hour rainfall depth for Douala will lie between 256mm and 204mm. The probability of depths below or within this interval is $1 - \frac{1}{T_r} = 1 - \frac{1}{34} = .97$. The probability of depths above this interval is 1/34 = 0.03. Indeed the largest value observed (Table V) is 238mm. The results of Table VI are plotted in Figure 7.

3. Simple Markov Chain Probability Model for Daily Rainfall Occurrence at a Station

a. The Probability Model. -- The objective is the estimation of the probability P_n of rainfall occurrence in n-1 days. If the model produces theoretical probabilities that fit the observed probabilities, then it can be used to estimate other properties of the observation.

In the simple Markov chain model, the probability of rainfall occurrence on any day depends on whether or not rain fell the preceding day. The probability is assumed to be independent of previous days.

The basic recursive formula for the model is

$$P_n = 1 - (1 - P_1)\ (1 - \rho_1)^{n-1} \qquad (3.1)$$

where ρ_1 = Pr{wet day/previous day dry}

P_1 = Pr{any day being wet}

$= \rho_1(1 - \tau_1 + \rho_1)^{-1}$

τ_1 = Pr{wet day/previous day wet} (3.2)

if $\rho_1 = \tau_1$ (i.e., previous day makes no difference), then $P_1 = \rho_1$ and the model is said to be random (Caskey, 1963).

The computational procedure is as follows: for a given station, observed frequencies are first obtained from the observations, and used to compute ρ_1 and τ_1. For the pair of values ρ_1 and τ_1, for each month or season, P_1 is then computed from Equation (3.2). With P_1 and ρ_1 determined, Equation (3.1) gives a theoretical curve for the Markov chain values of P_n. These values are plotted against n, as are the observed frequencies. The observed frequencies may also be plotted against the corresponding Markov chain values, and against the values computed from the random model. The random model, obtained by putting $P_1 = \rho_1$ in Equation 3.1, i.e.,

$$P_n = 1 - (1 - \rho_1)^n \qquad (3.3)$$

would be reasonable if persistence of daily rainfall occurrence were negligible (Caskey, 1963).

If the plot of the observed frequencies against the Markov chain values shows a good correlation between computed and observed probabilities, then the model may be used with confidence in estimating other properties of the observations of which the most important are (Gabriel and Neumann, 1961) the following:

(i) Probability of rainfall occurrence i days after a wet day:

$$P_1 + (1 - P_i)d^i \qquad (3.4)$$

where $d = \tau_1 - \rho_1$

(ii) Probability of rainfall occurrence i days after a dry day

$$P_1 + P_1 d^i \qquad (3.5)$$

(iii) Probability of a wet spell of length k (i.e., a sequence of k wet days preceded and followed by dry days)

$$(1 - \tau_1)\tau_1^{k-1} \qquad (3.6)$$

(iv) Probability of a dry spell of length m

$$\rho_1 \, (1 - \rho_1)^{m-1} \qquad (3.7)$$

(v) Probability of a weather cycle of n days(i.e., a combination of a wet spell and an adjacent dry spell)

$$\rho_1 \, (1-\tau_1) \, \frac{(1 - \rho_1)^{n-1} - \tau_1^{n-1}}{1 - \rho_1 - \tau_1} \qquad (3.8)$$

(vi) Probability of exactly s wet days among n days following a wet day

$$Pr\{S/n, 1\} = \tau_1^s \, (1 - \rho_1)^{n-s} \sum_{C=1}^{C_1} \binom{|s|}{a} \binom{n-s-1}{b-1} \left(\frac{1-\tau_1}{1-\rho_1}\right)^b \left(\frac{P_1}{\tau_1}\right)^a \qquad (3.9)$$

where

$$C_1 = \begin{cases} n + \frac{1}{2} - |2S - n + \frac{1}{2}| & \text{if } S < n \\ o & \text{and the sum involves only this term if } S = n \end{cases}$$

$a = \frac{1}{2}(C - 1)$

$b = \frac{1}{2} C$

are least integers

(vii) Probability of exactly s wet days among n days following a dry day

$$Pr\{S/n,\ o\} = \tau_1^{\,s}\,(1-\rho_1)^{n-S} \sum_{C=1}^{C_o} \binom{S-1}{b-1}\binom{n-S}{a}\left(\frac{1-\tau_1}{1-\rho_1}\right)^a\left(\frac{\rho_1}{\tau_1}\right)^b \qquad (3.10)$$

where

$$C_o = \begin{cases} n + \tfrac{1}{2} - |2S - n - \tfrac{1}{2}| & \text{if } S < n \\ 0 & \text{and the sum involves only this term if } S = n. \end{cases}$$

(viii) Probability of s wet days among n days

$$P_r\{S/n\} = P_1\ Pr\{S/n,\ i\} + (1 - P_1)\ Pr\{S/n,\ o\} \qquad (3.11)$$

(ix) For large n, the distribution of the number of wet days tends to normality with

mean $$E(S) = nP_1 \qquad (3.12)$$

and variance $$Var\ (S) = nP_1\ (1-P_1)\ \left(\frac{1+d}{1-d}\right) \qquad (3.13)$$

b. Results. -- Table VII shows, by month, the number of wet days, the estimates of the conditional probabilities ρ_1 and τ_1, and the estimate of the probability of any day being wet. The theoretical Markov chain model probability curves are found in Figure 8, while Figure 9 shows the observed probabilities for n = 2, ..., 30 plotted against the corresponding Markov chain values and also against values computed for random daily precipitation occurrences. Figure 9 shows the extent to which the Markov model improved the correlation between computed and observed probabilities for Douala over that given by the random model.

Equations (3.4) through (3.13) have not been applied.

4. Variance Density Spectrum Analysis

a. Definition. For the purpose of defining variance density spectrum or continuous spectrum, Figure 10 is used as a sample of the continuous hydrometeorological process $\{X_t\}$, e.g., rainfall. This finite series of length T may be fitted by trigonometric functions of the type

$$X_t = \mu_x + C_1 \text{ Cos } (2\pi f_1 t + \theta_1) + C_2 \text{ Cos } (2\pi f_2 t + \theta_2) + \ldots + C_j \text{ Cos } (2\pi f_j t + \theta_j) + \ldots + C_n \text{ Cos } (2\pi f_n t + \theta_n) \quad (4.1)$$

in which the ratio of any two frequency f_i/f_j is an irrational number, i.e., the frequencies are not commensurate. Such functions will fit every point of the series provided frequencies are sufficiently dense on the f-line and their parameters, the amplitudes C_j and angular phases θ_j are estimated for each f_j by a proper estimation technique.

If only a limited number of f-values is used as an approximate fit of the sample series, each particular discrete value f_j with the estimates of the amplitude C_j and the phase θ_j has the variance $C_j^2/2$ (Yevjevich, 1972, p.68). A plot of $C_j^2/2$ versus the ordinary frequencies, f_j, is called a line-spectrum, a discrete spectrum, or a periodogram. Using the angular frequency, $\lambda_j = 2\pi f_j$, the relation

$$C_j^2/2 = g(\lambda_j) \quad (4.2)$$

is the variance line-spectrum of the series, x_t, with

$$\sum_{j=1}^{n} C_j^2/2 = \text{var } x_t = \sigma^2_x \quad (4.3)$$

If $\Delta\lambda$ is an interval on the λ-line, and for each interval $\Delta\lambda$, at λ, the variance of all the fitted trigonometric functions is defined as ΔD, then (Yevjevich, 1972, p. 69)

$$\lim_{\Delta\lambda \to 0} \Delta D/\nu_\lambda \tag{4.4}$$

represents the variance density at any point λ of the λ-line. The function

$$\nu_\lambda = \psi(\lambda) \tag{4.5}$$

is the variance density spectrum, or the continuous spectrum. For a given population series, λ has the range 0 to 2π, so that the integral

$$\int_0^{2\pi} \nu_\lambda d\lambda = \int_0^{2\pi} \psi(\lambda) d\lambda = \text{var } x_t = \sigma_x^2 \tag{4.6}$$

is the population variance.

It is safe and convenient to use the discrete spectrum technique whenever the basic periods are known exactly from physical considerations. When the basic frequency and its harmonics are not known in advance and must be estimated, the use of the variance density spectrum is more appropriate, particularly when the interest is in knowing the explained variance of a variable x_t for various frequency intervals.

b. Variance density spectrum. Spectral densities may be conceived in either of two ways: their integral of Eq. (4.6) is equal to the variance σ_x^2 of the series x_t, or the variable x_t is standardized so that var $x_t = 1$ and the integral of variance densities is also unity. The spectral density function of the unit variance densities is designated by

$$\nu(\lambda) = \psi(\lambda)/\sigma_x^2 \tag{4.7}$$

A relation may be obtained either between the spectral density function $\chi(\lambda)$ and the covariance function, $f_c(\tau)$, of the x_t series, where

$$f_c(\tau) = \frac{1}{T-\tau} \int_0^{T-\tau} (X_t - \bar{X}_t)\ (X_{t+\tau} - \bar{X}_t)dt \qquad (4.8)$$

or between the spectral density function of the unit variance, $\nu(\lambda)$, and the autocorrelation function $\rho(\tau)$, Eq. (1). It is sufficient to multiply the relations obtained in this latter case by the variance $\sigma_x{}^2$ of x_t in order to reduce it to the former case.

The relations of the variance density function, $\nu(\lambda)$, of a continuous series x_t, and its corresponding continuous autocorrelation function, $\rho(\tau)$, are given by the Wiener-Khintchine equations (Yevjevich, 1972, p. 90)

$$\nu(\lambda) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \rho(\tau)e^{i\lambda\tau}d\tau = \frac{1}{2\pi} \int_{-\infty}^{\infty} \rho(\tau)\ \cos\lambda\tau d\tau \qquad (4.9)$$

and

$$\rho(\tau) = \int_{-\infty}^{\infty} \nu(\lambda)e^{i\lambda\tau}d\lambda = \int_{-\infty}^{\infty} \nu(\lambda)\ \cos\tau\lambda d\lambda \qquad (4.10)$$

which are similar to Fourier transforms

$$f(t) = \frac{1}{\pi} \int_0^{\infty} \psi(\lambda)e^{i\lambda t}\ d\lambda \qquad (4.11)$$

and

$$\psi(\lambda) = \int_0^{\infty} f(t)e^{-i\lambda t}\ dt \qquad (4.12)$$

Since $\rho(0) = 1$, the integral of Eq. (4.10) must satisfy this condition. By using only the right half of the λ-range, 0 to ∞, since $\nu(\lambda)$ is an even function (symmetrical about $\tau = 0$), $\nu(\lambda)$ in Eq. (4.10) must be doubled as $\gamma(\lambda) = 2\nu(\lambda)$ in order that its integral be between 0 and ∞ and equal to unity; therefore Eq. (4.10) should be modified. Since $\rho(\tau)$ is also an even function (symmetrical about $\tau = 0$), Eqs. (4.9) and (4.10) become

$$\gamma(\lambda) = 2\nu(\lambda) = \frac{2}{\pi}\int_0^\infty \rho(\tau)\cos\lambda\tau d\tau \qquad (4.13)$$

and

$$\rho(\tau) = \int_0^\infty \gamma(\lambda)\cos\tau\lambda d\lambda \qquad (4.14)$$

with ranges $0\leq\lambda\leq$ and $0\leq\tau\leq\infty$ and Eq. (4.14) satisfies the condition $\rho(0) = 1$.

By using the ordinary frequencies, f, instead of the angular (circular) frequencies, λ, with $\lambda = 2\pi f$, Eqs. (4.13) and (4.14) become

$$\gamma(f) = 4\int_0^\infty \rho(\tau)\cos 2\pi f\tau d\tau \qquad (4.15)$$

and

$$\rho(\tau) = \int_0^\infty \gamma(f)\cos 2\pi\tau f df \qquad (4.16)$$

The values of the functions $\gamma(f)$ and $\rho(\tau)$ are estimated by the corresponding sample functions $g(f)$ and $r(\tau)$.

For a discrete series X_i, the autocorrelation function $\rho(k)$ is discrete, so that Eq. (4.15) becomes

$$\gamma(f) = 2\{1 + 2\sum_{k=1}^\infty \rho(K)\cos 2\pi fk\} \qquad (4.17)$$

$$\gamma(\lambda) = \frac{1}{\pi}\{1 + 2\sum_{k=1}^{\infty} \rho(K)\cos\lambda K\} \qquad (4.18)$$

in which ρ_o is replaced by unity and k is the lag.

The expected sum on the right side of (4.17) is zero for an independent random variable (Yevjevich, 1972, p.92) so that the integrals of (λ) or (f) over the ranges $0\leq \lambda\pi$ and $0\leq f\leq 0.5$, respectively, are unities. Because f_{min} = 1/N where N is the length of record, then for $N\to\infty f_{min}\to 0$. The largest frequency f(max)= $1/2\Delta t$ is called the Nyquist or folding frequency. For Δt a time unit, then, f_{max} = 0.5. If the series is finite, the lower limit f_{min} = 1/N depends on the sample size. To avoid this dependence of the spectrum on the length of the series, f_{min} is usually taken as zero, and the small region $0\leq f\leq 1/N$ is estimated similarly as for the other frequencies.

A variance density spectrum of a series is then a representation of the partition of the variance, particularly of the variance unity for $\gamma(\lambda)$ or $\gamma(f)$ - functions, into a number of intervals or bands of frequencies. In practice, several coordinate systems are used for the spectral densities, such as $\gamma(\ln\lambda)$, $\gamma(\ln f)$ and $\gamma(\ln\omega)$ where $\omega = 1/f$ the cycle or period against ln λ, ln f, ln ω. In this case, the expressions are called logarithmic frequencies and logarithmic periods. When the spectral densities are expressed as $\gamma(\lambda)$, $\gamma(f)$ or $\gamma(\omega)$ against λ, f, or ω, they are called linear frequencies or linear periods. Some of these plots preserve the proportionality of the area under the spectral curve to the variance of the series, but some do not. When an exchange between λ, f, and ω is made the appropriate adjustment of variance densities must be made to preserve the area of unity. Thus

$\gamma(\lambda)d\lambda = \gamma(f)df$ with $\lambda = 2\pi f$ so that $\gamma(f) = 2\pi\gamma(\lambda)$. The use of $\ln\gamma(\lambda)$ versus $\ln \lambda$ or similarly that of $\ln \gamma(f)$ versus $\ln f$ or $\ln \gamma(\omega)$ versus $\ln \omega$, does not preserve the area-to-variance relation and the area of unity. To accomplish this for f, the transformation into the coordinate system $(f\gamma(f), \ln f)$ is performed. The area under any portion of the spectral curve in this coordinate system represents the variance between the frequencies f_i and f_{i+1} defining the segment of the curve (Reiter, 1966). This transformation is variance conserving because

$$\int_{f_i}^{f_{i+1}} f\gamma(f)d(\ln f) = \int_{f_i}^{f_{i+1}} \gamma(f)df \qquad (4.19)$$

c. Estimation of Variance Densities from Correlograms

The population continuous spectrum of a stochastic process such as rainfall is estimated by the sample variance density spectrum. Several difficulties arise in this estimation, particularly the selection of the range of frequencies, the approximation of the continuous spectra by a discrete sequence of spectral densities, and the smoothing of large variations of estimated sample densities about the expected population spectrum.

If the ordinary frequencies, $f=\frac{1}{\omega}$, are used, the range is $0\leq f\leq 0.5$. But the estimates of the variance densities between $f = 0$ and $f = 1/N$ are unreliable, because the fact that a series has values X_i observed at Δt or averaged over this interval, does not imply that the variance densities for $f>0.5$ are zeros. Only if the fluctuation of X_t inside Δt is minimal, or the series is defined in such a way that the properties inside Δt are not relevant, only then can these densities be neglected. If the properties of the series inside Δt are relevant, the variance densities of the range $0 \leq f \leq 0.5$ are biased because they are greater than the expected or population variance densities (Yevjevich, 1972, p.93).

To estimate a continuous spectrum in the given range, the range of frequencies $0 \leq f \leq 0.5$ is divided into intervals, Δf, so that $m = 1 + 0.5/\Delta t$ is the number of frequency density ordinates to be computed. If Eq. (4.17) is used, the procedure is equivalent to determining m values of g(f) of the line-spectrum. These estimates are both biased, i.e. (Yevjevich, 1972, p.93)

$$E[g(f) - \gamma(f)] = \Delta g \neq 0 \quad (4.20)$$

instead of zero as it should be for an unbiased estimate, and inefficient, i.e.,

$$\text{Var } g(f) = E\{[g(f) - \gamma(f)]^2\} \quad (4.21)$$

is not a minimum as it should be in the case of an efficient estimate. To obtain unbiased and efficient estimate, either the r(k)-function of Eq. (4.17) is smoothed prior to its transformation, or the computed adjacent line-spectrum estimates for a limited number of frequencies are smoothed. In this latter case, the finite correlogram with k_{max} = N-1 for a series of size N is smoothed by a smoothing function, D(k), also called filter, window, moving average scheme or model, weighting function, weight, or averaging function. Eq. (4.17) becomes

$$\gamma(f) = 2[1 + 2 \sum_{K=1}^{N-1} D(K)\rho(K)\cos 2\pi fK] \quad (4.22)$$

The function D(k) in the lag domain has an equivalent smoothing function S(f) in the frequency domain, which is a transform function of D(k).

The smoothing function S(f), also called the kernel, consists of discrete symmetrical weights for consecutive values of discrete line-spectrum of Eq. (4.17). Two such functions are that know. ıs hanning after the Austrian meteorologist Julius von Hahn,

$$S(f_j) = 0.25\ g(f_{j-1}) + 0.5\ g(f_j) + 0.25\ g(f_{j+1}) \qquad (4.23)$$

and the hamming, named after R.W. Hamming of the Bell Telephone Laboratories (Muller, 1966, p.14)

$$S(f_j) = 0.23\ g(f_{j-1}) + 0.54\ g(f_j) + 0.23\ g(f_{j+1}) \qquad (4.24)$$

with $S(f_j)$ the resulting value of S(f) at the position $S(f_j)$. The smoothing function corresponding to hanning in the autocorrelation domain is (Yevjevich, 1972, p.94)

$$D(k) = \frac{1 + \cos 2\pi fk}{2} \qquad (4.25)$$

d. Practical Estimation Procedures. Of the three practical approaches in estimating spectral densities currently in use, namely, (Yevjevich, 1972, p.100-104), the Tukey-Hanning procedure, the procedure proposed by Leppink, and the use of fast Fourier transforms, the first one is the most convenient because corresponding computer programs are available. If this procedure is used, a value m of the maximum number of lags is chosen, so that the correlogram needs to be computed from

r_1 to r_m. Usually, $m<N/3$ is selected, and often $m = N/20$, $N/10$, $N/5$, or similar numbers. The estimates $g(f)$ of $\gamma(f)$ by Eq. (4.17), with $\rho(k)$ estimated by $r(k)$, $k = 1, 2, \ldots, m$ in Eq. (1), are obtained at predetermined discrete points $f_j = j/2m$, $j = 1, 2, \ldots, m$, so that the equal intervals between the discrete estimates are $\Delta f = \frac{1}{2}m$. These estimates are called raw estimates. It is apparent that the selection of the truncation point, m, on the correlogram determines the interval Δf or the resolution, i.e., the details of the spectrum. On the other hand, given a series of length N, the variance of estimates is approximately proportional to the maximum number of lags m taken in computing the correlogram (Yevjevich, 1972, p.100). The larger m, the larger the variance of the estimates at each point. To avoid an increase in the variance requires a compromise between resolution and variability. The raw estimates are smoothed by the smoothing function of Eq. (4.23), with $f_i = f_{-1}$, and $f_{m+1} = f_{m-1}$ to obtain the smoothed estimates.

e. Sampling Distribution of Estimated Spectral Densities.

If $\hat{g}(f)$ computed by Eq. (4.22) with $\rho(k)$ replaced by $r(k)$ in the estimate of the population value $\gamma(f)$, it can be shown (Yevjevich, 1972, p.104) that

$$E[g(f)] \approx \gamma(f) \tag{4.26}$$

and

$$\mathrm{Var}[g(f)] \approx \frac{1}{N}\gamma^2(f)\int_0^{0.5} S^2(f)df \tag{4.27}$$

where S(f) is the kernel in the frequency domain. Then $\hat{g}(f)$ follows the approximate χ^2-distribution with the equivalent number of degrees of freedom, EDF (usually the difference between the number of observations and the number of constraints imposed) given by

$$\mathrm{EDF} = \frac{2E^2[\hat{g}(f)]}{\mathrm{var}[\hat{g}(f)]} = \frac{2N}{\int_0^{0.5} S^2(f)df} \tag{4.28}$$

For the filter of Eq. (4.25), the variance is

$$\mathrm{Var}[g(f)] = \frac{3m}{4N}\gamma^2(f) \text{ to } \frac{m}{N}\gamma^2(f) \tag{4.29}$$

and the equivalent degrees of freedom are

$$\mathrm{EDF} = \frac{8N}{3m} \text{ to } \frac{2N}{m} \tag{4.30}$$

with the first terms being applicable to normal variables and the second terms to non normal variables (Yevjevich, 1972, p.106). Current computer programs often use EDF = 2N/m when Eq. (4.25) is applied as a filter.

Finally, to draw the tolerance or confidence limits for ν = EDF, or for the parameters m, N, and $\nu = f(N,m)$, the χ^2-distribution tables give the two limits as soon as the confidence level, e.g., $\alpha = 0.05$, is selected. The limits are

$$C_1 = \frac{1 - \chi^2_{\alpha}(\nu)}{\nu}, \quad C_2 = \frac{\chi^2_{\alpha}(\nu)}{\nu} \tag{4.31}$$

where C_1 means the exceedence by 95 percent of all values, and C_2 the non exceedence by 95 percent of all values. Because the variances of spectral estimates at f = 0 and f = 0.50 are twice as large as they are at other frequencies, C_1 and C_2 should be multiplied by $(2)^{1/2} = 1.41$ (Yevjevich, 1972, p.106)

f. Results.

Using the record of daily values, the variance density spectrum analysis was performed as described above.

The total variance, σ^2_x, was found to be equal to $510mm^2$. Using the number of lag m = N/20 or 5% N, and a frequency interval $\Delta f = 0.0008$ day^{-1}, the raw estimates of the spectrum was obtained (Figure 11). This estimate was smoothed by hanning (Figure 11a,) normalized, and plotted on a log-log graph paper. (Figure 12)

Visual examination of Figure 12 reveals major spectral peaks at about $2.4x10^{-3}$ per day corresponding to a period of about 400 days or roughly 1 year. This peak is interpreted as the annual periodicity. Other peaks are located between 10^{-1} and $2x10^{-1}$ per day, corresponding to a period of 5 - 10 days; and at 2 to $3x10^{-1}$ per day or a period of 3 - 5 days. Spectral peaks such as these, if located outside the tolerance limits, can be considered indicative of the influence of particular atmospheric systems on the rainfall regime (Mukarami, 1971).

Since the coordinate system [ln f, ln g(f)] does not preserve the area of unity, the transformation into the coordinate system (ln f, fg (f)) was performed in accordance with Eq. (4.19) above. The resulting curve is seen in Figure 13 from which it is apparent that nearly all the variance in the daily rainfall regime at Douala is possibly explained by atmospheric phenomena having periods less than one month, with the most variability due to those phenomena having periods less than 5 days.

III. Discussion and Outlook

The rainfall data for Douala have been found to be free of any major inhomogeneity. The various methods of analysis applied to this record have led to the following results: (1) other than the annual periodicity, factors influencing the rainfall at Douala have a period less than one month; (2) although major storm events have variable durations, the modal duration is 1-3 days; (3) the simple Markov model of rainfall produces theoretical probabilities that fit the observed frequencies quite well. This suggests either persistence, or a predominant influence of phenomena with short periods, perhaps 1-3 days; (4) most of the variance in the daily rainfall series is explained by atmospheric phenomena having periods less than 5 days, i.e., synoptic processes.

The next steps will be as follows. Use of Eq. (4.31) with $\nu = 427$ EDF to objectively test the significance of the spectral peaks in Figure 12; extension of the analysis schemes, particularly the variance spectrum scheme, to the other stations in the study area to determine whether the above characteristics of the rainfall at Douala are valid for the region as a whole. Following this, the nature of the forcing mechanisms will be explored using the cross spectral analysis (Doberitz, 1968; Mukarami, 1971; Yevjevich, 1972) and the compositing technique (Williams, 1970; Reed _et.al._, 1971; Sikdar _et.al._, 1972). The objective is the estimation of the synoptic scale variations of weather disturbance activity over this part of Africa as seen in the rainfall regime (Eldridge, 1957; Garstang, 1966; Ilesanmi, 1971; Mandengué, 1965; Sadler, 1967; Tschirhart, 1958). This has relevance both for water resources planning and for understanding the role of convection in the existence of disturbances over Africa (Bernet, 1959; Burpee, 1971; Carlson, 1969a, 1969b, 1971).

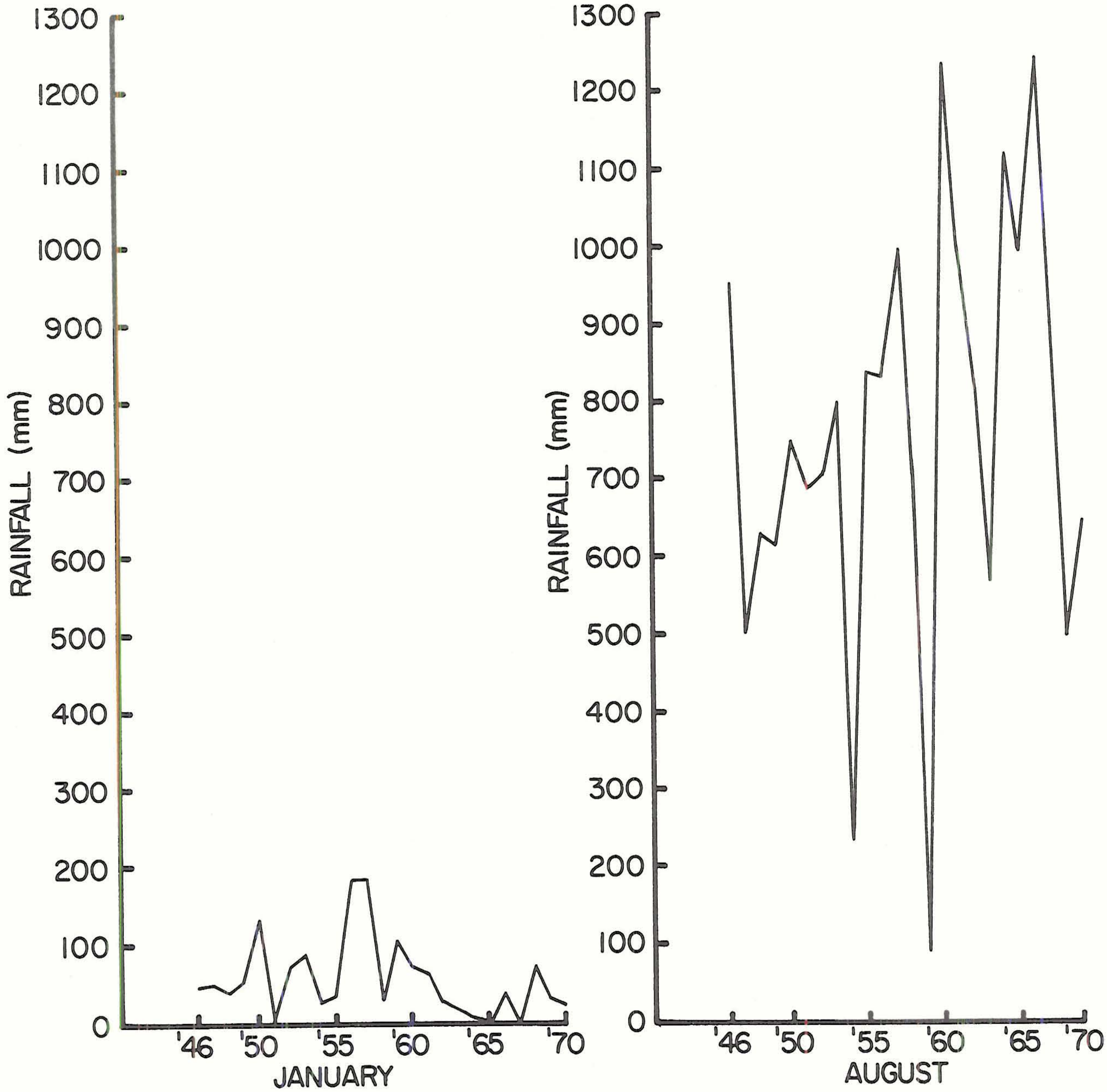


Figure 1. Fluctuations of monthly rainfall for January (1946-1970) and August (1946-1969) at Douala, Cameroun.

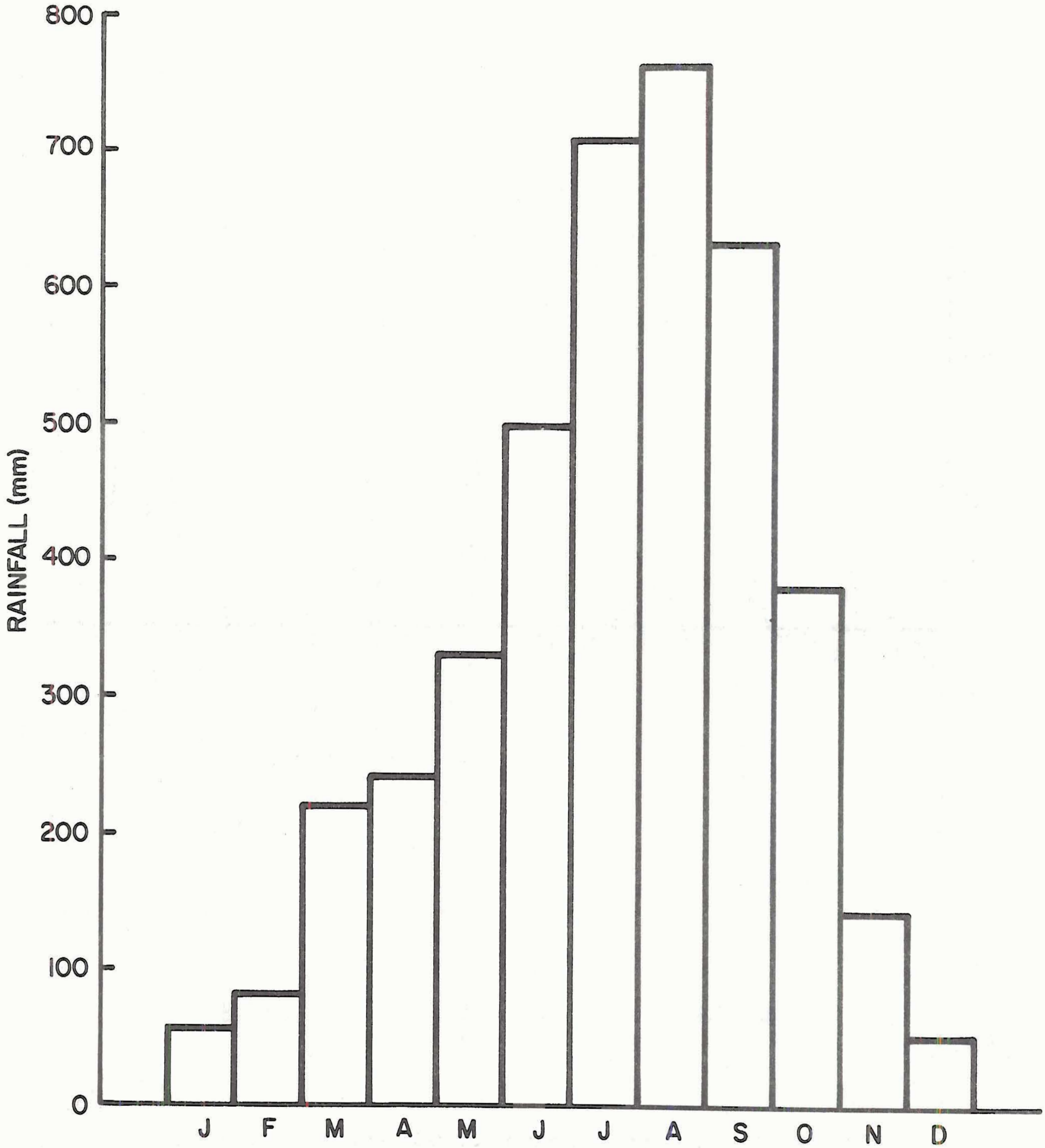


Figure 1a. Monthly mean rainfall for Douala, Cameroun, 1936-1969.

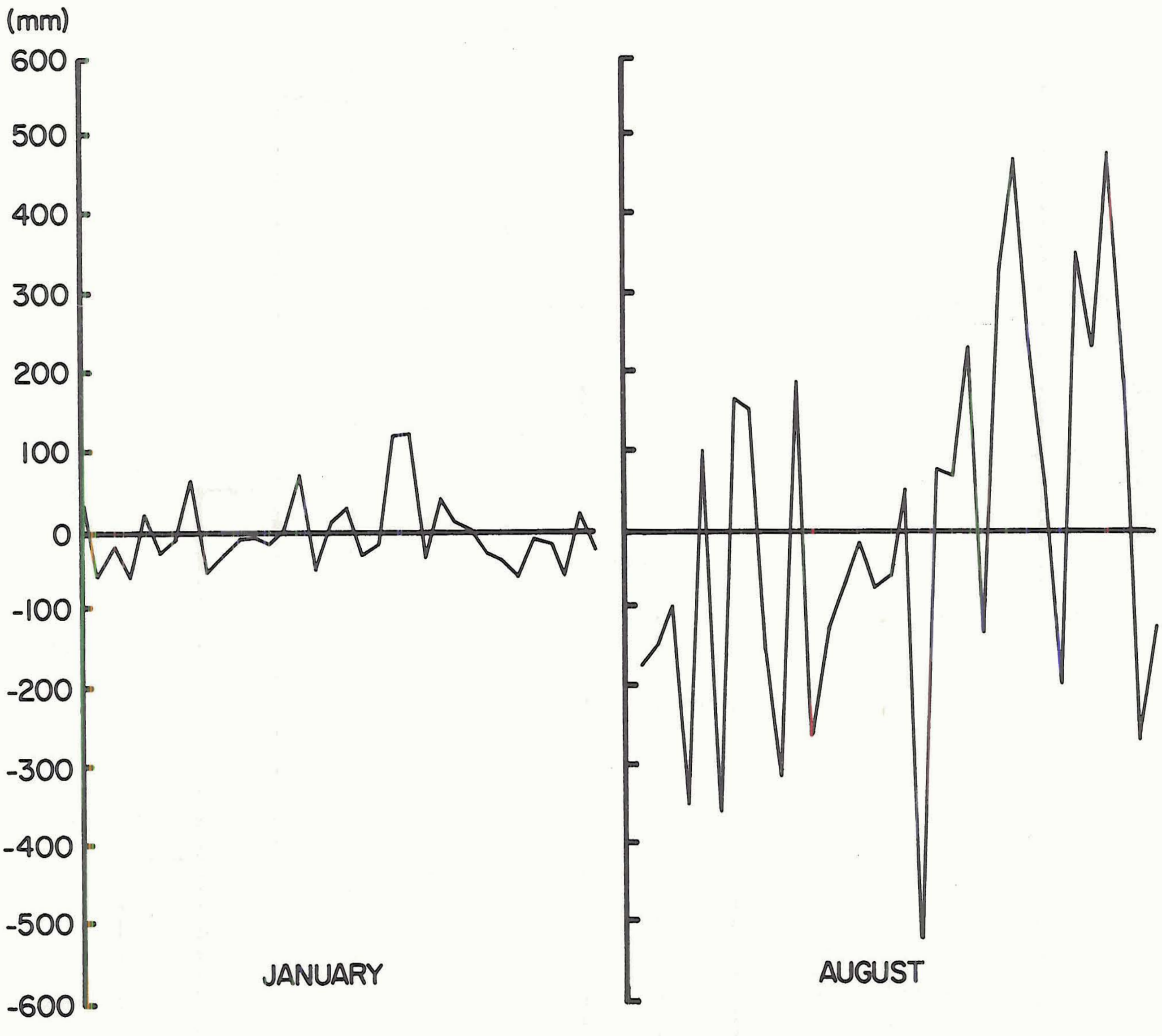


Figure 2. Fluctuations of monthly rainfall anomalies, $\varepsilon_i = X_{i\tau} - m_\tau$, for January and August at Douala, Cameroun, 1936=1969.

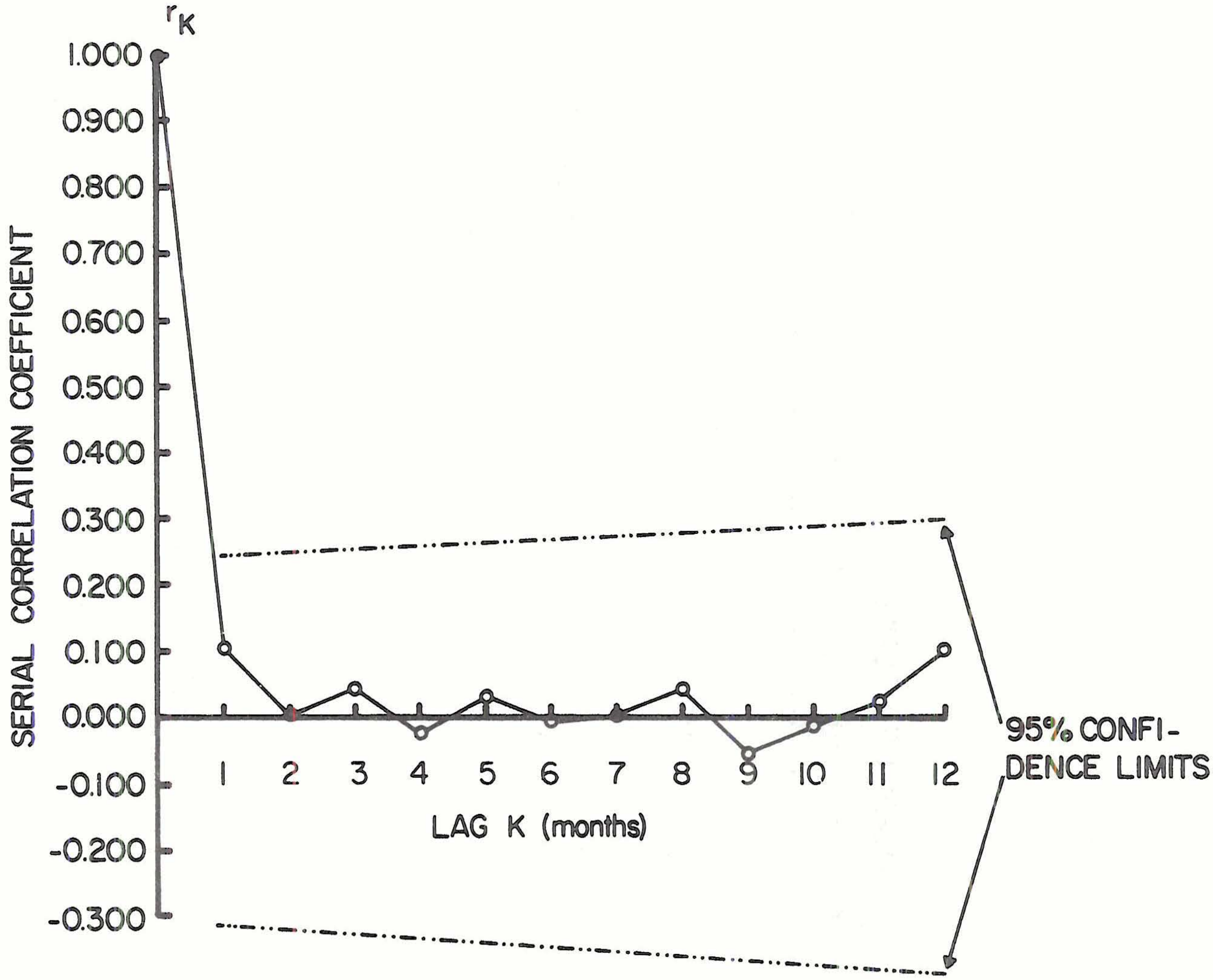


Figure 3. Serial correlation coefficients, monthly rainfall, Douala (1936-1969).

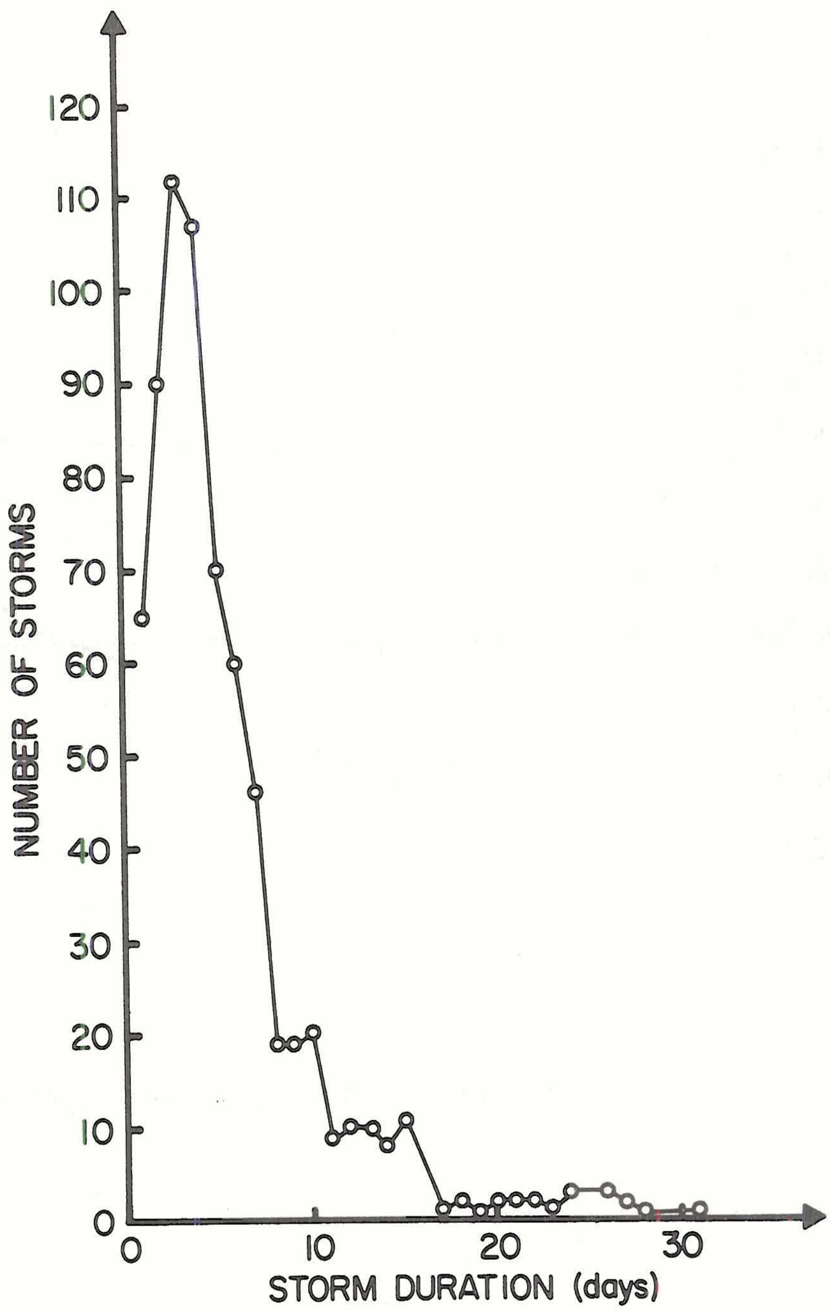


Figure 4. Number of storms with yield ≥ 50 mm. as a function of duration for Douala, Cameroun, 1936-1969.

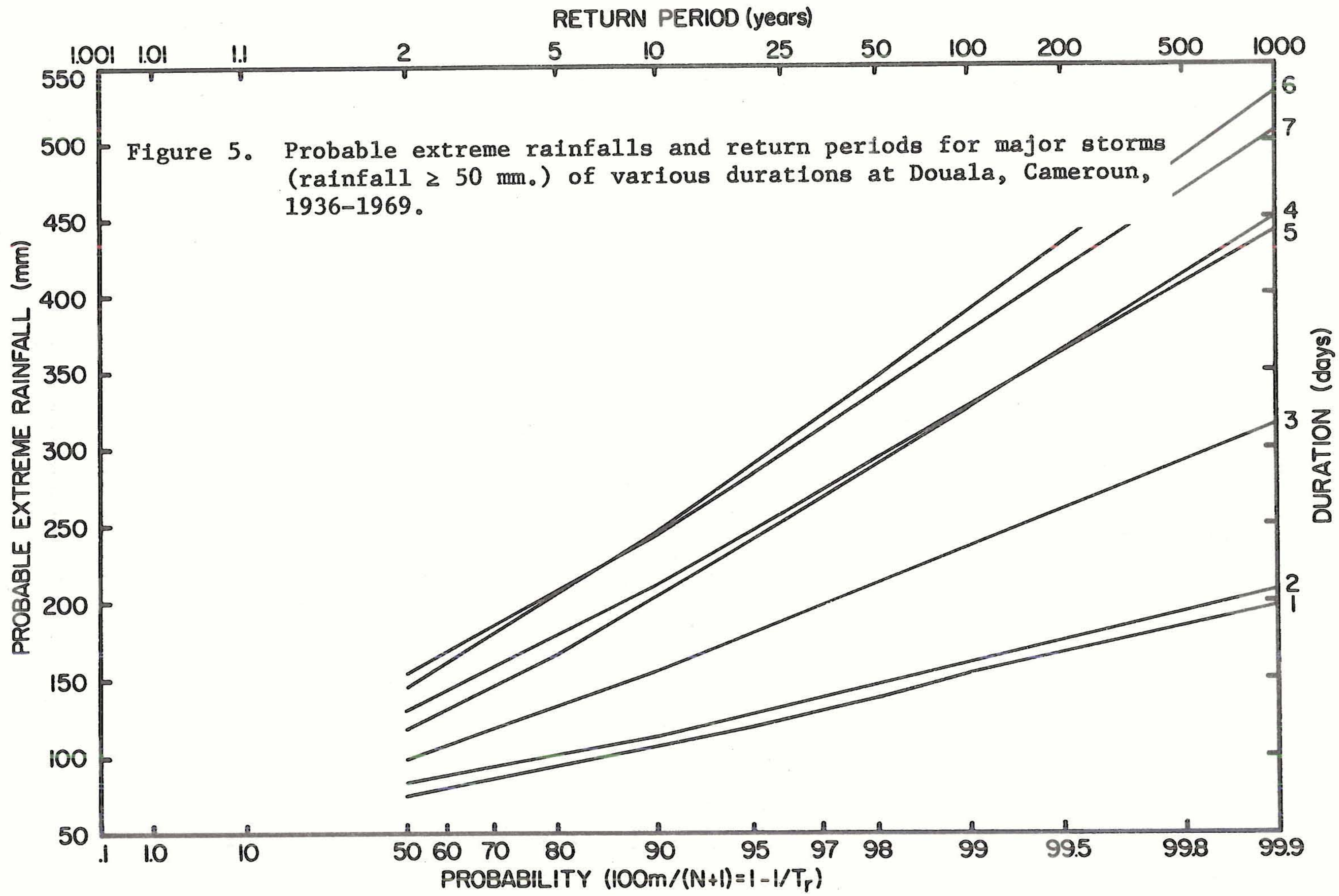


Figure 5. Probable extreme rainfalls and return periods for major storms (rainfall ≥ 50 mm.) of various durations at Douala, Cameroun, 1936-1969.

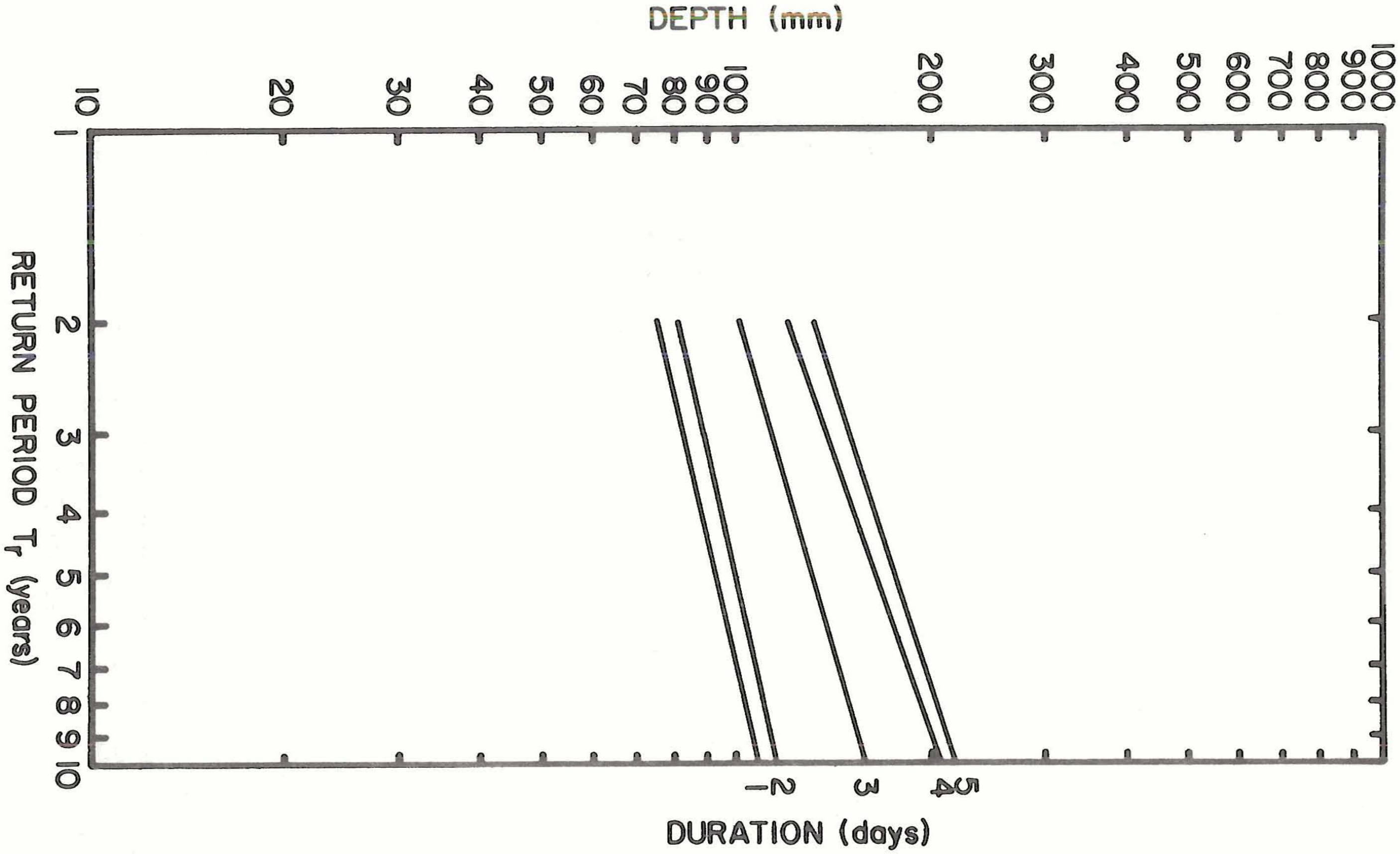


Figure 6. Depth-Duration-Frequency curves for major storms (rainfall ≥ 50 mm.) at Douala, Cameroun, 1936-1969.

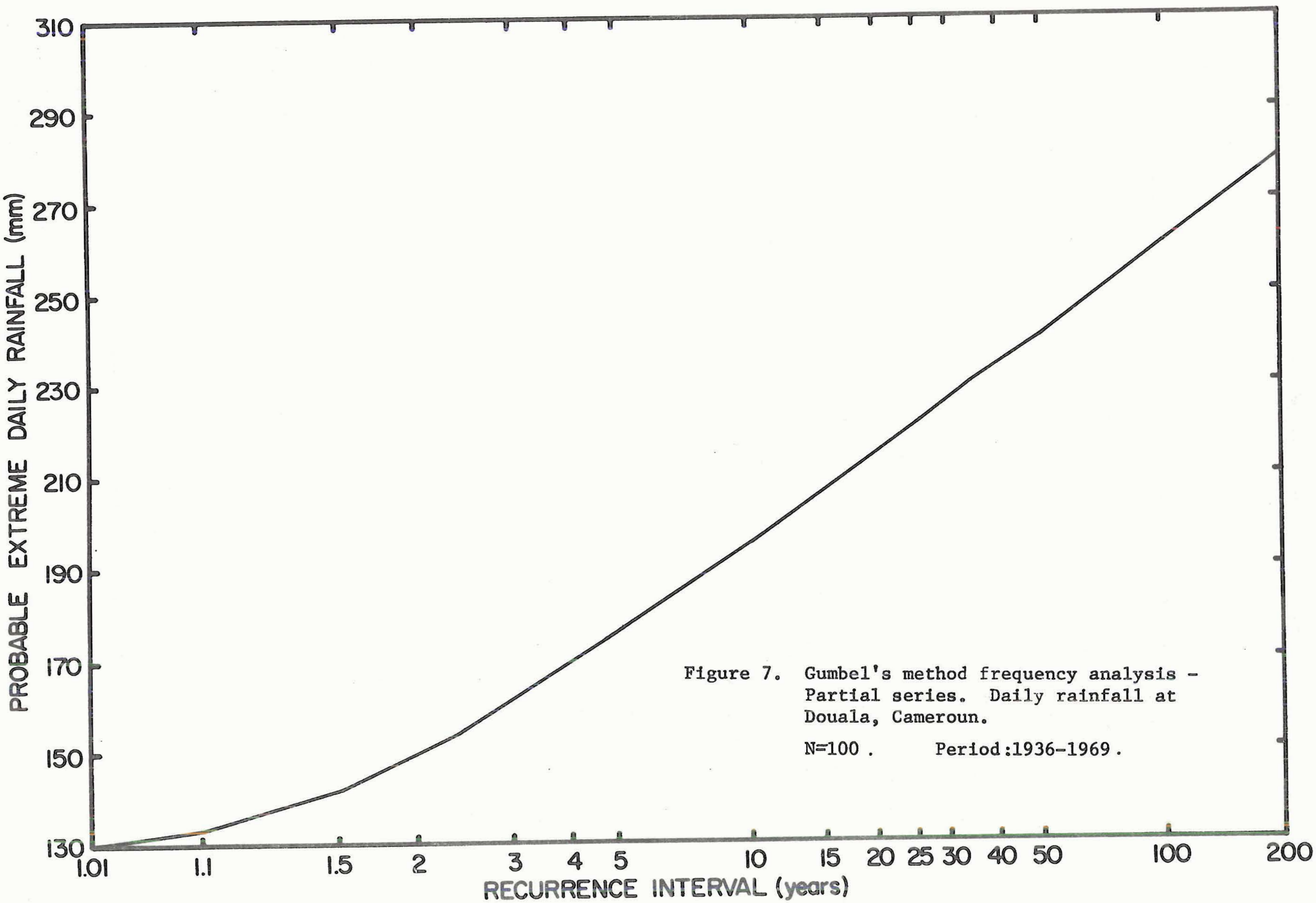


Figure 7. Gumbel's method frequency analysis - Partial series. Daily rainfall at Douala, Cameroun.

N=100 . Period:1936-1969 .

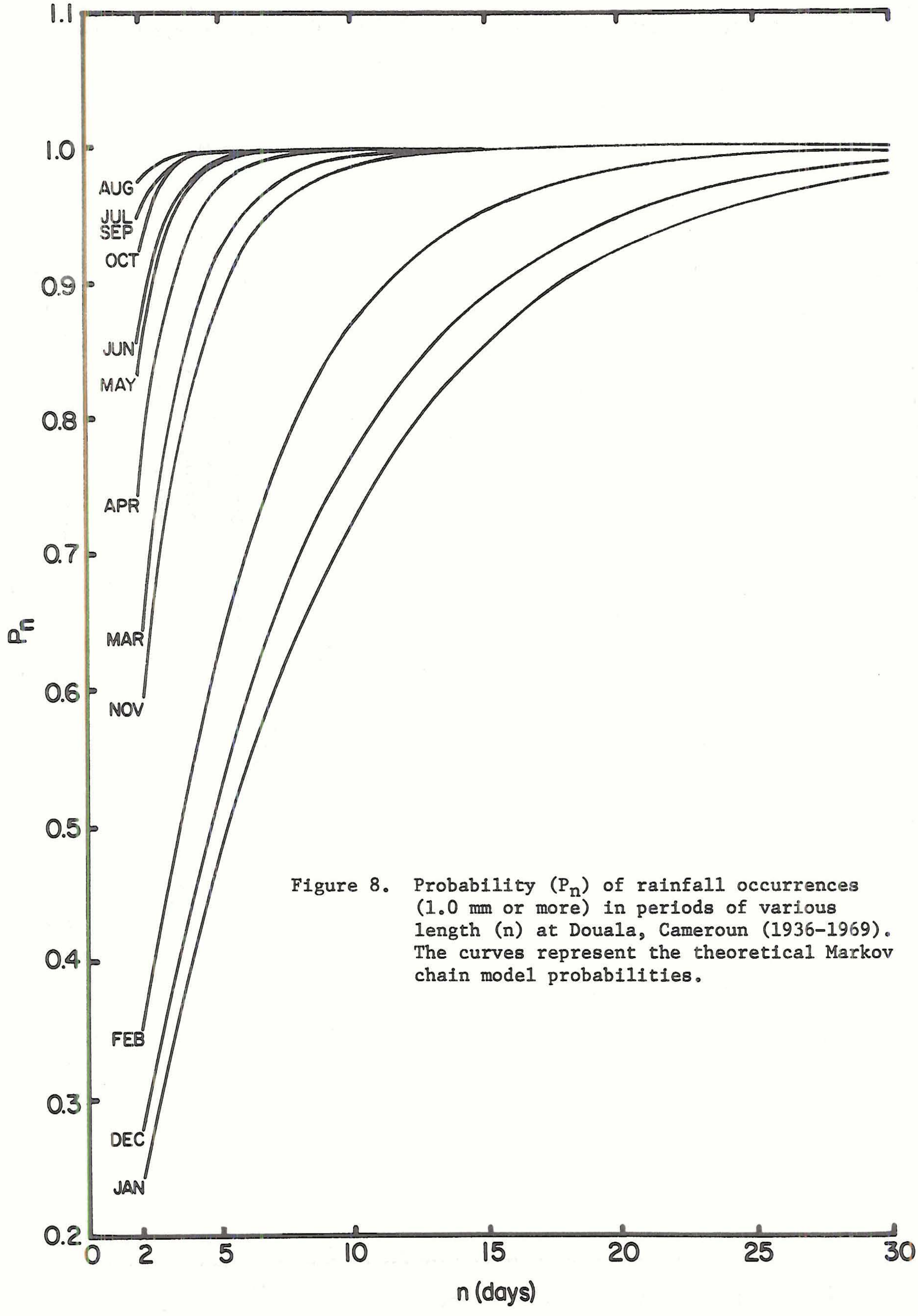
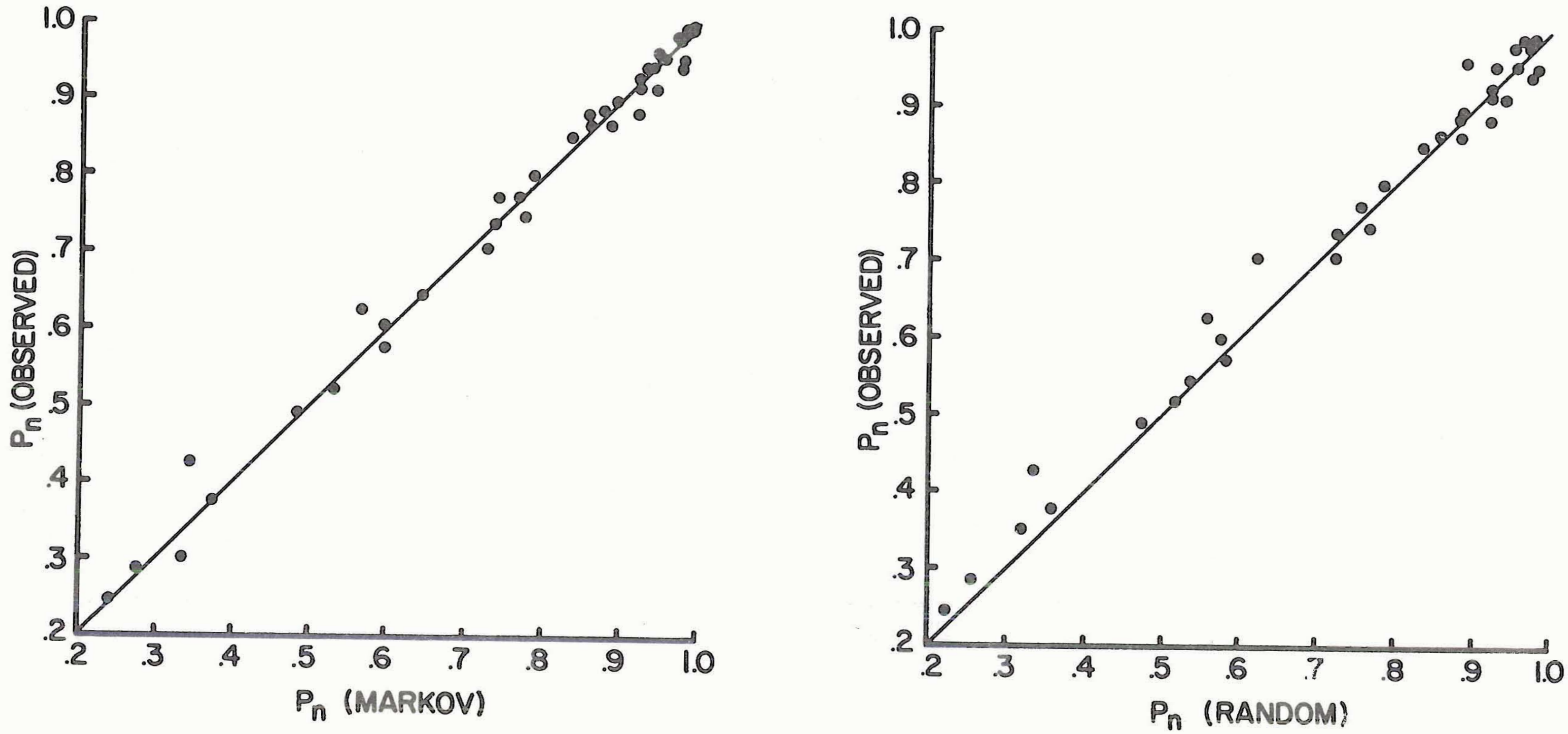


Figure 8. Probability (P_n) of rainfall occurrences (1.0 mm or more) in periods of various length (n) at Douala, Cameroun (1936-1969). The curves represent the theoretical Markov chain model probabilities.

Figure 9. P_n = Probability of rainfall occurrence in an interval of n days, n = 2, 3, . . .



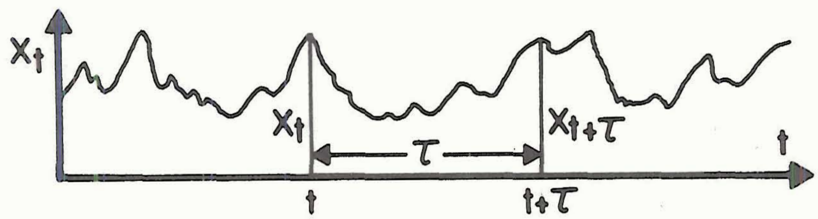


Figure 10. A continuous series for the definition of variance density spectrum.

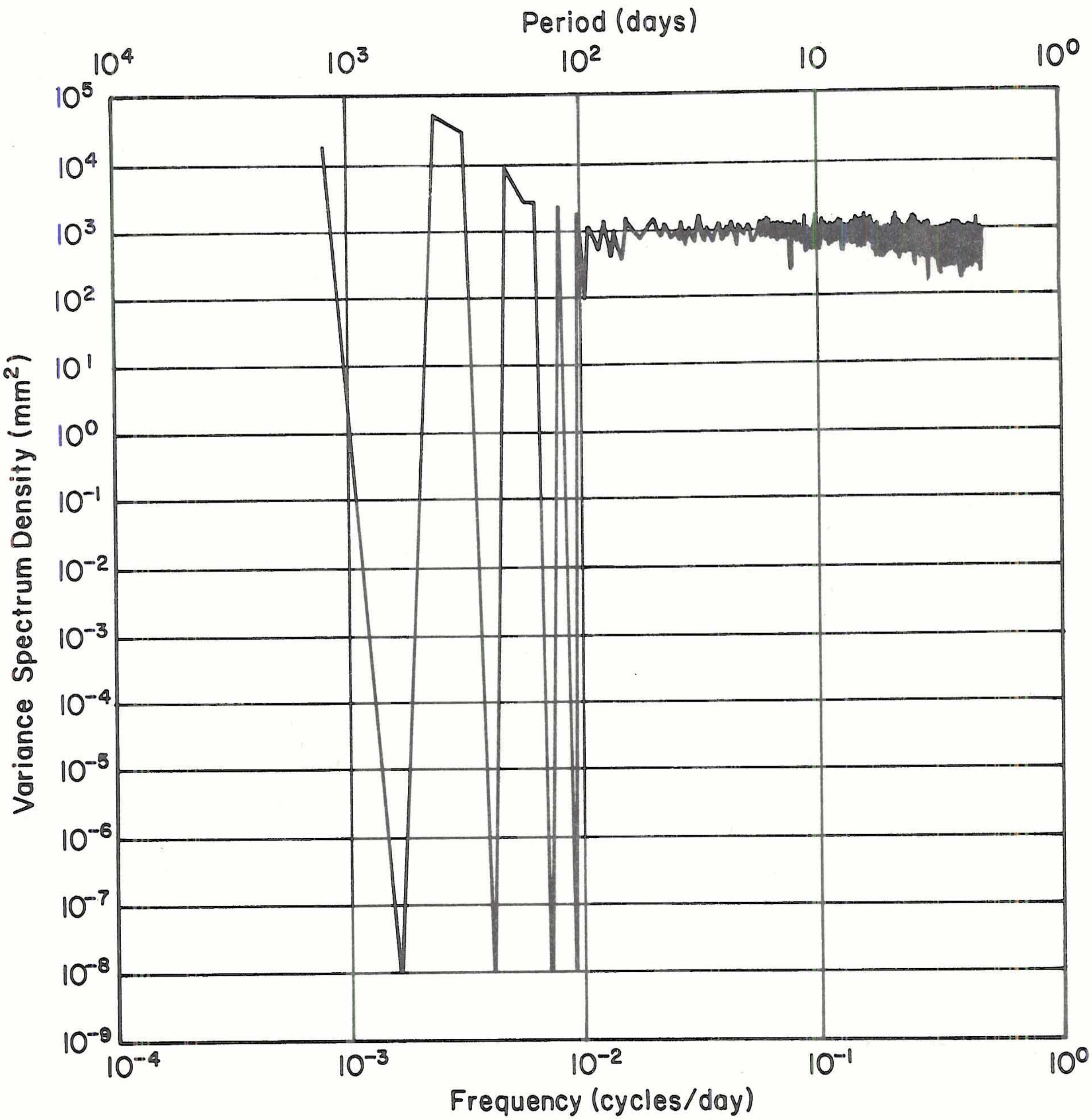


Fig. 11 Raw estimate of variance spectral density of daily rainfall at Douala, Cameroun, 1936-1969.

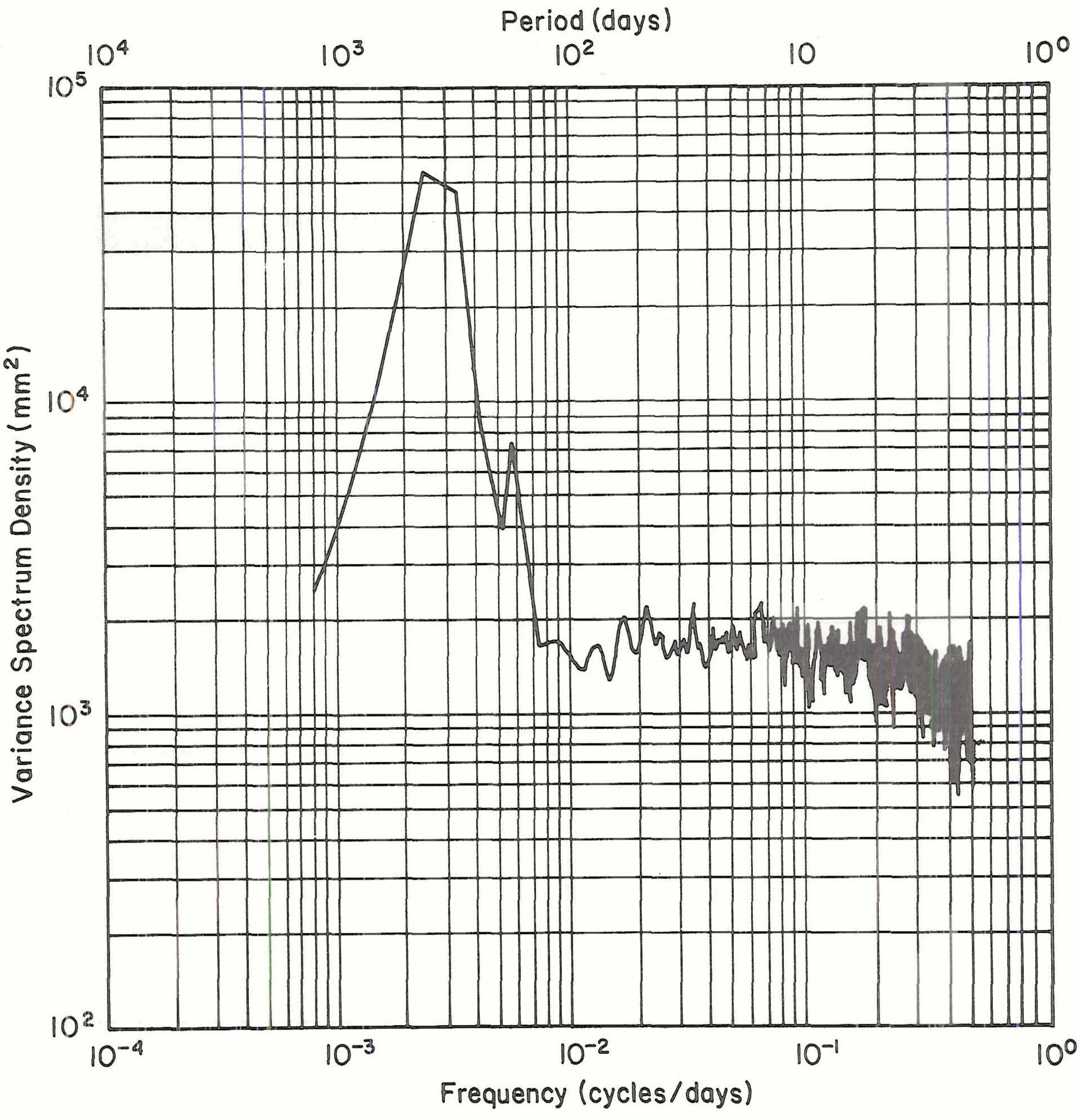


Fig 11a Smoothed non-normalized estimate of variance density spectrum of daily rainfall at Douala, Cameroun, 1936-1969.

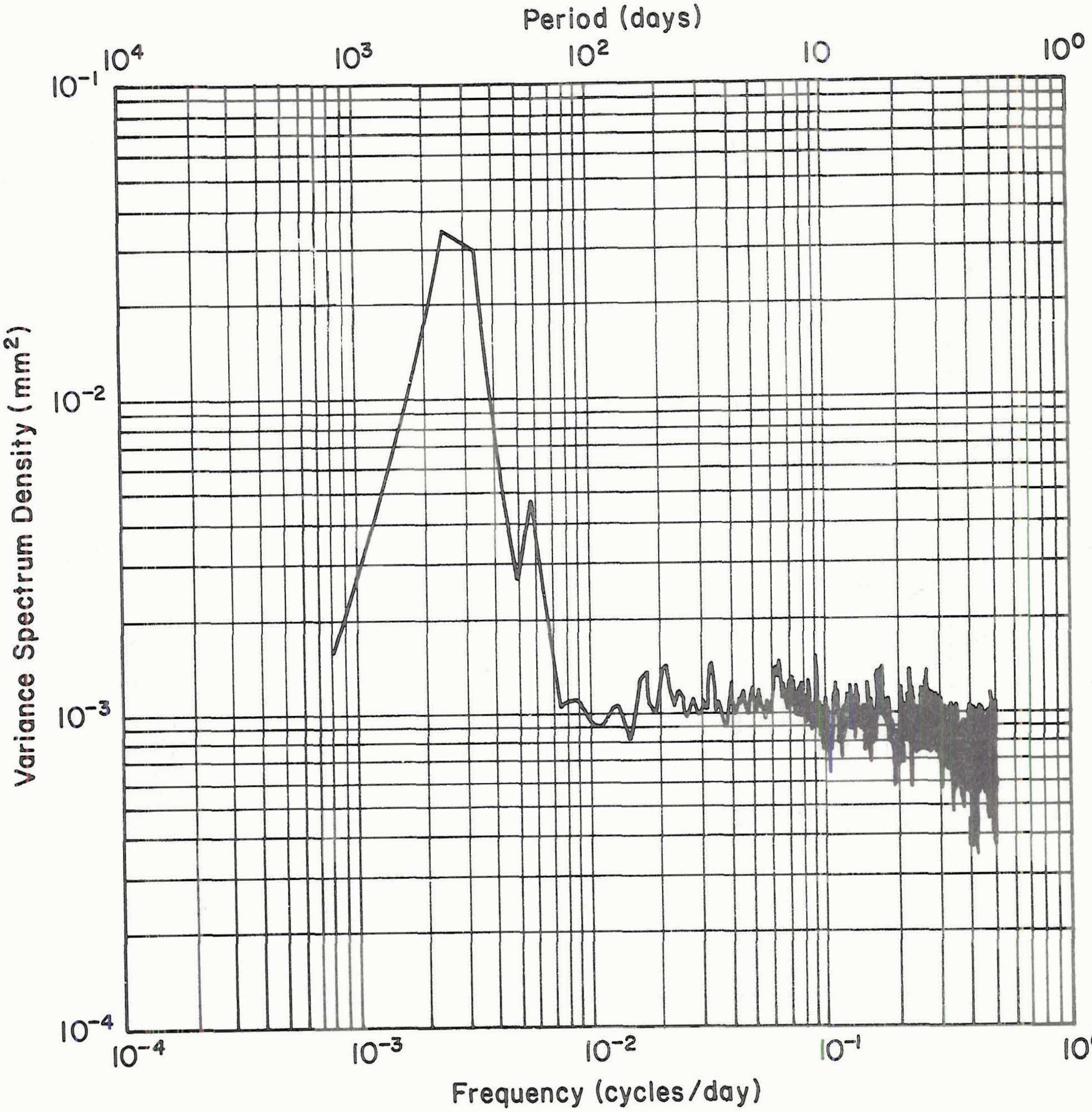


Fig. 12 Smoothed normalized estimate of variance density spectrum of daily rainfall at Douala, Cameroun, 1936-1969.

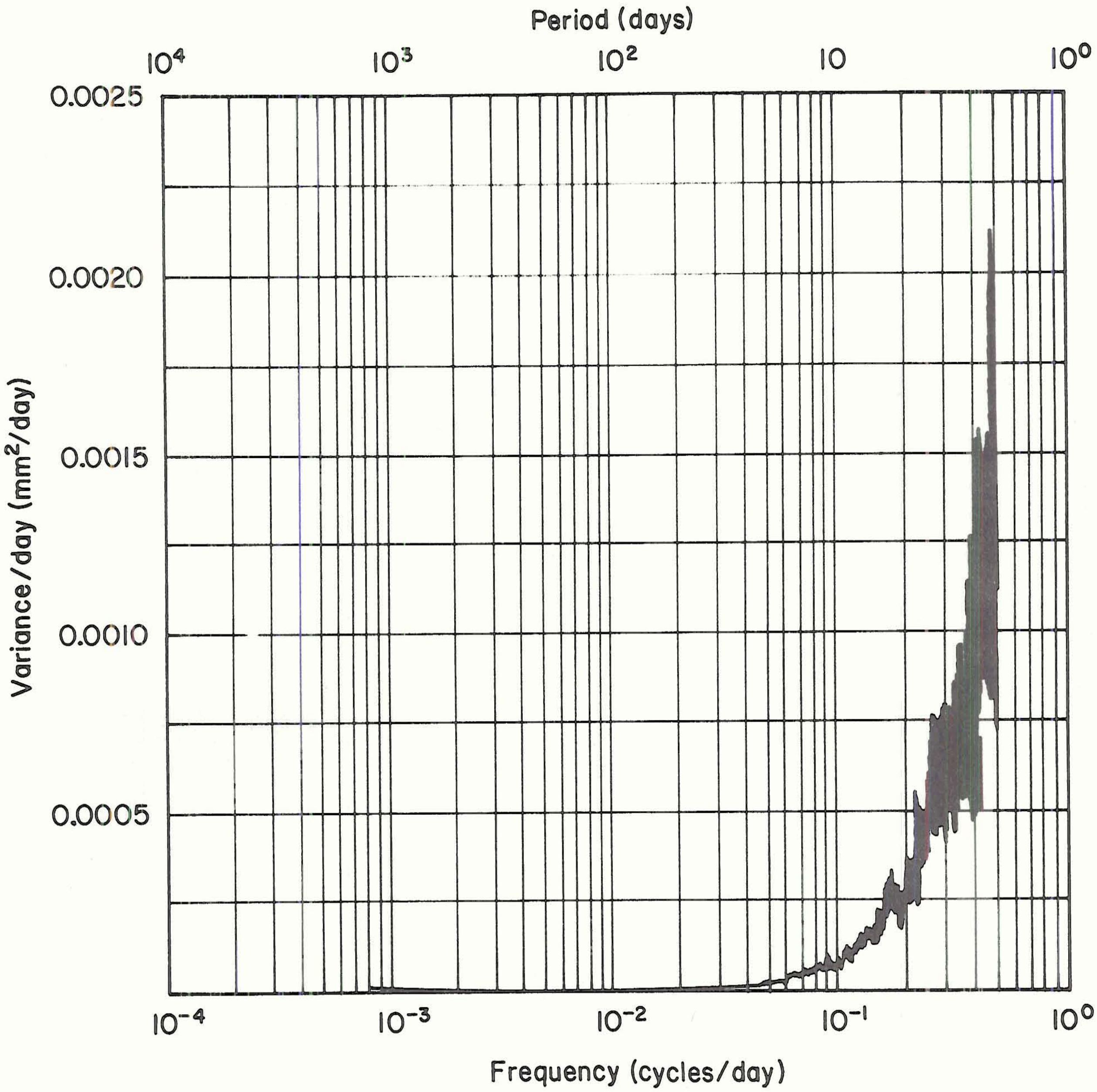


Fig. 13 Smoothed normalized estimate of variance density spectrum of daily rainfall at Douala, Cameroun, 1936-1969. Ordinate in terms of fg(f) (see text)

TABLE I
Data on rainfall stations in the study area.

Name of the station	Latitude (deg. and min.)	Longitude (deg. and min.)	Elevation (meters)	Number of years	Period of record	Country
Abong-Mbang	03 58N	13 12E	689	19	1950 - 1969	Cameroun
Akonolinga	03 47N	12 15E	-	19	1950 - 1969	Cameroun
Ambam	02 23N	11 17E	602	19	1950 - 1969	Cameroun
Bafia	04 44N	11 15E	498	19	1950 - 1969	Cameroun
Bangangte	05 10N	10 30E	1,340	19	1950 - 1969	Cameroun
Banyo	06 47N	11 49E	1,110	19	1950 - 1969	Cameroun
Batouri	04 25N	14 24E	655	19	1950 - 1969	Cameroun
Bertoua	04 36N	13 44E	671	19	1950 - 1969	Cameroun
Betare-Oya	05 36N	14 04E	804	19	1950 - 1969	Cameroun
Douala	04 04N	09 41E	13	34	1936 - 1969	Cameroun
Ebolowa	02 54N	11 10E	628	19	1950 - 1969	Cameroun
Edea	03 46N	10 04E	32	19	1950 - 1969	Cameroun
Eseka	03 37N	10 44E	399	19	1950 - 1969	Cameroun
Garoua	09 20N	13 23E	249	19	1950 - 1969	Cameroun
Kaele	10 05N	14 27E	387	19	1950 - 1969	Cameroun
Kribi	02 56N	09 54E	19	19	1950 - 1969	Cameroun
Lomie	03 09N	13 37E	640	19	1950 - 1969	Cameroun
Maroua	10 28N	14 16E	405	19	1950 - 1969	Cameroun
Meiganga	06 32N	14 22E	1,000	19	1950 - 1969	Cameroun
Nanga-Eboko	04 39N	12 24E	624	19	1950 - 1969	Cameroun
Ndikinimeki	04 45N	10 48E	-	19	1950 - 1969	Cameroun
Ngaoundere	07 17N	13 19E	1,119	19	1950 - 1969	Cameroun
Nkongsamba	04 56N	09 55E	877	19	1950 - 1969	Cameroun
Poli	08 29N	13 15E	436	19	1950 - 1969	Cameroun
Sangmelima	02 56N	11 57E	713	19	1950 - 1969	Cameroun
Yagoua	10 21N	15 17E	-	19	1950 - 1969	Cameroun
Yaounde	03 52N	11 32E	760	19	1950 - 1969	Cameroun

Yokadouama	03 31N	15 06E	640	19	1950 - 1969	Cameroun
Yoko	05 33N	12 22E	1,031	19	1950 - 1969	Cameroun
Bitam	02 05N	11 29E	599	14	1950 - 1964	Gabon
Coco-Beach	01 00N	09 36E	16	14	1950 - 1964	Gabon
Franceville	01 38S	13 34E	426	14	1950 - 1964	Gabon
Lambarene	00 43S	10 13E	82	14	1950 - 1964	Gabon
Lastourville	00 50S	12 43E	483	14	1950 - 1964	Gabon
Libreville	00 27S	09 25E	12	14	1950 - 1964	Gabon
Makokou	00 34N	12 52E	516	14	1950 - 1964	Gabon
Mayumba	03 25S	10 39E	40	14	1950 - 1964	Gabon
Mitzic	00 47N	11 32E	583	14	1950 - 1964	Gabon
Mouila	01 52S	11 01E	-	14	1950 - 1964	Gabon
Oyem	01 37N	11 35E	669	14	1950 - 1964	Gabon
Port-Gentil	00 42S	08 45E	6	14	1950 - 1964	Gabon
Brazzaville	04 15S	15 15E	314	14	1950 - 1964	Congo
Djambala	02 32S	14 46E	797	14	1950 - 1964	Congo
Dolisie	04 11S	12 40E	346	14	1950 - 1964	Congo
Fort-Rousset	00 29S	15 55E	335	14	1950 - 1964	Congo
Gamboma	01 54S	15 51E	377	14	1950 - 1964	Congo
Impfondo	01 37N	18 04E	326	14	1950 - 1964	Congo
Makoua	00 01S	15 39E	346	14	1950 - 1964	Congo
Mouyondzi	04 00S	13 56E	-	14	1950 - 1964	Congo
Mpouya	02 37S	16 13E	312	14	1950 - 1964	Congo
Ouesso	01 37N	16 03E	340	14	1950 - 1964	Congo
Pointe-Noire	04 49S	11 54E	17	14	1950 - 1964	Congo
Sibiti	03 41S	13 21E	-	14	1950 - 1964	Congo
Souanke	02 04N	14 03E	547	14	1950 - 1964	Congo

Bambari	05 46N	20 40E	448	14	1950 - 1964	Centrafrican Republic
Bangassou	04 44N	22 50E	500	14	1950 - 1964	Centrafrican Republic
Bangui	04 23N	18 34E	381	14	1950 - 1964	Centrafrican Republic
Berberati	04 15N	15 47E	594	14	1950 - 1964	Centrafrican Republic
Birao	10 17N	22 47E	465	14	1950 - 1964	Centrafrican Republic
Bossangoa	06 29N	17 26E	465	14	1950 - 1964	Centrafrican Republic
Bossambele	05 16N	17 38E	674	14	1950 - 1964	Centrafrican Republic
Bouar	05 56N	15 35E	936	14	1950 - 1964	Centrafrican Republic
Bouoa	06 30N	18 16E	458	14	1950 - 1964	Centrafrican Republic
Bria	06 32N	21 59E	584	14	1950 - 1964	Centrafrican Republic
N'Dele	08 24N	20 39E	510	14	1950 - 1964	Centrafrican Republic
Obo	05 24N	26 30E	660	14	1950 - 1964	Centrafrican Republic
Yalinga	06 30N	23 16E	602	14	1950 - 1964	Centrafrican Republic
Abecher	13 50N	20 50E	542	14	1950 - 1964	Tchad
Am-Timan	11 02N	20 17E	436	14	1950 - 1964	Tchad
Ati	13 13N	18 19E	334	14	1950 - 1964	Tchad
Bousso	10 29N	16 43E	336	14	1950 - 1964	Tchad
Faya-Largeau	18 00N	19 10E	234	14	1950 - 1964	Tchad
Fort-Archambault	09 08N	18 23E	365	14	1950 - 1964	Tchad
Fort-Lamy	12 08N	15 02E	295	14	1950 - 1964	Tchad
Mao	14 07N	15 19E	358	14	1950 - 1964	Tchad
Mongo	12 12N	18 47E	430	14	1950 - 1964	Tchad
Moundou	08 37N	16 04E	422	14	1950 - 1964	Tchad
Pala	09 22N	14 58E	464	14	1950 - 1964	Tchad

TABLE II
Storm duration, frequency, and yield for
Douala, Cameroun, 1936 - 1969.

Duration (days)	Frequency	Yield (mm)				
		193.2	79.2	72.3	63.7	55.8
		167.3	78.8	71.7	62.9	55.8
		140.8	78.0	70.8	62.5	55.0
		127.8	76.0	70.7	61.5	54.6
		97.1	75.8	69.8	61.0	53.7
1	65	92.0	75.5	69.4	61.0	53.3
		91.0	75.3	69.2	60.8	52.7
		90.0	75.0	68.9	59.7	52.6
		87.1	73.7	68.9	58.3	52.4
		87.0	73.5	68.3	57.5	52.3
		83.5	73.5	65.7	57.5	51.2
		83.4	73.0	65.7	57.0	51.0
		83.3	72.6	65.0	56.7	50.8
		198.2	100.3	77.0	67.2	57.7
		159.3	98.0	76.6	66.3	57.5
		139.1	95.2	76.0	64.9	57.5
		130.6	95.2	75.9	64.8	56.7
		125.9	94.8	75.7	64.2	56.5
		120.0	92.4	75.3	63.9	56.5
		115.2	91.2	73.6	63.4	55.6
		113.1	89.1	73.2	63.3	55.2
2	90	112.3	88.2	72.7	62.2	55.0
		110.6	82.6	72.4	61.1	54.6
		109.6	82.2	72.4	59.6	54.0
		109.0	82.0	71.9	59.3	53.6

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Douala	04 04N	09 41E	13	34	1936 - 1969	Cameroun
Ebolowa	02 54N	11 10E	628	19	1950 - 1969	Cameroun
Edea	03 46N	10 04E	32	19	1950 - 1969	Cameroun
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Kaele	10 05N	14 27E	387	19	1950 - 1969	Cameroun
Kribi	02 56N	09 54E	19	19	1950 - 1969	Cameroun
Lomie	03 09N	13 37E	640	19	1950 - 1969	Cameroun
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Ndikinimeki	04 45N	10 48E	-	19	1950 - 1969	Cameroun
Ngaoundere	07 17N	13 19E	1,119	19	1950 - 1969	Cameroun
Nkongsamba	04 56N	09 55E	877	19	1950 - 1969	Cameroun
Poli	08 29N	13 15E	436	19	1950 - 1969	Cameroun
Sangmelima	02 56N	11 57E	713	19	1950 - 1969	Cameroun
Yagoua	10 21N	15 17E	-	19	1950 - 1969	Cameroun
Yaounde	03 52N	11 32E	760	19	1950 - 1969	Cameroun

Yokadouama	03 31N	15 06E	640	19	1950 - 1969	Cameroun
Yoko	05 33N	12 22E	1,031	19	1950 - 1969	Cameroun
Bitam	02 05N	11 29E	599	14	1950 - 1964	Gabon
Coco-Beach	01 00N	09 36E	16	14	1950 - 1964	Gabon
Franceville	01 38S	13 34E	426	14	1950 - 1964	Gabon
Lambarene	00 43S	10 13E	82	14	1950 - 1964	Gabon
Lastourville	00 50S	12 43E	483	14	1950 - 1964	Gabon
Libreville	00 27S	09 25E	12	14	1950 - 1964	Gabon
Makokou	00 34N	12 52E	516	14	1950 - 1964	Gabon
Mayumba	03 25S	10 39E	40	14	1950 - 1964	Gabon
Mitzic	00 47N	11 32E	583	14	1950 - 1964	Gabon
Mouila	01 52S	11 01E	-	14	1950 - 1964	Gabon
Oyem	01 37N	11 35E	669	14	1950 - 1964	Gabon
Port-Gentil	00 42S	08 45E	6	14	1950 - 1964	Gabon
Brazzaville	04 15S	15 15E	314	14	1950 - 1964	Congo
Djambala	02 32S	14 46E	797	14	1950 - 1964	Congo
Dolisie	04 11S	12 40E	346	14	1950 - 1964	Congo
Fort-Rousset	00 29S	15 55E	335	14	1950 - 1964	Congo
Gamboma	01 54S	15 51E	377	14	1950 - 1964	Congo
Impfondo	01 37N	18 04E	326	14	1950 - 1964	Congo
Makoua	00 01S	15 39E	346	14	1950 - 1964	Congo
Mouyondzi	04 00S	13 56E	-	14	1950 - 1964	Congo
Mpouya	02 37S	16 13E	312	14	1950 - 1964	Congo
Ouesso	01 37N	16 03E	340	14	1950 - 1964	Congo
Pointe-Noire	04 49S	11 54E	17	14	1950 - 1964	Congo
Sibiti	03 41S	13 21E	-	14	1950 - 1964	Congo
Souanke	02 04N	14 03E	547	14	1950 - 1964	Congo

Bambari	05 46N	20 40E	448	14	1950 - 1964	Centrafrican Republic
Bangassou	04 44N	22 50E	500	14	1950 - 1964	Centrafrican Republic
Bangui	04 23N	18 34E	381	14	1950 - 1964	Centrafrican Republic
Berberati	04 15N	15 47E	594	14	1950 - 1964	Centrafrican Republic
Birao	10 17N	22 47E	465	14	1950 - 1964	Centrafrican Republic
Bossangoa	06 29N	17 26E	465	14	1950 - 1964	Centrafrican Republic
Bossambele	05 16N	17 38E	674	14	1950 - 1964	Centrafrican Republic
Bouar	05 56N	15 35E	936	14	1950 - 1964	Centrafrican Republic
Bouoa	06 30N	18 16E	458	14	1950 - 1964	Centrafrican Republic
Bria	06 32N	21 59E	584	14	1950 - 1964	Centrafrican Republic
N'Dele	08 24N	20 39E	510	14	1950 - 1964	Centrafrican Republic
Obo	05 24N	26 30E	660	14	1950 - 1964	Centrafrican Republic
Yalinga	06 30N	23 16E	602	14	1950 - 1964	Centrafrican Republic

Abecher	13 50N	20 50E	542	14	1950 - 1964	Tchad
Am-Timan	11 02N	20 17E	436	14	1950 - 1964	Tchad
Ati	13 13N	18 19E	334	14	1950 - 1964	Tchad
Bousso	10 29N	16 43E	336	14	1950 - 1964	Tchad
Faya-Largeau	18 00N	19 10E	234	14	1950 - 1964	Tchad
Fort-Archambault	09 08N	18 23E	365	14	1950 - 1964	Tchad
Fort-Lamy	12 08N	15 02E	295	14	1950 - 1964	Tchad
Mao	14 07N	15 19E	358	14	1950 - 1964	Tchad
Mongo	12 12N	18 47E	430	14	1950 - 1964	Tchad
Moundou	08 37N	16 04E	422	14	1950 - 1964	Tchad
Pala	09 22N	14 58E	464	14	1950 - 1964	Tchad

TABLE II
Storm duration, frequency, and yield for
Douala, Cameroun, 1936 - 1969.

Duration (days)	Frequency	Yield (mm)				
		193.2	79.2	72.3	63.7	55.8
		167.3	78.8	71.7	62.9	55.8
		140.8	78.0	70.8	62.5	55.0
		127.8	76.0	70.7	61.5	54.6
		97.1	75.8	69.8	61.0	53.7
1	65	92.0	75.5	69.4	61.0	53.3
		91.0	75.3	69.2	60.8	52.7
		90.0	75.0	68.9	59.7	52.6
		87.1	73.7	68.9	58.3	52.4
		87.0	73.5	68.3	57.5	52.3
		83.5	73.5	65.7	57.5	51.2
		83.4	73.0	65.7	57.0	51.0
		83.3	72.6	65.0	56.7	50.8
		198.2	100.3	77.0	67.2	57.7
		159.3	98.0	76.6	66.3	57.5
		139.1	95.2	76.0	64.9	57.5
		130.6	95.2	75.9	64.8	56.7
		125.9	94.8	75.7	64.2	56.5
		120.0	92.4	75.3	63.9	56.5
		115.2	91.2	73.6	63.4	55.6
		113.1	89.1	73.2	63.3	55.2
2	90	112.3	88.2	72.7	62.2	55.0
		110.6	82.6	72.4	61.1	54.6
		109.6	82.2	72.4	59.6	54.0
		109.0	82.0	71.9	59.3	53.6

		107.4	81.7	71.9	59.2	53.5
		107.0	81.4	70.9	59.2	53.4
		106.7	79.3	70.7	58.5	51.7
		104.2	79.0	68.7	58.3	51.1
		102.2	77.8	68.1	58.1	50.4
		100.6	77.1	68.1	58.0	50.3
		285.5	173.1	135.2	118.9	109.8
		238.2	162.9	129.3	116.8	108.5
		219.8	159.0	128.2	114.8	107.2
3	112	217.8	151.6	127.9	114.6	106.7
		215.9	143.8	127.1	114.4	101.0
		184.4	140.7	126.8	112.0	101.0
		184.0	140.1	125.8	111.8	100.6
		174.5	137.6	124.8	110.2	99.2
		98.3	80.4	71.4	62.8	55.1
		98.2	79.5	70.9	62.5	55.0
		97.7	79.5	70.5	62.2	54.3
		94.6	78.2	69.3	61.4	53.3
		93.4	78.2	68.0	61.3	53.2
		92.6	77.7	67.4	61.2	52.9
		91.0	77.3	66.6	61.1	52.3
		88.8	76.6	66.5	60.3	52.0
		87.9	75.9	66.1	60.1	51.3
		87.5	75.3	65.9	60.0	50.7
		87.3	74.3	65.9	59.6	50.3
		84.1	74.0	65.5	59.5	50.3
		83.8	71.8	64.7	58.0	
		82.6	71.8	64.7	56.1	
		82.0	71.5	62.9	55.7	

		460.6	155.1	101.0	75.6	62.0
		425.6	151.9	99.6	74.2	61.0
		276.5	146.3	97.7	73.5	60.3
		262.4	139.8	94.8	73.4	59.9
		238.3	139.5	94.2	73.3	59.3
		226.4	137.0	93.6	71.7	59.0
		202.0	134.5	93.4	70.2	58.2
		198.6	127.1	93.2	70.1	56.9
		197.3	125.0	91.8	69.8	56.8
		192.9	120.3	89.9	68.1	56.4
4	107	187.2	118.5	89.4	68.1	56.4
		184.6	116.9	88.2	68.0	55.4
		184.4	116.6	87.7	67.9	53.1
		177.0	115.8	87.0	67.5	52.9
		176.2	112.0	86.1	66.8	52.8
		173.7	108.9	83.8	66.7	51.5
		172.8	108.6	83.1	65.4	51.2
		169.9	108.3	80.7	65.3	50.7
		168.7	107.9	80.7	64.0	
		166.3	105.3	78.8	63.2	
		164.1	102.8	77.5	62.9	
		160.1	102.8	76.8	62.6	
		366.8	172.1	137.7	106.5	90.3
		340.6	169.6	135.1	106.0	89.6
		280.4	168.4	133.9	103.1	88.2
		272.3	156.1	132.6	100.8	88.0
		234.5	155.8	131.4	100.8	86.3
5	70	227.4	155.3	127.4	99.9	85.5
		195.4	153.2	122.1	99.7	84.9
		190.9	144.2	119.6	97.7	82.6
		189.9	142.5	115.0	92.9	78.4
		180.0	140.7	113.8	92.0	77.1
		176.1	138.7	109.3	91.9	75.7

		74.6	66.6	60.6	56.1	52.6
		68.0	62.8	60.2	54.5	
		67.2	62.7	59.2	53.3	
		395.4	205.4	130.0	96.3	80.1
		341.7	184.0	127.8	95.1	78.0
		332.0	172.1	123.6	94.6	70.9
		295.4	168.4	122.6	93.9	68.7
		279.1	167.2	118.3	91.1	67.4
		272.6	154.5	117.2	89.8	66.4
6	60	267.7	144.9	115.4	88.8	65.7
		249.2	144.6	113.6	88.3	65.0
		223.9	141.5	107.1	86.0	61.6
		214.1	138.8	105.1	85.8	61.0
		210.6	134.0	99.7	84.2	54.4
		209.7	133.7	98.3	82.0	50.7
		387.2	208.8	133.2	109.3	74.3
		290.1	207.4	128.4	99.0	73.6
		280.9	176.8	126.8	98.6	60.8
		265.1	175.6	125.1	97.9	59.5
7	46	243.1	175.0	121.1	92.3	58.6
		229.4	164.6	119.9	91.2	52.9
		223.5	158.3	118.9	88.1	
		221.5	149.9	114.6	82.9	
		218.4	146.1	114.0	82.8	
		210.7	145.3	113.5	76.3	
		412.6	225.5	167.8	131.9	70.4
		404.6	216.7	162.0	123.0	69.8
8	19	365.4	197.2	158.5	99.8	67.8
		275.0	196.0	144.8	96.9	

		446.7	258.9	235.5	167.7	99.2
		434.0	246.6	229.0	149.0	92.2
9	19	300.9	244.0	222.9	143.2	81.5
		287.2	243.7	221.5	115.3	
		677.4	360.2	261.4	190.8	138.9
		527.6	288.0	251.5	162.7	124.1
10	20	500.1	283.0	242.8	148.3	110.7
		394.0	281.3	241.9	145.7	78.1
		520.1	447.5	372.9	178.2	133.8
11	9	494.8	429.4	314.6	156.0	
		583.0	331.3	320.9	317.2	210.6
12	10	340.9	329.1	318.4	220.5	103.1
		564.9	477.3	405.3	381.7	236.3
13	10	551.4	458.2	386.1	375.3	162.7
14	8	525.9	484.2	416.2	362.6	
		493.3	448.7	389.4	291.1	
		777.0	506.2	430.0	361.6	
15	11	607.9	470.6	410.9	272.9	
		537.5	456.1	377.3		
17	1	437.2				

18	2	730.9	614.4	
19	1	353.9		
20	2	749.0	437.6	
21	2	600.0	224.3	
22	2	856.3	539.9	
23	1	498.6		
24	3	681.1	589.6	524.1
26	3	815.7	747.8	617.6
27	2	740.7	727.3	
28	1	865.7		
31	1	887.6		

TABLE III
Probable rainfall depths for storms of various durations and return periods at Douala, Cameroun, 1936 - 1950.

Duration (days)	Return Period (years)	Probable rainfall depth (mm)	95% Confidence limits (±mm)
	1	62	32
	2	76	7
1	3	84	7
	4	89	11
	5	107	11
	10	126	25
	1	68	33
	2	82	8
2	3	90	8
	4	96	11
	5	100	11
	10	114	25
	1	76	57
	2	100	13
3	3	114	13
	4	124	19
	5	132	19
	10	156	43

	1	82	87
	2	119	20
4	3	140	20
	4	155	29
	5	167	29
	10	204	66
	1	97	81
	2	132	27
5	3	152	19
	4	166	27
	5	177	27
	10	212	62

TABLE IV
Mean rainfall yields and their variability for storms of various durations. Douala, Cameroun, 1936 - 1969.

Duration (days)	Number of storms with rainfall amounts $\geq$ 50mm	Mean rain-fall amount, $\bar{x}$ (mm)	Standard deviation, S_x (mm)	Coefficient of variation, $C_x = S_x/x$
1	65	73	25	0.34
2	90	79	26	0.33
3	112	96	45	0.47
4	107	112	68	0.61
5	70	126	64	0.51
6	60	141	79	0.56
7	46	148	73	0.49

TABLE V
Highest observed 24-hour rainfall amounts(mm),
at Douala, Cameroun, 1936 - 1969.

104.3	216.1	179.0	145.0	193.4
193.2	108.7	128.3	158.7	178.6
127.8	189.6	223.5	154.3	126.8
124.6	117.8	128.7	169.0	121.8
126.7	168.1	177.5	206.1	104.2
107.1	163.8	162.1	156.1	134.9
112.0	182.1	169.8	169.6	138.4
160.0	113.1	170.4	110.2	188.5
108.9	149.3	180.4	237.8	125.9
140.8	100.6	118.0	146.3	159.1
140.0	176.4	104.4	214.0	152.1
167.5	103.7	162.0	235.2	100.4
112.0	195.0	131.2	113.0	101.2
120.0	192.5	115.0	104.0	143.6
170.6	214.0	136.4	192.7	115.0
100.5	105.7	132.0	123.6	167.3
115.0	155.2	115.0	113.9	150.5
217.3	125.0	172.9	102.5	106.8
168.1	131.5	118.9	126.2	111.9
147.1	215.0	123.9	102.2	105.5

TABLE VI

Probable 24-hour largest rainfall amounts (mm) using the Gumbel extreme value theory for Douala, Cameroun, 1936 - 1969.

Return period, T_r (years)	Probable rainfall, $X(T_r)$ (mm)	95% Confidence limits (±mm)
1.01	130	26
1.1	133	26
1.5	142	26
2.0	150	26
2.33	154	26
5	176	26
10	195	26
25	221	26
34	230	26
50	240	26
100	260	34
200	279	34
500	305	34
1,000	325	34

TABLE VII

Number of wet days (1.0 or more) and all days classified by rainfall occurrence (1.0mm or more) on preceding day, by month. Estimates of conditional probabilities of wet-day occurrence. Probability of any day being wet. Douala, Cameroun, 1936 - 1969.

Month	Preceding Day	Actual day Wet	Actual day Total	Conditional Probability ρ_1	Conditional Probability τ_1	Probability of any day being wet, P_1
January	wet	33	141		.23	.14
	dry	106	879	.12		
February	wet	51	196		.26	.20
	dry	134	729	.18		
March	wet	168	413		.40	.40
	dry	243	607	.40		
April	wet	201	465		.43	.47
	dry	265	521	.51		
May	wet	349	597		.58	.59
	dry	251	332	.59		
June	wet	456	654		.70	.66
	dry	192	332	.58		

July	wet	744	857		.87	.84
	dry	109	163	.67		
August	wet	824	909		.83	.89
	dry	86	111	.77		
September	wet	659	795		.83	.81
	dry	140	191	.73		
October	wet	516	725		.71	.71
	dry	213	295	.72		
November	wet	156	373		.42	.38
	dry	214	613	.35		
December	wet	50	166		.30	.16
	dry	116	854	.13		

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