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14. Abstract/Notes

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15. Remarks

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ABSTRACT

The annual rainfall series at Fortaleza, Ceara in the northeast of Brazil, for 1849-1976 was subjected to Maximum Entropy Spectral Analysis (MESA) and Least Squares Linear Prediction (LSLP). Two major periodicites viz. T = 12.9 and 25.1 years and several minor ones were detected. These were found to be useful for predicting a possibility of droughts during 1979-83. In future, minor droughts during 1993-1996 and major droughts during 2003-2012 are envisaged. However, some limitations of the method used and large uncertainties in the results (specially those for yearly values) warrant great caution in using these predictions.

1. Introduction

Study of periodicities in time series has been a popular exercise in many fields. In Meteorology,such studies have been conducted for rainfall time series in many parts of the world and some solar-weather relationships have been suggested (see review by King, 1975 and references therein). For the South-American region, the northeast region of Brazil seems to have received considerable attention, due to its frequent droughts. Apart from very early references like Derby (1885), Mossman (1919), Walker (1928) and Ferraz (1929) mentioning relationships between drought periods and sunspots, and droughts and meteorological events at distant locations in the tropics and subtropics of both hemispheres, Markham (1974) seems to have been the first to use the Blackman and Tukey (1959) method of autocorrelation for the long rainfall series at Fortaleza (Ceara), which is a sea-port situated at (4^{o}S, 39^{o}W), on the northeast coast of Brazil in South America (see Fig. 1). Markham reported periodicities of 13 and 26 years, the former one with a apriori significance level as high as 99%, which was later contested by Jones and Kearns (1976) who showed that the significance level was much lower (about 90% a posteriori).

Recently, Girardi and Teixeira (1978) examined the rainfall series at Fortaleza, attempted to fit to it sinusoids of periodicities of 26 years and 13 years and (peak to trough) rainfall amplitudes of 2000 mm and 1400 mm respectively, adjusted their phases to match some of the earlier drought years and found that, if extrapolated in near future , the fit indicated a possibility of droughts during 1979-1985. This paper was soon followed by another similar paper by Strang (1979). Almeida et al (1980) and Nobre et al (1982) critized the work of Girardi and Teixeira (1978) and Strang (1979). However, some of the last few years (1979, 1980 and 1983) do seem to have suffered droughts. In the present paper we examine the Fortaleza rainfall series with more rigorous methods, to check whether some indications of drought-prone periods could be obtained.

2. Methods of Analysis

In most of the earlier works, the methods of spectral analysis have been Fourier (Harmonic) analysis or the Blackman and Tukey (1959) method based on autocorrelation. Burg (1967) was the first to introduce the method of Maximum Entropy Spectral Analysis (MESA) which is superior to the earlier methods and detects periodicities even comparable to the data length. However, the MESA method has some well--known defects. In the Blackman and Tukey method, there is a lag factor m which can be chosen arbitrarily and frequencies(1/2 m), (2/2 m), (3/2 m) etc. can be explored. For low m, not much resolution is obtained. However, whereas larger m gives better resolution, a limit of m=20% or less of the data length is generally recommended, as larger m is expected to produce instabilities. We believe this limit to be unduly conservative (Kane, 1977). In Burg's MESA, the parameter somewhat equivalent to lag m, is the Length of the Prediction Error Filter (LPEF). For low LPEF, not much resolution is obtained. For larger LPEF, larger periodicities are revealed; but lower periodicity peaks start showing peak-splitting. Also, large periodicities may have errors (frequency shifts) as large as 20%, which can be corrected by using the elaborate program of Fougere (1977). For determining the optimum LPEF, Ulrych and Bishop (1975) suggested the use of Akaike's (1969) Final Prediction Error (FPE) criterion, where FPE is plotted versus LPEF and the LPEF corresponding to the minimum FPE is the optimum LPEF. However, this method often fails and, in that case, Ulrych and Bishop recommended LPEF=50% of the data length. Our experience (Kane 1977, 1979) indicated that for samples containing peaks in a wide range of frequency, LPEF=50% of the data length was adequate to resolve frequencies exceeding the fifth harmonic, but for lower harmonics (larger periodicities), LPEF even as high as 90% was sometimes needed, with the danger of peak-splitting and frequency shifting ever present.

Though Girardi and Teixeira (1978) used the method of harmonic analysis only, one of the authors (Kantor) who contributed to the report Almeida et al. (1980), did use the Burg's MESA method for analysis of the Fortaleza rainfall series and reported in the same report his priliminary results. Later, he published a detailed report (Kantor, 1982), in which he used an auto-regressive process for prediction for which the coefficients were calculated by Burg's MESA. When applied to the Fortaleza annual rainfall series (mean about 1425 mm), he found that the residual standard error of prediction was rather large (about 300 mm). Also, assuming that a rainfall below

1000 mm could be considered as drought, Kantor concluded that there was only a 50% probability that 1981 and 1983 would be drought years.

As mentioned earlier, Burg's MESA has some well-known defects, notably frequency shifts in higher periodicities which are revealed only at large LPEF. It is likely that this defect affected the results reported by Kantor. These defects of the Burg algorithm are caused mainly due to its imposition of a Toeplitz structure on the matrix of the system of equations which yield the AR (auto regressive) parameters. This procedure, while giving computational efficiency to the Burg's algorithm, results in inferior spectra (less accuracy in frequency determination) as compared to those obtained by using Least-Square (LS) solutions to the AR model. (See Ulrych and Clayton, 1976).

Estimation of AR parameters by LS methods, though known to be superior, was unpopular so far mainly because of the large computational effort involved. Recently, Barrodale and Erickson (1980a, b) developed an algorithm for solving the Least-Square Linear Prediction (LSLP) problem directly. Their algorithm (called FABNE by them) is claimed by them to be superior to Burg's MESA algorithm. We have confirmed this by using artificial samples as inputs (Kane and Trivedi, 1982). Therefore, in what follows, we propose to adopt the following methodology:

a) Subject the Fortaleza annual series to MESA and LSLP (FABNE) methods and locate the appropriate periodicities T_1, T_2 ... T_K, (for $T < 30$ from Burg spectra of LPEF=25% and for $T > 30$, from FABNE spectra of LPEF=50% or more).

b) Use an expression of the type:

$$f(t) = A_0 + \sum^{K} r_K \sin(2\pi \; t/T_K + \phi_K) \qquad (1)$$

where A_0 represents the series mean, and conduct statistical (least square fit) analysis to obtain the best estimates of r_K and ϕ_K and their standard errors, using the Fortaleza annual rainfall series f(t) for t=1 to 128 i.e. for years 1849-1976. It may be noted that this procedure looks like Fourier (Harmonic) analysis but it is not so. In Fourier analysis, the periodicities T_K are all interrelated, as simple fractions of a fundamental period T. In the present case, the various T_K are in principle, unrelated. The method used is briefly outlined in the appendix.

c) Using the right-hand side of equation (1), predict f(t) for t=129, 130 etc. i.e. for years 1977, 1978 etc. and see if these indicate drought conditions for 1979-1985.

3. Results

A) Illustration for an Artificial sample

Fig. 2 shows the results of a spectral analysis of an artificial sample of 101 data points (years) composed from six sinusoids (all of amplitude unity) of periods T_1=5, T_2=10, T_3=20, T_4=40, T_5=80 and T_6=160 years. Fig. 2(a) shows at the top the plot of the 101 values under consideration and below it, Fig. 2(b) shows the Blackman and Tukey spectra, where the smoothed spectral density is obtained by the procedure outlined in Jenkins and Watts (1968). For data of 101 points, the lag m usually recommended is 20. However, as can be seen in Fig. 2(b), m=20 shows virtually no resolution. Even for m=40, only T=5 and 10 are resolved. A still larger lag m=75 reveals only T=5, 10, 20.

Fig. 3 shows (in the lower half) the results of Burg (MESA) and FABNE methods for the same artificial sample. The top curve is for Blackman and Tukey method for m=75 and is the same as the bottom curve of Fig. 2(b) except that the abscissa scale for Fig. 3 is log T (instead of f). The vertical lines (equally spaced) indicate the locations of the expected peaks at T=5, 10, 20, 40, 80, 160. The superiority of the Burg and FABNE methods over the Blackman and Tukey method is very obvious, with much sharper peaks even at low LPEF. For larger periodicities, FABNE gives slightly better accuracy in frequency determination. An interesting aspect is that, even though all the input sinusoids have the same amplitudes (unity), the various peaks in all these methods are of different heights. Hence, we consider the amplitude estimates unreliable and use the alternative method mentioned earlier in the Method of Analysis (equation (1)). When applied to the present artificial sample having sinusoids all of amplitude unity, we obtained the following estimates of the amplitudes:

T =	5	10	20	40	80	160
Input Amplitude	1.0	1.0	1.0	1.0	1.0	1.0
Estimated Amplitude	0.99 ± 0.01	0.99 ± 0.01	1.00 ± 0.01	1.00 ± 0.01	1.04 ± 0.02	1.02 ± 0.03

Considering the fact that the sample had a Gaussian noise of 0.001 added to it, the fit seems to be very satisfactory indeed, giving us confidance that this method would give reasonably good estimates of the amplitudes.

B) Analysis of Fortaleza annual rainfall series

All Rainfall data discussed in this paper were obtained from Vols. I, II, III of "Dados Pluviometricos Mensais (Monthly Rainfall Data) for data up to about 1967 and furthur similar data, distributed by the Superintendencia do Desenvolvimento do Nordeste (SUDENE) of Brazil. In Fig. 4, the top curve shows a plot of the annual rainfall (year = Jan. to Dec.) for Fortaleza. The full curve represents data from 1849 to 1976 which will be used for spectrum analysis and the rest, 1977-1983, are shown as dots, to be used for comparing with predicted values. The rainfall at Fortaleza is very erratic, with values as low as 468 mm (in 1877) and as large as 2793 mm (in 1894). Years of deficit or excess rainfall (less than 1090 mm or exceeding 1760 mm) are shaded black in Fig. 4. The second and third rows in Fig. 4 show moving averages over two and three consecutive values. Here, some intervals of wet and dry spells are revealed. There are also indications of periodicities, which will be the topic of study of this paper.

Fig. 5 shows a histogram of the rainfall distribution in the 134 years (1849-1982). The mean value is about 1423 mm with a standard deviation σ of about 496 mm and a probable error (0.66σ) of about 331 mm. Dividing the period into groups of Normal years (Rainfall 1423 $\mp$ 331 mm = about 1090 to 1760 mm) which account for about half the total data (66 years), Drought years (Rainfall less than 1090 mm) which account for 36 years and High (excess) rainfall years (Rainfall more than 1760 mm) which account for 32 years, the various years could be classified into categories of single, two consecutive and, three or more consecutive years of different types as shown in Table 1. As can be seen, nine drought years and eleven excess rainfall years fall into the category of single years and account for 12 + 8 = 20% of the total Variance, while another 7 + 8 = 15% Variance goes to years when successive years showed erratic, contrasting rainfall (high rainfall followed by low rainfall, or vice versa). Thus, about 35% of the total Variance can be attributed to single, erratic rainfall years, numbering 30 years. It seems to us that these years will be beyond the reach of any reasonable mathematical scheme of prediction based on analysis of yearly data. The rest of the 104 years have 66 Normal years (Variance 7%) and 38 years when rainfall was low (drought) or high (excess rain) for two or more consecutive years, (combined Variance 58%). The purpose of the present analysis is to examine whether the periods of possible dry spells, can be predicted with any reasonable accuracy.

Fig. 6 shows the spectral analysis of the Fortaleza rainfall annual mean series. The abscissa scale is log T. The top part shows the Blackman and Tukey smoothed spectral density. For the lag m=25 (about 20% of the data length 128), only peaks at T=2.4, 3.5 and 4.8 years are revealed. For m=50, many more peaks are revealed, including the peaks at T = 12.9 and 25.0. For lag m = 75, which is normally considered highly prohibitive but was nevertheless used by Markham (1974), the number of peaks increases. However, the two most prominent peaks are still at T = 13.0 and 24.5 years.

The middle part of Fig. 6 shows the Burg (MESA) spectra. Even at LPEF = 32 (i.e. 25% of the data length 128), peaks are revealed similar to those for m = 75 for Blackman and Tukey method. For higher LPEF, peaks at lower periodicities show splitting; but a new peak at T=61 is revealed.

The lower part of Fig. 6 shows the FABNE spectra. These are almost similar to the Burg spectra. The heights of all these peaks do not represent their relative amplitudes and are unreliable for amplitude estimations. Hence, we used these for selection of peaks only, from Burg spectra for $T < 30$ and from FABNE for $T > 30$, as given in Table 2 and obtained the amplitude estimates mentioned therein for Group 1, by using the method of equation (1).

As can be seen, the periodicities $T = 12.9$ and 25.1 had the largest amplitudes. The error was about ±45 mm for all periodicities. As some periodicities have larger amplitudes than others, we omitted some of the smaller ones and formed Group 2 and reestimated the amplitudes, which are give in Table 2 under Group 2. The amplitudes did not change much. We omitted a few more to form Group 3 and finally Group 4 which contained only T=12.9 and 25.1 years. For these two periodicities, the amplitudes were almost the same (about 250 mm) for all the groups.

With these amplitudes r_K, the corresponding phases ϕ_K were also obtained. These are not given in Table 2 as the phases do not have any special significance. However, these were needed and used for prediction purposes for substitution in the right hand side of equation (1). The prediction was carried out for each group separately. Fig. 7 illustrates the results. The top curve is for Group 1 (all periodicities). Up to 1976, the full line shows the original values (from 1944 onwards only). After 1976, the full dots and lines represent actually observed rainfall values for 1977-83. The crosses represent the predictions.

As seen from Fig. 7, the interval 1979-83 is indicated as drought-prone by the crosses. This tendency is seen in all the four groups. Table 3 gives the details. For the predicted values of individual years, the errors for all groups are rather large. However, for moving averages over 2, 3, 4 and 5 consecutive values (years), the errors are reduced and, (a) the observed and expected values show good resemblance and (b) the expected values are lower, by about 300-400 mm and at about a 2σ level, than the mean value 1423 mm of the Fortaleza rainfall series. Thus, a tendency for drought during the period 1979-83 is clearly foreseen. In Fig. 7, the expected values (crosses) and observed values (full lines) tally reasonably well for 1976 backwards for Group 1. However, we consider this fact rather trivial as, a composition from a large number of periodicities is bound to give a good fit. It does not gurantee a good fit for future.

The present drought in northeast, though bad enough, is not the only one in Brazil's history. There were severe droughts earlier too. The years 1950-60 had a conspicuous low rainfall. Could this have been foreseen? For this, we subjected the 100 year time series (1849-1948) for Fortaleza to Burg-FABNE analysis, picked up possible periodicities, estimated the amplitudes (and phases) and obtained predicted rainfall for 1949 onwards. The results are shown in Fig. 8. Up to 1948, the full line represents the observed data (from 1936 onwards only). For later years, the full dots represent the observed values and crosses represent the predicted values. Except for some erratic deviations, the two seem to resemble fairly well. In particular, the drought during

1953-56 is clearly seen in the crosses, though the prediction for 1958 itself, a well-known drought year, does not come out correct. Also, excess rainfall in 1963-65 is missed. However, a possible drought during 1979-83 is seen. Thus the 100 year data (1849-1948) was adequate to foresee a possible drought-prone period about 6 years in advance (1953-56) and also foresee a drought-prone period about 35 years later (1979-83).

C) Fortaleza versus the interior of Northeast

The northeast of Brazil is well known to be a region of high variability and heterogeneity of rainfall, not only in the total amount of precipitation and its standard deviation but also in the season of precipitation (Kousky and Chu, 1978; Kousky, 1979). The eastern coastal areas can receive annual rainfall up to 2000 mm or more while some interior valley regions may receive 400 mm or less. The high rainfall areas have in general a smaller percentage of year-to-year variability (about 20% or less) than the low rainfall areas (about 40% or more). The maximum rainfall occurs during March-April in the northern part (e.g. Ceara), during November-December in the southern part (e.g. Bahia) and during May-July in the eastern coastal areas. The dynamical causes for such an interannual variability are various. Namias (1972) reported a possible connection between the 700mb circulation pattern over the North Atlantic and the rainfall at the location Quixeramobim (Ceara). Markham and McLain (1977) and Hastenrath and Heller (1977) studied the correlation between sea surface temperature and rainfall in the northeast. Hastenrath and Heller (1977) showed a close link between the rainfall in Ceara and the meridional displacement and strength of the Intertropical Convergence Zone (ITCZ), while Moura and Shukla (1981) pointed out that the ITCZ is probably not the only factor involved. Ramos (1975) and Yamazaki and Rao (1977) studied the role of tropical disturbances and showed that rainfall systems moved westward from the Atlantic to the northeast, causing precipitation. Kousky and Chu (1978) and Kousky (1979) showed a considerable disagreement between the rainfall patterns in the northern part (Ceara) and southern part (Bahia) and demonstrated the role of southern hemisphere cold fronts (or their remains) in causing enhanced rainfalls, as the fronts moved northeastward along the northeast coast. Kousky (1980) showed the influence of systems of local wind circulation on rainfall and Kousky and Gan (1981) investigated the effects of upper tropospheric cold lows on cloudiness.

In view of this heterogeneous situation of rainfall in the northeast, the question arises, does Fortaleza represent anything at all in this region? Some evidence is already available. Girardi and Teixeira (1978) chose six locations (see list in Table 4 bottom and the locations marked as triangles in Fig. 9) all within 500 km of Fortaleza and obtained their average rainfall and got a reasonably high correlation of +0.74 between this group average and Fortaleza, for the period 1912-1956. Hastenrath and Heller (1977) obtained an average rainfall series (deviations from mean in units of std. dev. σ) for locations in the northern part of northeast. The years of extreme drought in their series tallied with the extreme droughts at Fortaleza. On the other hand, Almeida et al. (1980) mention that for locations outside Ceara, the correlation with Fortaleza was very poor. Nobre et al. (1982) showed that the Fortaleza rainfall is representative of a large area of northeast only in years of extreme drought for the whole region.

From SUDENE data for 1910-1970, we selected some locations as given in Table 4 and shown in the map in Fig. 9. The farthest location is Palmas de Monte Alto, about 1275 km away from Fortaleza (shown as big full dot in Fig. 9). Fig. 10 shows a plot of the annual rainfall at these locations. In each case, the mean line is drawn and the regions above average are shown hatched while the regions below average are shown black. The black shadings include droughts. A visual inspection clearly shows that whereas the rainfall above average is not well correlated everywhere, the droughts are almost common everywhere (see the vertical lines). Thus, in affluence (excess rainfall), each location may have its own vagaries and, an excess rainfall at Fortaleza guaranteed nothing for the interior. But, in adversity (severe droughts), almost all locations were in unison, probably because all of the various mechanisms responsible for rainfall either weakened or failed simultaneously. Thus, a forecast of extreme droughts at Fortaleza would mean drought for a large part of the northeast. This is in agreement with Nobre et al. (1982). For Fortaleza, the data for the 56 years (1912-1967) were divided into 14 years of deficit rainfall (below 1050 mm), 28 years of normal rainfall (1050-1800 mm) and 14 years of excess rainfall (exceeding 1800 mm). For these groups, the rainfall was -41%, 0 and +43% for Fortaleza. For the same year groups, deviations for other locations are shown in Table 4. As can be seen, negative deviations are prevalent up to about 400 km from Fortaleza, in some cases much farther away. Of course, some vagaries like those pointed out by Kousky and Chu (1978) cannot be ruled out where, for example in 1919, there was severe drought in the north (even north Bahia) but excess rainfall in the southern and central parts of Bahia. At the bottom of Fig. 10 we have shown the group average rainfall used by Girardi and Teixeira (1978) and deviations from mean in units of standard deviation σ used by Hasternrath and Heller (1977). For these also, the concurrence of droughts with Fortaleza is obvious.

Kousky and Chu (1978) selected several stations from different parts of the northeast and obtained their spectral density profiles for the period 1910-1970 (about 50-60 years). Since they used the Blackman and Tukey method (1958) (with smoothening procedures outlined in Jenkins and Watts, 1968) with a maximum lag of only 20 (about 35% of the data length), they obtained only approximate results such as the presence of peaks at 3-5 years in the north, 2-3 years in the south and east and a peak in the range 10-20 years in many areas throughout the northeast region and concluded that the actual peaks obtained were not significant enough to be used for forecasting. With our experience for the Fortaleza series, it seems to us that a similar analysis for other regions may throw additional light on the analysis and conclusions obtained by Kousky and Chu. In Fig. 11, we compare the Burg spectra for Fortaleza with two locations in the interior viz.

Quixeramobim and Missão Velha, about 180 km and 385 km respectively from Fortaleza (locations Nos. 8 and 15 in Table 4 and Fig. 9). The top curves are for Fortaleza for 128 years and Quixeramobim for 81 years. The large periodicities which were T=12.9, 25.1, 61.7 years for Fortaleza are slightly different viz. T=13.3, 23.4, 42.7 for Quixeramobim, In the lower half of Fig. 11, we show Burg spectra for Fortaleza, Quixeramobim and Missão Velha for the common period 1912-1967 (56 years), for an LPEF = 37 (=67% of data length 56 years). The spectra are reasonably similar, indicating that at least up to Missão Velha (about 400 km), the influence of Fortaleza prevails. In future, we propose to investigate the Burg spectra of all other locations in the northeast to see whether any distinct categories can be identified.

Since Quixeramobim had a fairly long series of 81 years (1849-1976), we used its Burg peaks for prediction purposes. Fig. 12 shows the results, where the top curve is for Fortaleza for Group 3 (same as in Fig. 7) and the rest are for Quixeramobim for four groups with selected periodicities as shown. In all cases, the years 1980 and 1981 are predicted as drought years. However, the actually observed values show droughts in 1979 and 1981. Thus, Quixeramobim does not seem to be a good predictor. In 1980, Quixeramobim had rainfall above average. Table 5 shows the monthly rainfalls for Fortaleza and Quixeramobim. As can be seen, the rainfall in Feb. -Mar. 80 was 622 and 609 mm at the two places i.e. almost comparable. Vagaries like these are quite common in northeast and are beyond the reach of our prediction scheme.

4. Discussion

In Fig. 13, we have reproduced the major diagram of Girardi and Teixeira (1978), which illustrates the basis for their conclusions. There are a few unsatifactory aspects of their analysis. Firstly, in their subjective analysis, they chose the periodicities of 26 years and 13 years (taking a hint from Markham, 1974) and attributed to these the amplitudes of 2000 mm and 1300 mm, arbitrarily. By amplitudes, they obviously meant the range (peak to trough), as is clear from Fig. 13. For our nomenclature of r_K in equation (1), their values would be about 1000 mm and 650 mm respectively. These values are still about 3-4 times larger than the values we obtained (about 250 mm). However, this arbitrariness of their choice of amplitudes is not as disastrous as it looks. Because the main crux of their curve fitting is in adjusting the phases, which they did in such a way that for the four prolonged dry spells (critical periods) in the past (viz. 1877-89, 1901-1907, 1927-1933 and 1953-1959) both these sinusoids would have their minima occurring simultaneously. When this was achieved and the trend was extrapolated, they observed that 1979-1985 would also be a critical period. This was their prediction of a drought. For this, the actual values of the amplitudes hardly mattered.

Secondly, in their objective analysis, they used the method of Fourier (harmonic) analysis of 128 years of data. In this method, only harmonics of the basic frequency f = (1/128) could be obtained and if the curve is recomposed from the harmonics, the pattern of 128 years has to repeat itself in future. As noted by the authors themselves, this is absurd. The reason why it did not lead to absurd results was purely fortuitous. The period T=128 years has the harmonic periods, 64, 42.7, 32.0, 25.6, 21.3, 16.0, 14.2, 12.8 years etc., out of which at least three (underlined) happen to be very near the major real periodicities involved in the series, as seen from our Burg analysis. Thus, generality was not completely lost. Had they chosen say, T=110 years, the harmonics 55, 36.7, 27.5, 22.0, 18.3, 15.7, 13.8, 12.3, 11.0 years would have been somewhat different from the real values and the predictions would have been in error.

Thirdly, in Fig. 13, the predicted rainfall is shown with an alternate year zigzag. Such a Quasi-Biennial Oscillation (QBO) cannot be produced by the 26 or 13 year periodicities, nor by adding the other harmonics viz. T=18.3, 9.14 and 4.9 years, which Girardi and Teixeira have used later. We suspect that this zigzag has been added by them arbitrarily, taking a cue from the fact that occassionally, the rainfall series did show such a zigzag in the past e.g. during 1956-1972 (see Fig. 7 and 8).

However, none of these unsatisfactory aspects seem to have made a major difference for their main conclusion viz. that 1979-85 would be a period of possible droughts.

Let us now examine the points of criticism offered by Almeida et al. (1980).

(i) Possibility of random or semi-random origin

It was shown by Almeida et al. (1980), that an artificially produced Markovian series of sufficient length (1000 points) could show patches where some periodicities appeared. This may still be true. In fact, we have presented no evidence whatsoever against such a possibility. All that we claim in the present analysis is that, for some reasons unknown to us (and probably not known to anybody else either, so far), the Fortaleza rainfall series exhibits some long-term and short-term periodicities. And, whereas there is no guarantee that these will exist forever, the long periodicities seemed to be stable enough in the past (amplitudes not varying drastically) and hence will probably be operative for about a decade or two more. Whereas academically it would be very satisfying and fruitful to search for their physical causes (if any exist), for statistical purposes, this information does not seem to be necessary and successful forecasting of possible drought-prone intervals could be done just the same (for about a decade in advance) even without understanding the causes.

Skeptical opinions about periodicities in meteorological parameters are not new. Ward and Shapiro (1961) mention that the literature is full of reports about periodicities sufficient to produce an almost continuous spectrum, obviously a ridiculous situation. Lorenz (1963) mentions that the incessant fluctuations of the state of the atmosphere are noted to be irregular. Regular periodicities, if any, are very well hidden. Nevertheless, examples like the present one do give hope, that probable drought-prone intervals could be foreseen about a decade in advance. An earlier attempt by one of us (Kane, 1977) for predicting the rainfall in Gujarat, India, did not succeed, probably because there were no strong, long-term periodicities involved therein. However, the study of extended wet and dry spells over northeast of South Africa (Dyer and Tyson, 1977; Tyson and Dyer, 1978), indicated a dry spell in 80's (which proved to be true) and a wet spell in late 80's and early 90's.

Since the periodicities observed may not be longlasting (the QBO was present only during 1956-1972), the data used for prediction should be immediately preceding the interval to be predicted. Thus, whereas one could use Fig. 7 (for 1849-1976) for prediction upto perhaps the end of the present century, and thus foresee a mini-drought in 1993-96, a better procedure would be to update the analysis by using data for 1849-1982. The results of such an analysis are shown in Fig. 14. For immediate future, a recovery from drought conditions is indicated.

However, vagaries for individual years are frequent and beyond the reach of the present analysis. Hence, 1984 could have been a drought year though, in reality, it seems to have been a year of rainfall above normal (exceeding 1900 mm). In near future, a period of about 7 years of respite (up to 1991) is envisaged. During 1992-1994, a small scale drought is indicated, followed by a 7-8 year period of respite again (1996-2002). During 2003-2011, another period of severe droughts is indicated. However, single years of normal rainfall during the dry spells, or, single years of drought outside the dry spells cannot be ruled out.

Generally, one would imagine that longer the data series available, better the accuracy of forecast. However, in view of the expected long range instability of the various periodicities, it may well turn out that a 100 year data series immediately preceding the interval to be predicted may be more useful than a 200 year data series. In view of the scarcity of long data series, it is difficult to confirm this, but such a possibility should always be kept in mind.

(ii) Very low probability of 7 consecutive years of drought

Almeida et al. (1980) estimated that in the last 250 years, there were about 45 drought years, giving a probability of about 18% for any one year. For two consecutive drought years one would expect a probability of about $(0.18)^2 = 0.0324$ i.e. about 3.2%, which for a 128 years series, would give about 4 events. However, as can be seen from Table 1, there were about 13 pairs of consecutive years of drought. The reason for this excess is obvious. Almeida et al. have assumed a binomial distribution, which is not true for cases where regular periodicities may be involved. In such cases, the probability of consecutive years having similar rainfall, increases. Girardi and Teixeira (1978) overstated their case when they hinted at seven years of continuous drought. The actual annual rainfall at Fortaleza for the five consecutive years 1979-83 turned out to be 985, 1095, 1100, 1104 and

884 mm, all below the series mean 1423 mm. The rainfall for 1984 seems to be above normal (exceeding 1900 mm).

Since Burg MESA and LSLP (FABNE) differ only slightly and only for very large periodicities (not very important in the present case) and since we have used mostly Burg spectra for picking the periodicities, it looked surprising that our conclusions should be so different from those of Kantor (1980) who also used Burg spectra. When we scrutinised his reported results in detail, we found that he had obtained for 1980-83 the predictions 838, 1095, 1480 and 1011 mm. Since his estimated error in each was about ±300 mm, he concluded that none was significantly different from the series mean 1423. However, he missed the fact that his predicted average for those four years would be 1106 ± 150 mm which was significantly below the series mean 1423 mm and thus, droughts during 1980-83 were clearly implied even in his analysis.

(iii) Fortaleza rainfall not representative of the interior

Almeida et al. (1980) have laid great emphasis on the fact that the rainfall patterns in various parts of the northeast region are very different and hence Fortaleza rainfall cannot be considered a good representative for the northeast. For overall correlation, this argument is correct and a large rainfall at Fortaleza seems to have poor relation with rainfalls in the interior. However, extreme droughts at Fortaleza seem to be well related to drought conditions at locations up to about 400 km away from Fortaleza. Thus, notwithstanding vagaries in single years, prolonged extreme droughts seem to be a common feature of a large portion of the northeast.

(iv) Periodicities highly unstable and transient

Since we do not know the sources of these periodicities, we can say nothing about their nature of variability. Some of the smaller periodicities do seem to be short-lived e.g. QBO which appeared strongly during 1956-1972 only. However, the larger periodicities do seem to be stable enough to yield meanigful predictions for a decade or two. Though academically unsatisfactory, the situation still has practical utility, as shown by our analysis. If data for about 100 years immediately preceding the interval for prediction are used, the results will have optimum utility.

It may be noted that, besides statistical methods, like the present one of ours, attempts are also being made to provide short-term predictions of rainfall. Hastenrath (1983) outlines a method for prediction of seasonal rainfall from the antecedent circulation departures. From a multiple regression analysis, he identifies the sea level pressure (SLP), sea surface temperature (SST) and the zonal (u) and meridional (v) components of wind over the tropical Atlantic as the most important predictors and says that information about these parameters is required on a timely basis which could be done by remote sensing by satellites. If and when successful, this method could give predictions for the stray, single years of low or high rainfall which were found beyond the reach of the present analysis. Incidentally, there must be some difficulties in applying this method. Hastenrath did not predict the recent drought of 1983. Recently, Nobre and Moura (1984) have reported a teleconnection between the North Atlantic and the rest of the globe through wave train patterns. Their study seems to be capable of foreseeing heavy precipitations or severe droughts with a precedence of a few months.

There is some reason to believe that the rainfall in different regions in the southern hemisphere may be correlated. Vines (1980) reports a remarkable coherence of rainfall figures of certain areas of South Africa, S.E. Australia and New Zeland. Moura and Kagano (1983) report a teleconnection between South America and W. Africa. Thus, drought occurrences over northeast Brazil may not be of a local nature and may have telltale evidences in other regions, which could be useful for predictions if some timelags are involved. This needs detailed exploration.

In Tables 1, 2 and 3, we have given details and predictions obtained from an analysis of yearly values. It is clear from these, however, that predictions for single years are not likely to be reliable and, only drought-prone <u>intervals</u> can possibly be predicted. The two prominent periodicities (T = ~13 and 25 years) seem to explain only about 23% of the total variance (see last row of Table 2). Even the 16 peaks of Group 4 explain only about 59% of the total variance. In that case, one may argue, why not minimise the year-to-year fluctuations, by using averages over longer intervals e.g. 2 years, 3 years etc.? The plots for these are already shown in Figure 4. For analysis, only non-overlapping periods were used e.g. 64

bi-yearly averages for the period 1849-1976 and 43 tri-yearly averages for the period 1849-1977. Table 6 shows the comparative results. The prominent periodicities were still T = about 13 and 25 years. Also, the amplitudes of these periodicities were in the range 230-250 mm for all cases; but the mean Variance was smallest for the 3 year data. Hence, these two periodicities could explain about 44% of the Variance of the 3 year data, in contrast to 23% for the yearly data. For the period 1981-83, rainfall below 1000 mm was predicted in all cases and compared very well with the observed value viz. 1001 mm (see Table 3).

For further smoothing, moving averages over five consecutive values were calculated. The smoothed series of 124 data points (centered at years 1851, 1852, ... 1974) had a mean value of 1420 mm and a standard deviation 281 mm. The prominent periodicities were T = 12.9 and 25.1 years with amplitudes 196 and 230 mm respectively and the two could explain about 58 % of the Variance of the series of the 5 year moving averages. If one more periodicity viz. T = 63 years of amplitude 150 mm was also considered, the three periodicities could explain about 73% of the Variance and the predicted and observed values were as given below. (The plots are shown in Figure 15). The analysis also revealed two more substantial periodicities viz. T=10.1 and 18.6 years with amplitudes of about and 100 and 105 mm, thus contributing about 6% each to the Variance. Hence, the five periodicities T = 10.1, 12.9, 18.6, 25.1, 63.0 years could explain about 85% of the Variance and the small differences between the expected and observed values in the Table below and Figure 15 (based on T=12.9, 25.1, 63.0 years only) could be reduced further.

5 YEAR INTERVAL	CENTERED AT	PREDICTIONS	OBSERVED VALUES
1973-77	1975	1792	1996
1974-78	1976	1693	1880
1975-79	1977	1561	1575
1976-80	1978	1416	1438
1977-81	1979	1282	1375
1978-82	1980	1182 ±40	1187
1979-83	1981	1133	1014
1980-84	1982	1141	1216
1981-85	1983	1201	
1982-86	1984	1299	
1983-87	1985	1413	

(For 1984, the observed value is assumed to be 2000 mm).

As can be seen, the agreement between the expected and observed values is very good and the 5 year interval 1979-83 is indicated as of low rainfall in both.

5. Conclusions

a) The Fortaleza rainfall series for 134 years (1849-1982) had a mean of 1423 mm and standard deviation of 496 mm. Considering rainfall less than 1090 mm as low (deficit) and larger than 1760 mm as high (excess), it was observed that about 35% of the total variance was due to low and high rainfall which occurred in single years. Being erratic loners, these are essentially unpredictable by the statistical methods described above, but may be amenable to prediction with antecedence of a few months by methods based on studies of physical phenomena, as illustrated in some recent works.

b) The series had also some reasonably stable periodicities, notably 12.9 and 25.1 years. These could be used for predictions of possible drought-prone periods. For example, an analysis of the 100 years data (1849-1948) was capable of foreseeing possible drought-prone periods in 1952-56 and in 1979-82. The data for 128 years (1849-1976) could foresee possible droughts during 1979-83.

c) An analysis for 134 years (1849-1982) revealed the following possibilities for future:

- Period of respite (normal or excess rain) during 1985-1992. (about 8 years)

- A mini-drought during 1993-96. (about 4 years)

- Respite during 1997-2002 (about 6 years)

- Severe drought during 2003-2012 (about 10 years)

- However, single years of normal rainfall during these dry spells or, stray drought years outside these dry spells could occur and cannot be predicted by this study of periodicities.

d) The overall correlation between rainfall at Fortaleza and the interior may not be very good. But extreme droughts at Fortaleza seem to be associated with severe droughts at least up to about 400 km (sometimes much more) in the interior. Notable exceptions could occur in single years, for some locations or areas.

e) Since the short periodicities are highly transient and the longer periodicities also could change, even abruptly, it is obvious that great caution should be exercised in issuing forecasts. Predictions for individual years should be considered unreliable. Predictions for longer intervals could be considered with greater confidence and may be useful for some general, long-term planning.

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APPENDIX

Multiple regression analysis is described in many books on statistical analysis (e.g. Bevington, 1969; Johnston, 1963). It is used to fit a linear relationship between a dependent variable Y and several independent variables X_1, X_2 ... X_κ, when a sample of n observations is available. Thus,

$$Y = A_0 + A_1X_1 + A_2X_2 \ldots + A_\kappa X_\kappa + U \qquad \text{(i)}$$

where A_j (j=0 to κ) are the κ+1 regression coefficients to be determined and U is the error in estimating the observed value of viz. Y_i (i = 1 to n). In matrix notation,

$$Y = XA + U \qquad \text{(ii)}$$

where

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \cdot \\ \cdot \\ \cdot \\ Y_n \end{bmatrix} \qquad X = \begin{bmatrix} 1 & X_{11} & X_{21} & \ldots & X_{\kappa 1} \\ 1 & X_{12} & X_{22} & \ldots & X_{\kappa 2} \\ \cdot & \cdot & \cdot & \ldots & \cdot \\ \cdot & \cdot & \cdot & \ldots & \cdot \\ \cdot & \cdot & \cdot & \ldots & \cdot \\ 1 & X_{1n} & X_{2n} & \ldots & X_{\kappa n} \end{bmatrix}$$

$$A = \begin{bmatrix} A_1 \\ A_2 \\ \cdot \\ \cdot \\ \cdot \\ A_n \end{bmatrix} \quad U = \begin{bmatrix} U_1 \\ U_2 \\ \cdot \\ \cdot \\ \cdot \\ U_n \end{bmatrix} \quad \hat{A} = \begin{bmatrix} \hat{A}_0 \\ \hat{A}_1 \\ \cdot \\ \cdot \\ \cdot \\ \hat{A}_K \end{bmatrix} \quad e = \begin{bmatrix} e_1 \\ e_2 \\ \cdot \\ \cdot \\ \cdot \\ e_n \end{bmatrix}$$

$\hat{A}$ are the estimates of A and

$$Y = X\hat{A} + e$$

where e denotes the column vector of the n residuals $(Y-X\hat{A})$.

Using the principle of least squares, the coefficients $\hat{A}$ are obtained by minimizing Z, the sum of the squares of the n residuals e_n.

$$Z = \sum_{i=1}^{n} e_i^2 = e'e$$

$$= (Y - X\hat{A})' (Y - X\hat{A})$$

$$= Y'Y - 2\hat{A}'X'Y + \hat{A}X'X\hat{A} \qquad \text{(iii)}$$

(where the superfix' indicates the transpose).

Putting $\frac{\partial Z}{\partial \hat{A}} = \frac{\partial}{\partial \hat{A}} (e'e) = -2X'Y + 2X'X\hat{A} = 0$

$$X'X\hat{A} = X'Y$$

This is a system of simultaneous equations generally known as normal equations.

$$\text{Hence } \hat{A} = (X'X)^{-1} X'Y \qquad \text{(iv)}$$

The standard error of $\hat{A}$ turns out to be:

$$\sigma_{\hat{A}} = [\Sigma\, e_i^2/(n-\kappa-1)]^{1/2} (a_{ii}^{-1})^{1/2}$$

$$= S(a_{ii}^{-1})^{1/2} \qquad \text{(v)}$$

where

$S^2 = (Y'Y - \hat{A}'X'Y) / (n-\kappa-1)$ is the unbiased estimator of the disturbance variance and,

(a_{ii}^{-1}) = the i^{th} diagonal element of the matrix $(X'X)^{-1}$.

Regression analyis can be used to make a prediction of Y corresponding to a set of X values. Let C be a vector given by $C(1,, X_{1,n+1}, \ldots X_{\kappa,n+1})$ for which prediction of the expected value of Y i.e. Y_{n+1} is required. Thus,

$$\hat{Y}_{n+1} = C'\hat{A} \qquad \text{(vi)}$$

The standard error $\sigma_{\hat{Y}}$ of $\hat{Y}$ turns out to be

$$\sigma_{\hat{Y}} = \pm S(C' (X'X)^{-1} C)^{1/2} \qquad \text{(vii)}$$

In our present case, Y is the yearly rainfall and the X are the components cos $\omega_j t$, sin $\omega_j t$, where t=years 1 to n, and $\omega_j = 2\pi/T_j$ where T_j(j=1 to κ) are the various periodicities T_1, T_2 ... T_κ observed in the power spectrum of the Y values. One a_j and b_j and their standard erros σ_{aj}, σ_{bj} are obtained by using (iv) and (v), the amplitudes and phases r_j, ϕ_j and the standard error σ_{rj} are obtained as:

Since

$$r_j \sin(\omega_j t + \phi_j) = a_j \cos \omega_j t + b_j \sin \omega_j t,$$

$$r_j = (a_j^2 + b_j^2)^{1/2}$$

$$\phi_j = \tan^{-1}(a_j/b_j)$$

$$\sigma_{rj} = (a_j^2 \sigma_{aj}^2 + b_j^2 \sigma_{bj}^2)^{1/2}/r_j \qquad \text{(viii)}$$

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Captions for Figures

Fig. 1 - Map of the South-American Continent, showing Brazil and its northwest (shaded) and the town of Fortaleza (Ceara).

Fig. 2 - (a) Plot of artificial sample of 101 data points composed of sinusoids of periodicities T_1=5, T_2=10, T_3=20, T_4=40, T_5=80 and T_6=160, all of amplitude unity, plus white noise 0.001.

(b) Blackman and Tukey spectra (smoothed by the Jenkins and Watts procedure) for the above artificial sample, for lags m = 20, 40, 75.

Fig. 3 - Comparison of Blackman and Tukey spectra (top part, lag m = 75) and Burg and FABNE spectra (lower part, LPEF = 18, 40, 60, 80) for the artificial sample of sinusoids of periodicities 5, 10, 20, 40, 80, 160, marked by equally spaced vertical lines, for an abscissa scale of log T.

Fig. 4 - Fortaleza annual rainfall series for 1849-1976 (full lines) and for 1977-1983, (big dots). Top curve represents original values, and the second and third rows show moving averages over two and three successive values, respectively. Excess or deficit rainfall (high or low) is shown shaded black. Years of well-known droughts are indicated.

Fig. 5 - Histogram of the distribution of annual rainfall for 1849-1982 at Fortaleza.

Fig. 6 - The Balckman and Tukey spectra (lag = 25, 50, 75), Burg spectra (LPEF = 32, 64, 96) and FABNE spectra (LPEF = 30, 60) for the Fortaleza annual rainfall series for 1849-1976.

Fig. 7 - Fortaleza annual rainfall, original values up to 1976 (full lines) and for 1976-83, (big dots and lines). The crosses show the predicted values, indicating a drought (values below average) during 1979-83 in all the four groups.

Fig. 8 - Fortaleza annual rainfall, original values up to 1948 (full lines) and for 1949-83 (big dots and lines). The crosses show the predicted values and indicate droughts (values below average) during 1953-56 and 1979-83, in all the four groups.

Fig. 9 - Locations of selected stations in the northeast of Brazil. The triangles indicate the six locations selected by Girardi and Teixeira (1978).

Fig. 10 - Annual rainfall at several locations during 1912-1967. Values below average are shaded black and include droughts. Values above average are shown hatched.

Fig. 11 - Burg spectra for annual rainfall series for Fortaleza for 1849-1976 (128 years) at the top for LPEF = 64 (50%), for Quixeramobim for 1896-1976 (81 years) in the second row for LPEF = 41 (50%) and for Fortaleza, Quixeramobim and Missão Velha for 1912-1967 (56 years) for LPEF = 37 (67%) in the lower portion.

Fig. 12 - Fortaleza and Quixeramobim annual rainfall, original values up to 1976 (full lines) and for 1976-82 (big dots and lines). The crosses show the predicted values.

Fig. 13 - Diagram reproduced from Girardi and Teixeira (1978). The 13 and 26 year sinusoids have simultaneous minima during 1979-85, indicating a critical (drought) period.

Fig. 14 - Fortaleza annual rainfall, original values up to 1982 (full lines) and predicted values for 1983 onwards (crosses). A minor drought in 1993-96 and a major drought in 2003-2012 is indicated.

Fig. 15 - Moving averages over five successive observed values of Fortaleza annual rainfall, centered at years 1851, 1852 ... 1974 (full lines), which were used for prediction analysis. Using the periodicities T = 12.9, 25.1, 61.0 years with amplitudes 192, 225, and 164 mm, respectively the predicted values are shown as crosses. For 1975-1982, observed values are shown with big dots and full lines.

TABLE 1. Characteristics of Fortaleza Annual Rainfall Series (Source, SUDENE)

Total number of years (1849-1982) = 134 years

Total rainfall for 134 years = 190659 mm

Total variance for 134 years = 32994191 $(mm)^2$

Normal years = Rainfall 1423 ∓ 331 = ~ 1090 to 1760 mm

Low rainfall (drought) years = Rainfall less than 1090 mm

High (excess) rainfall years = Rainfall more than 1760 mm

Year = Calendar year (January-December)

Mean rainfall (1849-1982) = 1423 mm,

Mean variance (1849-1982) = 246225 $(mm)^2$

Standard deviation σ = 496 mm

Probable error = 0.66 σ = 331 mm

TYPE	NORMAL YEARS	LOW RAINFALL (DROUGHT) YEARS	HIGH (EXCESS) RAINFALL YEARS	YEARS OF CONTRAST (LOW FOLLOWED BY HIGH, OR VICE VERSA)
Single years	1890 1955 1901 1957 1911 1959 1916 1968 1920 1970 1935 1972 1940 1976 1948 1978 1952 (17 years) Variance (1%)	1884 1936 1891 1956 1915 1958 1919 1960 1928 (9 years) Variance (12%)	1856 1949 1921 1967 1924 1969 1934 1971 1939 1977 1947 (11 years) Variance (8%)	
Two consecutive years	1892-93 1922-23 1937-38 1961-62 1965-66 (10 years) Variance (1%)	1888-89 1902-03 1907-08 1932-33 1950-51 1953-54 (12 years) Variance (12%)	1872-73 1917-18 1963-64 (6 years) Variance (11%)	1866 (High), 1867 (Low) 1909 (Low), 1910 (High) (4 years) Variance (7%)
Three or more consecutive years	1852-55 (4 years) 1857-65 (9 years) 1868-71 (4 years) 1874-76 (3 years) 1880-83 (4 years) 1885-87 (3 years) 1904-06 (3 years) 1925-27 (3 years) 1929-31 (3 years) 1944-46 (3 years) (39 years) Variance (5%)	1877-79 (3 years) 1941-43 (3 years) 1979-82 (4 years) (10 years) Variance (12%)	1894-97 (4 years) 1912-14 (3 years) 1973-75 (3 years) (10 years) Variance (23%)	1849 (High), 1850 (Low), 1851 (High) 1898 (Low), 1899 (High), 1900 (Low) (6 years) Variance (8%)
TOTAL	(66 years) Variance (7%)	(31 years) Variance (36%)	(27 years) Variance (42%)	(10 years) (5 High, 5 Low) Variance (15%)

TABLE 2 - Amplitude estimates (mm) and their standard errors for various periodicities (selected from the Burg-FABNE spectra) for Fortaleza annual rainfall series for 128 years (1849-1976).

PERIOD T (years)	GROUP 1	GROUP 2	GROUP 3	GROUP 4
2.07	146	140	138	
2.24	81			
2.37	72			
2.77	81			
3.02	46			
3.39	95			
3.63	139	150		
4.42	88			
4.84	125	116		
5.69	125	130		
8.71	94			
10.1	147	143	143	
12.9	249	251	253	248
18.0	105	101		
25.1	243	245	246	243
61.0	166	169	164	
Std. error	±47	±48	±52	±56
Variance explained	59%	49%	37%	23%

TABLE 3 - Observed and predicted values of the Fortaleza annual rainfall for 1977 to 1983 for different groups.

YEAR	OBSERVED RAINFALL (YEARLY) (mm)	PREDICTED RAINFALL (mm)							
		GROUP 1		GROUP 2		GROUP 3		GROUP 4	
		T = 2.07, 2.24, 2.37, 2.77 3.02, 3.39, 3.63, 4.42 4.84, 5.69, 8.71, 10.1 12.9, 18.0, 25.1, 61.0		T = 2.07, 3.63, 4.84 5.69, 10.1, 12.9 18.0, 25.1, 61.0		T = 2.07, 10.1 12.0, 25.1 61.0		T = 12.9 25.1	
1977	1941	1260		1274		1489		1433	
1978	1752	1554		1559		1399		1261	
1979	985	1039		1054		984		1104	
1980	1095	926	±207	934	±157	1075	±125	991	± 89
1981	1100	855		852		836		942	
1982	1004	1637		1366		1183		966	
1983	884	978		1099		1095		1057	
1977 - 1978	1846	1407		1417		1444		1347	
1978 - 1979	1396	1296		1307		1192		1183	
1979 - 1980	1040	982	±148	994	±112	1030	±90	1048	± 63
1980 - 1981	1098	890		893		956		967	
1981 - 1982	1052	1246		1109		1010		954	
1982 - 1983	944	1308		1233		1139		1012	
1977, 78, 79	1559	1284		1296		1291		1266	
1978, 79, 80	1277	1173		1182		1152		1119	
1979, 80, 81	1060	940	±118	946	±90	965	±71	1012	± 51
1980, 81, 82	1066	1139		1051		1031		966	
1981, 82, 83	996	1157		1106		1038		988	
1977 - 1980	1443	1195		1206		1237		1198	
1978 - 1981	1247	1093	±104	1100	±79	1074	±63	1075	± 45
1979 - 1982	1046	1114		1052		1020		1001	
1980 - 1983	1021	1099		1063		1048		990	
1977 - 1981	1375	1127		1135		1157		1146	
1979 - 1982	1187	1202	±90	1153	±68	1095	±54	1053	± 39
1979 - 1983	1014	1087		1061		1035		1012	

TABLE 4. Selected locations in the Northeast of Brazil and their values for 1912-1967.

SR. NO.	STATION		GEOGRAPHIC		DISTANCE FROM FORTALEZA (km)	AVERAGE ANNUAL RAINFALL (mm) (1912-1967)	AVERAGE PERCENTAGE DEVIATION FROM NORMAL RAINFALL WHEN FORTALEZA HAD RAINFALL		
			LAT	LONG			LOW (14 years)	NORMAL (28 years)	HIGH (14 years)
Ref.	Fortaleza	(CE)	03°46'S	38°34'W	0	1414	- 41%	- 1%	+ 43%
1	Acarau	(CE)	02°53'S	40°07'W	195	1032	- 39%	+ 5%	+ 33%
2	Itapipoca	(CE)	03°30'S	39°35'W	110	1108	- 38%	+ 2%	+ 36%
3	Aracati	(CE)	04°34'S	37°46'W	120	903	- 45%	+ 4%	+ 40%
4	Jaguaruana	(RN)	04°50'S	37°48'W	145	730	- 47%	+ 2%	+ 46%
5	Vicosa do Ceará	(CE)	03°34'S	41°05'W	285	1305	- 27%	+ 5%	+ 22%
6	Santa Quitéria	(CE)	04°20'S	40°10'W	190	777	- 49%	+ 7%	+ 37%
7	Salão	(CE)	04°25'S	39°19'W	105	642	- 46%	- 1%	+ 47%
8	Quixeramobim	(CE)	05°12'S	39°19'W	180	743	- 32%	- 1%	+ 36%
9	José de Freitas	(PI)	04°45'S	42°35'W	460	1487	- 23%	+ 1%	+ 21%
10	Castelo do Piauí	(PI)	05°20'S	41°34'W	385	1024	- 25%	+ 1%	+ 25%
11	Independência	(CE)	05°23'S	40°20'W	265	618	- 35%	+ 7%	+ 24%
12	Pereiro	(CE)	06°03'S	38°28'W	250	1098	- 32%	+ 3%	+ 26%
13	Arneiroz	(CE)	06°20'S	40°08'W	335	577	- 28%	- 1%	+ 31%
14	Campos Sales	(CE)	07°04'S	40°23'W	415	677	- 19%	- 2%	+ 21%
15	Missão Velha	(CE)	07°15'S	39°09'W	385	966	- 29%	- 5%	+ 39%
16	Jaicos	(PI)	07°22'S	41°08'W	495	669	- 14%	- 2%	+ 17%
17	Simplício	(PI)	07°51'S	41°55'W	585	706	- 19%	+ 4%	+ 16%
18	Flores	(PE)	07°50'S	37°59'W	450	731	- 25%	+ 1%	+ 30%
19	Água Branca	(AL)	09°17'S	37°56'W	610	984	- 15%	+ 1%	+ 14%
20	Curaca	(BA)	08°59'S	39°54'W	595	437	- 15%	- 3%	+ 21%
21	Remanso	(BA)	09°41'S	42°04'W	765	570	- 16%	- 3%	+ 23%
22	Araci	(BA)	11°20'S	38°57'W	840	643	- 12%	- 5%	+ 21%
23	Rio de Contas	(BA)	31°34'S	41°49'W	1140	830	+ 4%	- 7%	+ 10%
24	Palmas de Monte Alto	(BA)	14°16'S	43°10'W	1275	753	+ 2%	- 6%	+ 10%
Δ	Girardi group				160-490	~ 700	- 32%	+ 2%	+ 31%
	Crato	(CE)	07°13'S	39°23'W	385	1075			
	Currais Novos	(RN)	06°16'S	36°31'W	360	374			
	Iguatu	(CE)	06°22'S	39°18'W	295	760			
	Limoeiro do Norte	(CE)	05°09'S	38°06'W	160	705			
8	Quixeramobim	(CE)	05°12'S	39°19'W	180	740			
	Ouricuri	(PE)	07°53'S	40°04'W	490	620			
	Hastenrath group				< 500	620	- 0.74 σ	+ 0.09 σ	+ 0.75 σ

Years of Low, Normal and High annual rainfall at Fortaleza during 1912-67 (56 years)

Low rainfall years (1049 mm or less)	14 years	1915, 1919, 1928, 1932, 1933, 1936, 1941, 1942, 1943, 1951, 1954, 1956, 1958, 1960
Normal rainfall years (1050 to 1800 mm)	28 years	1916, 1920, 1922, 1923, 1925, 1926, 1927, 1929, 1930, 1931, 1935, 1937, 1938, 1940, 1944, 1945, 1946, 1948, 1950, 1952, 1953, 1955, 1957, 1959, 1961, 1962, 1965, 1966
High rainfall years (1801 mm or more)	14 years	1912, 1913, 1914, 1917, 1918, 1921, 1924, 1934, 1939, 1947, 1949, 1963, 1964, 1967

TABLE 5. Monthly rainfall (mm) for Fortaleza and Quixeramobim

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	AVERAGE
a) Long-term average													
Fortaleza	92	185	294	336	232	117	57	23	18	15	17	37	1423
Quixeramobim	57	97	172	160	105	48	22	10	3	2	5	22	703
b) For 1980													
Fortaleza	177	443	179	57	44	73	53	30	23	0	7	9	1095
Quixeramobim	44	312	297	118	23	120	4	1	0	0	8	14	941
c) For 1981													
Fortaleza	95	111	531	140	123	33	0	6	0	0	5	56	1100
Quixeramobim	72	50	331	36	9	13	1	0	0	0	0	98	610

TABLE 6 - Comparison of results of analysis of original yearly values and smoothed data.

DATA USED		Yearly averages obtained from		
		1 year data	2 year data	3 year data
Sample data points		128	64	43
Years		128 (1849-1976)	128 (1849-1976)	129 (1849-1977)
Mean Rainfall (mm)		1428	1428	1432
Mean Variance (mm²)		248290	140249	119324
Standard deviation (mm)		498	375	345
Amplitudes of the two prominent peaks. (in mm)	T=13yr	248 } ± 55	234 } ± 55	239 } ± 60
	T=25yr	243	226	234
Variance explained by these two prominent peaks		23%	36%	44%
Rainfall (mm) predicted from the two prominent peaks, for the years.	1979	1104 } ± 90		
	1980	991		
	1981	942		
	1982	966		
	1983	1057		
	1984	1194		
	1977-1978	1347 } ± 65	1388 } ± 90	
	1979-1980	1048	1090	
	1981-1982	954	973	
	1983-1984	1126	1114	
	1985-1986	1425	1398	
	1978-1980	1119 } ± 50		1178 } ± 90
	1981-1983	988		969
	1984-1986	1348		1292

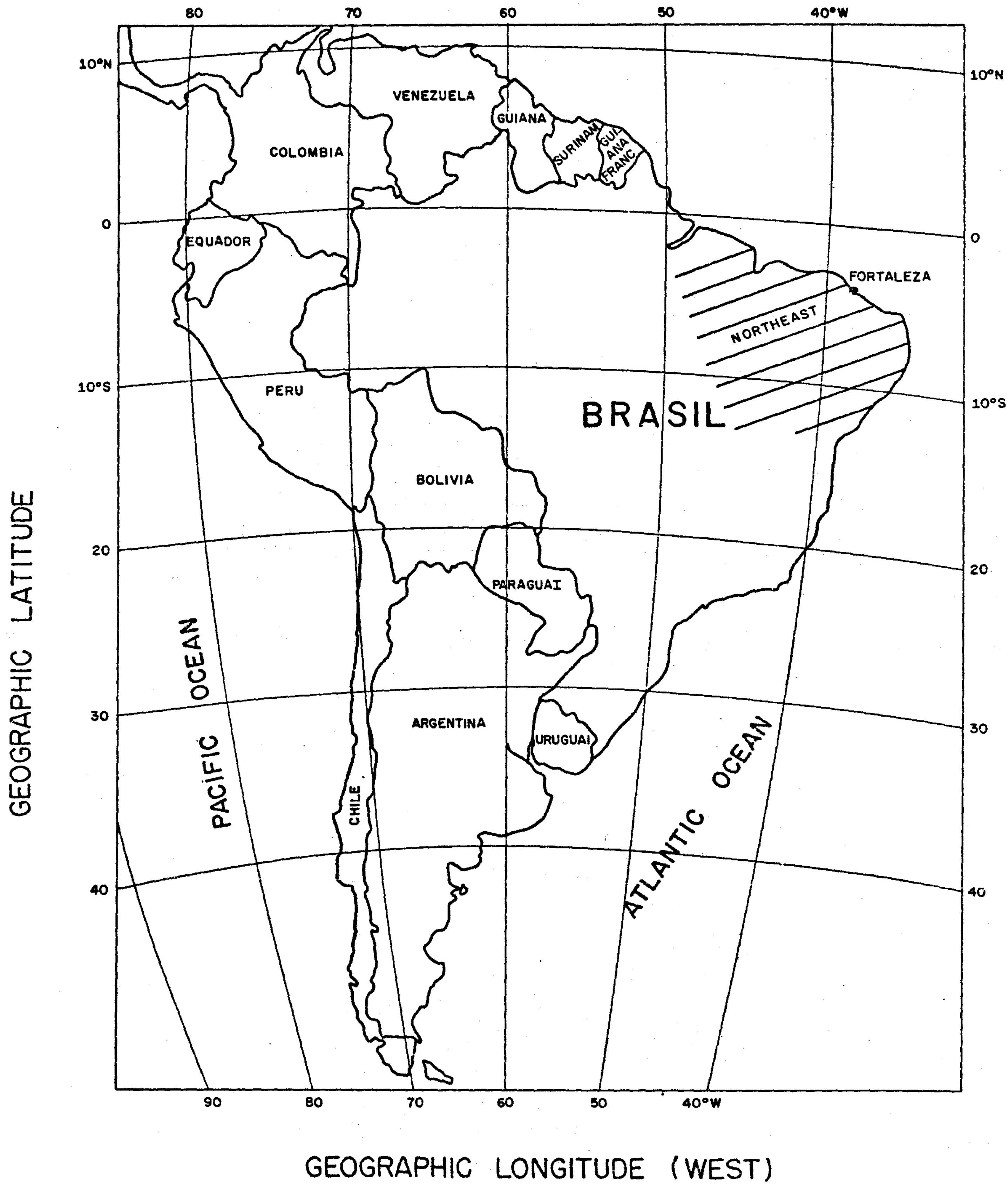

80
70
60
50
40°W
10°N
0
10°S
20
30
40
VENEZUELA
GUIANA
SURINAM
GUI ANA FRANC
COLOMBIA
EQUADOR
FORTALEZA
NORTHEAST
PERU
BRASIL
BOLIVIA
PARAGUAI
PACIFIC OCEAN
ARGENTINA
URUGUAI
CHILE
ATLANTIC OCEAN
90
80
70
60
50
40°W
GEOGRAPHIC LATITUDE
GEOGRAPHIC LONGITUDE (WEST)

Fig. 1

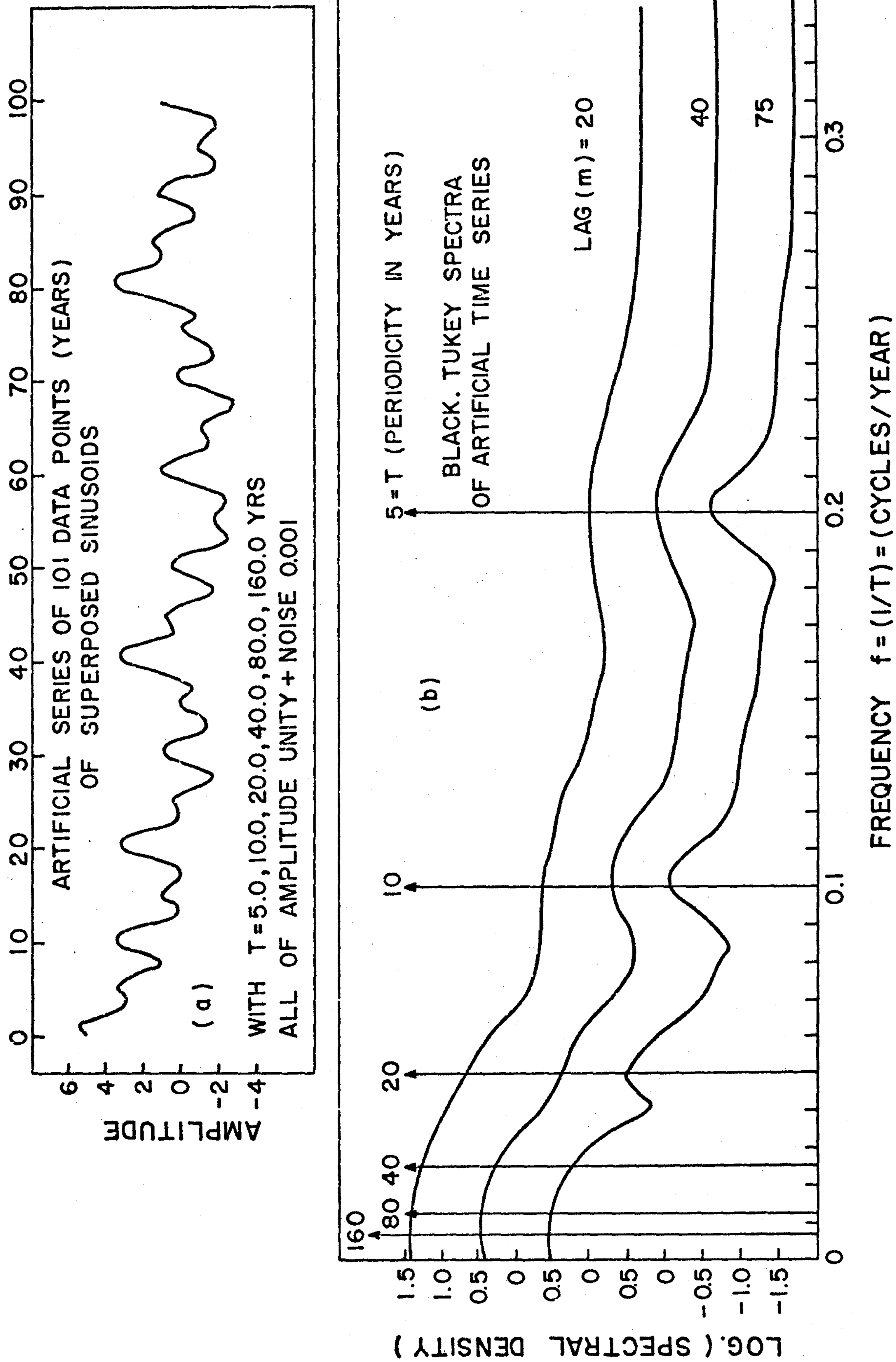

ARTIFICIAL SERIES OF 101 DATA POINTS (YEARS)
OF SUPERPOSED SINUSOIDS
(a)
WITH T = 5.0, 10.0, 20.0, 40.0, 80.0, 160.0 YRS
ALL OF AMPLITUDE UNITY + NOISE 0.001
AMPLITUDE
6
4
2
0
-2
-4
0
10
20
30
40
50
60
70
80
90
100
5 = T (PERIODICITY IN YEARS)
BLACK. TUKEY SPECTRA
OF ARTIFICIAL TIME SERIES
LAG (m) = 20
40
75
(b)
10
20
40
80
160
LOG. (SPECTRAL DENSITY)
1.5
1.0
0.5
0
0.5
0
0.5
0
-0.5
-1.0
-1.5
0
0.1
0.2
0.3
FREQUENCY f = (1/T) = (CYCLES/YEAR)

Fig. 2

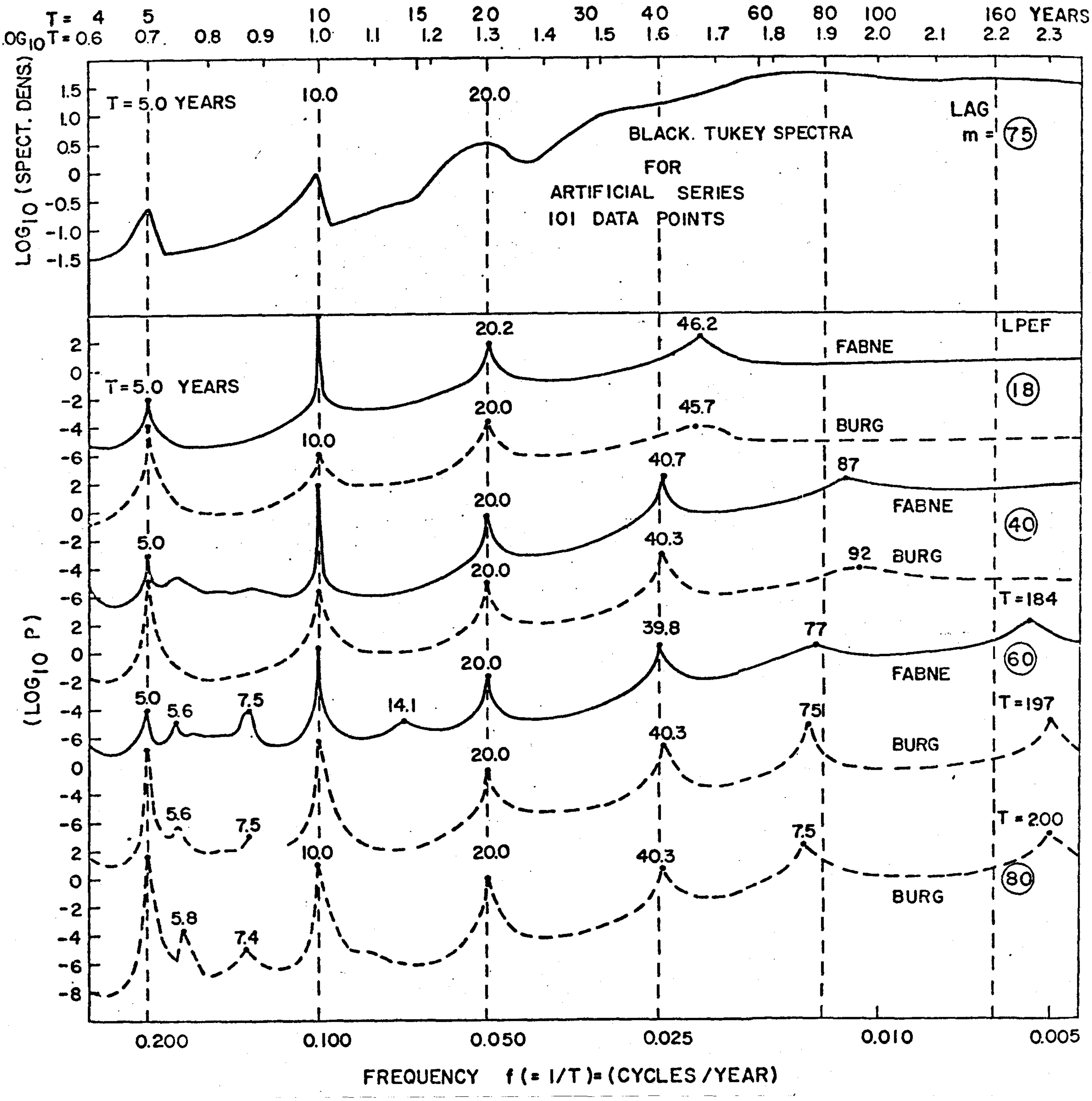

T= 4 5 10 15 20 30 40 60 80 100 160 YEARS
LOG10 T = 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3
LOG10 (SPECT. DENS)
T = 5.0 YEARS
10.0
20.0
LAG m = 75
BLACK. TUKEY SPECTRA FOR ARTIFICIAL SERIES 101 DATA POINTS
LPEF
20.2
46.2
FABNE
18
T=5.0 YEARS
20.0
45.7
BURG
10.0
40.7
87
FABNE
20.0
40
5.0
40.3
92 BURG
20.0
T=184
(LOG10 P)
39.8
77
60
FABNE
20.0
5.0 5.6 7.5
14.1
751
T=197
40.3
BURG
20.0
5.6
7.5
T = 200
7.5
10.0
20.0
40.3
80
BURG
5.8
7.4
0.200 0.100 0.050 0.025 0.010 0.005
FREQUENCY f (= 1/T) = (CYCLES / YEAR)

Fig. 3

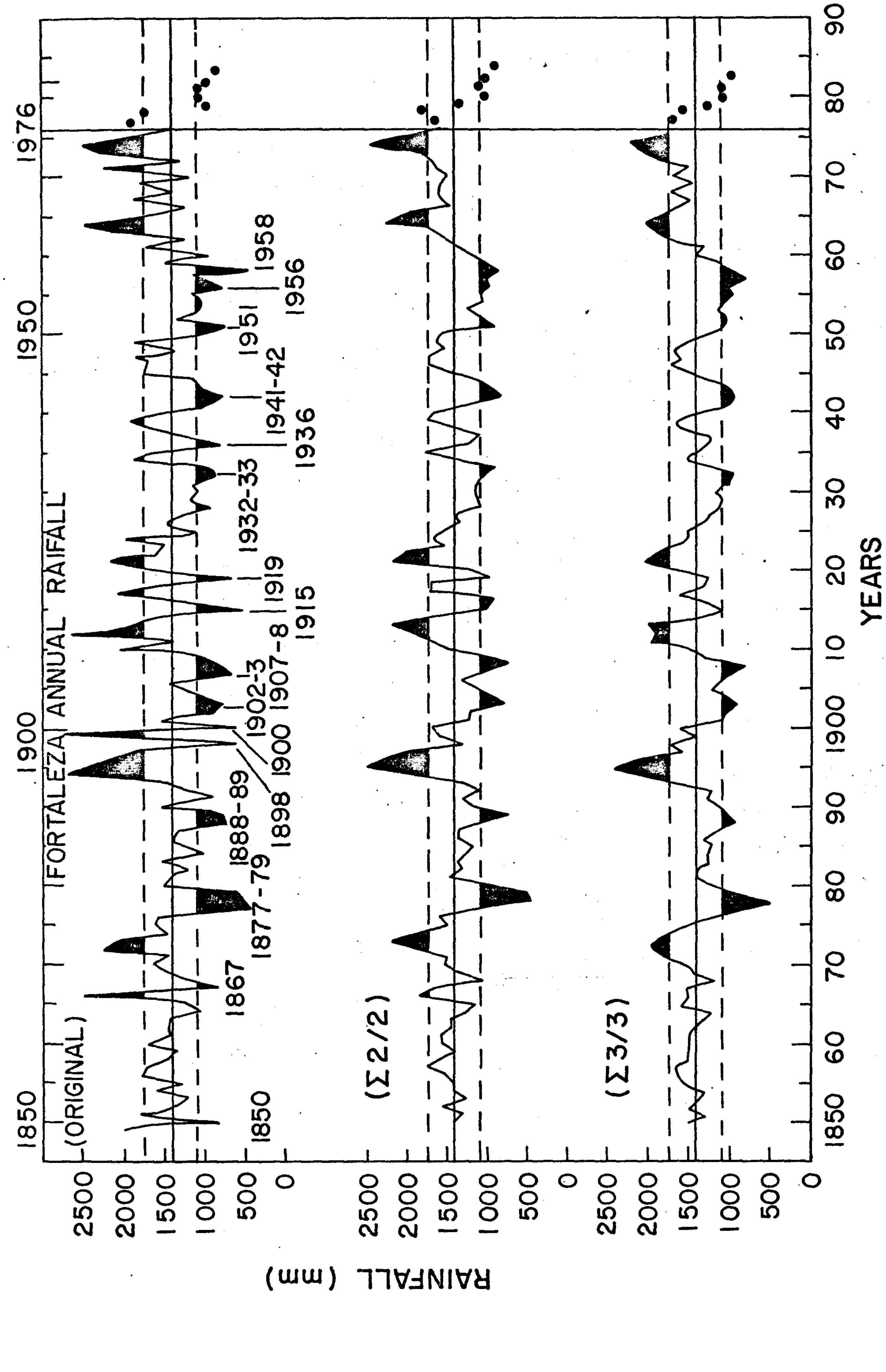

FORTALEZA ANNUAL RAIFALL
(ORIGINAL)
(Σ2/2)
(Σ3/3)
RAINFALL (mm)
YEARS
1850
1900
1950
1976
1850
1867
1877-79
1888-89
1898
1900
1902-3
1907-8
1915
1919
1932-33
1936
1941-42
1951
1956
1958
2500
2000
1500
1000
500
0

Fig. 4

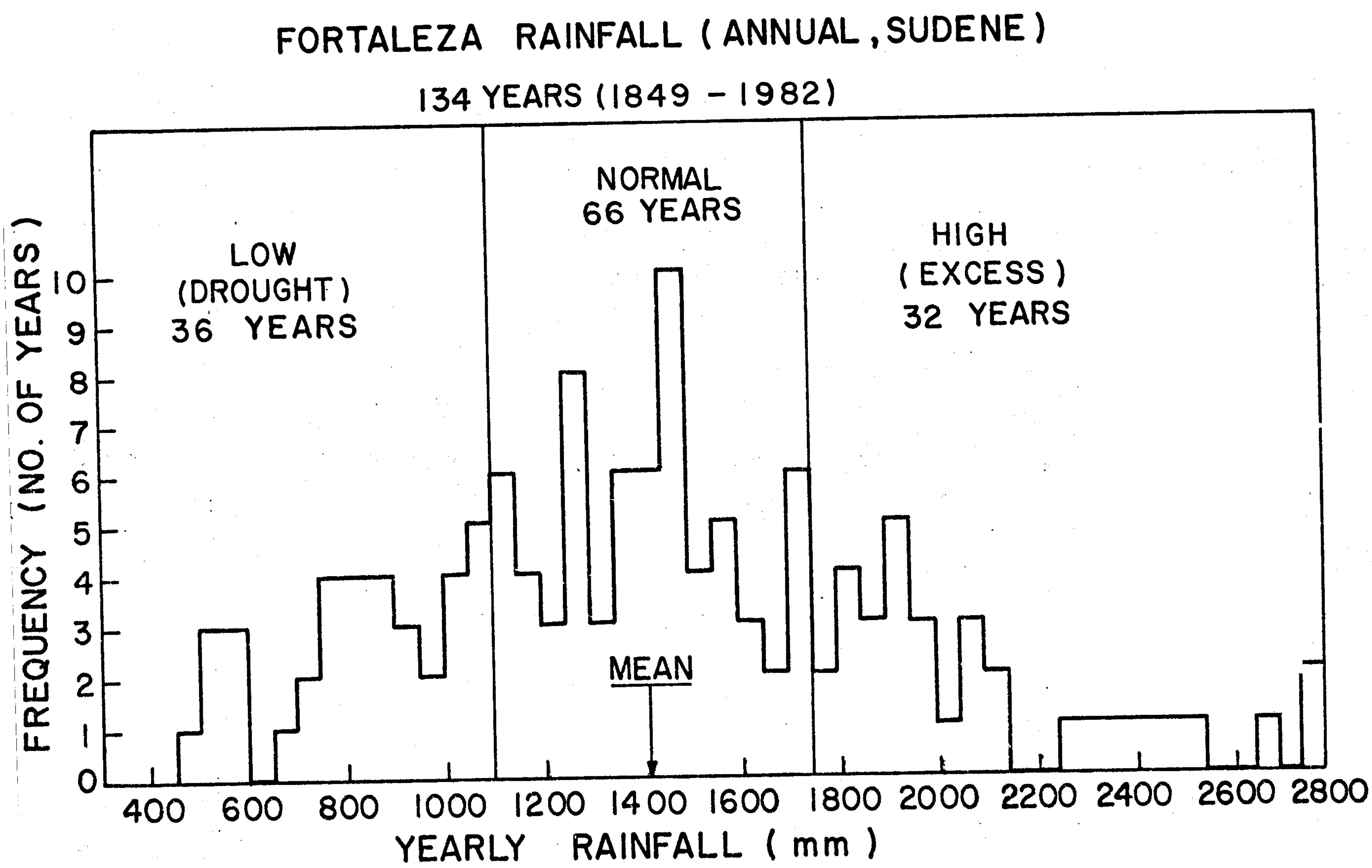

FORTALEZA RAINFALL (ANNUAL, SUDENE)
134 YEARS (1849 - 1982)
LOW
(DROUGHT)
36 YEARS
NORMAL
66 YEARS
HIGH
(EXCESS)
32 YEARS
MEAN
FREQUENCY (NO. OF YEARS)
0
1
2
3
4
5
6
7
8
9
10
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
YEARLY RAINFALL (mm)

Fig. 5

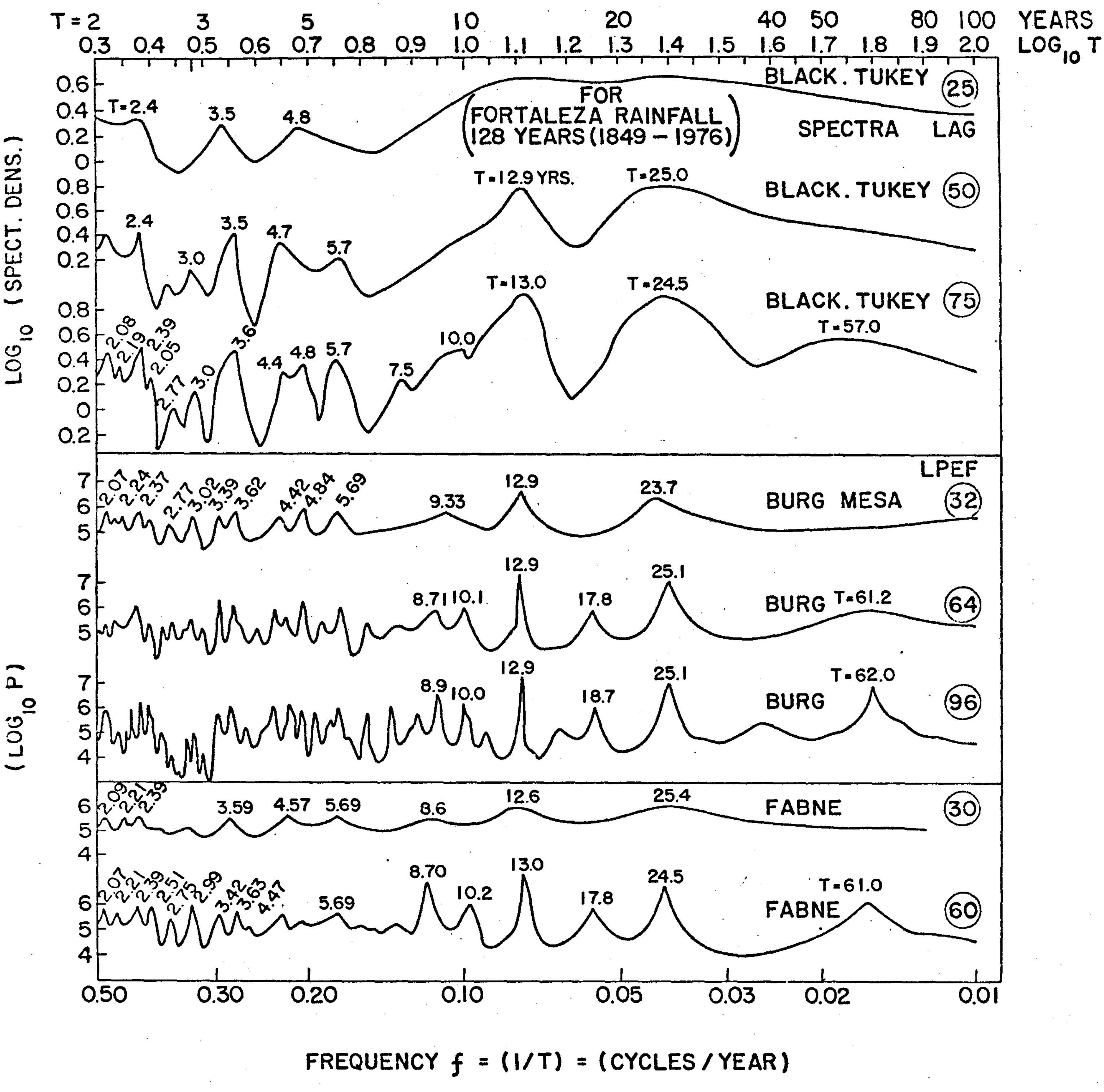

T = 2 3 5 10 20 40 50 80 100 YEARS
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 LOG10 T
LOG10 (SPECT. DENS.)
BLACK.TUKEY (25)
SPECTRA LAG
FOR
FORTALEZA RAINFALL
128 YEARS (1849 – 1976)
T=2.4
3.5
4.8
BLACK.TUKEY (50)
T=12.9 YRS.
T=25.0
BLACK.TUKEY (75)
T=13.0
T=24.5
T=57.0
LPEF
BURG MESA (32)
BURG (64)
T=61.2
BURG (96)
T=62.0
(LOG10 P)
FABNE (30)
FABNE (60)
T=61.0
0.50 0.30 0.20 0.10 0.05 0.03 0.02 0.01
FREQUENCY f = (1/T) = (CYCLES / YEAR)

Fig. 6

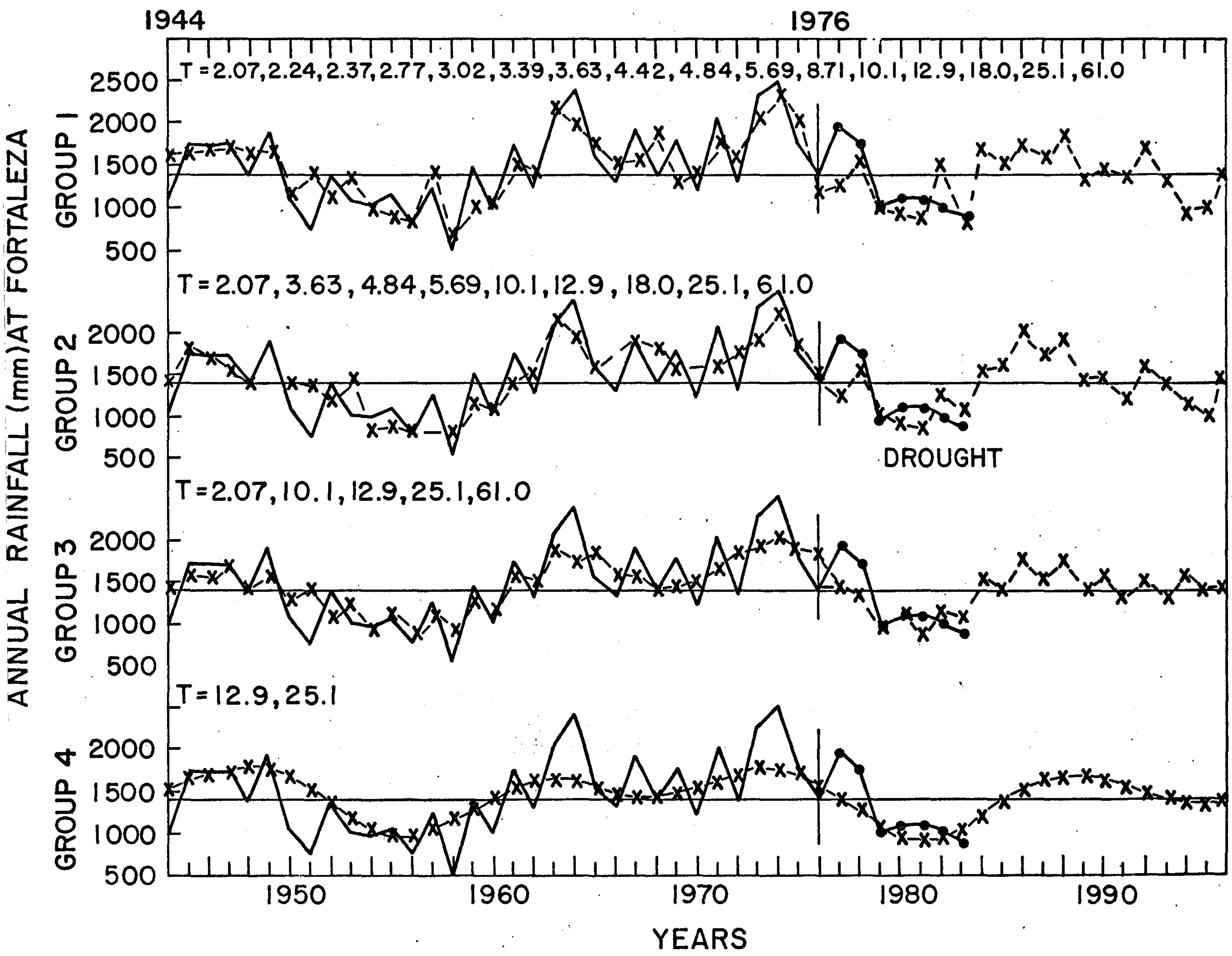
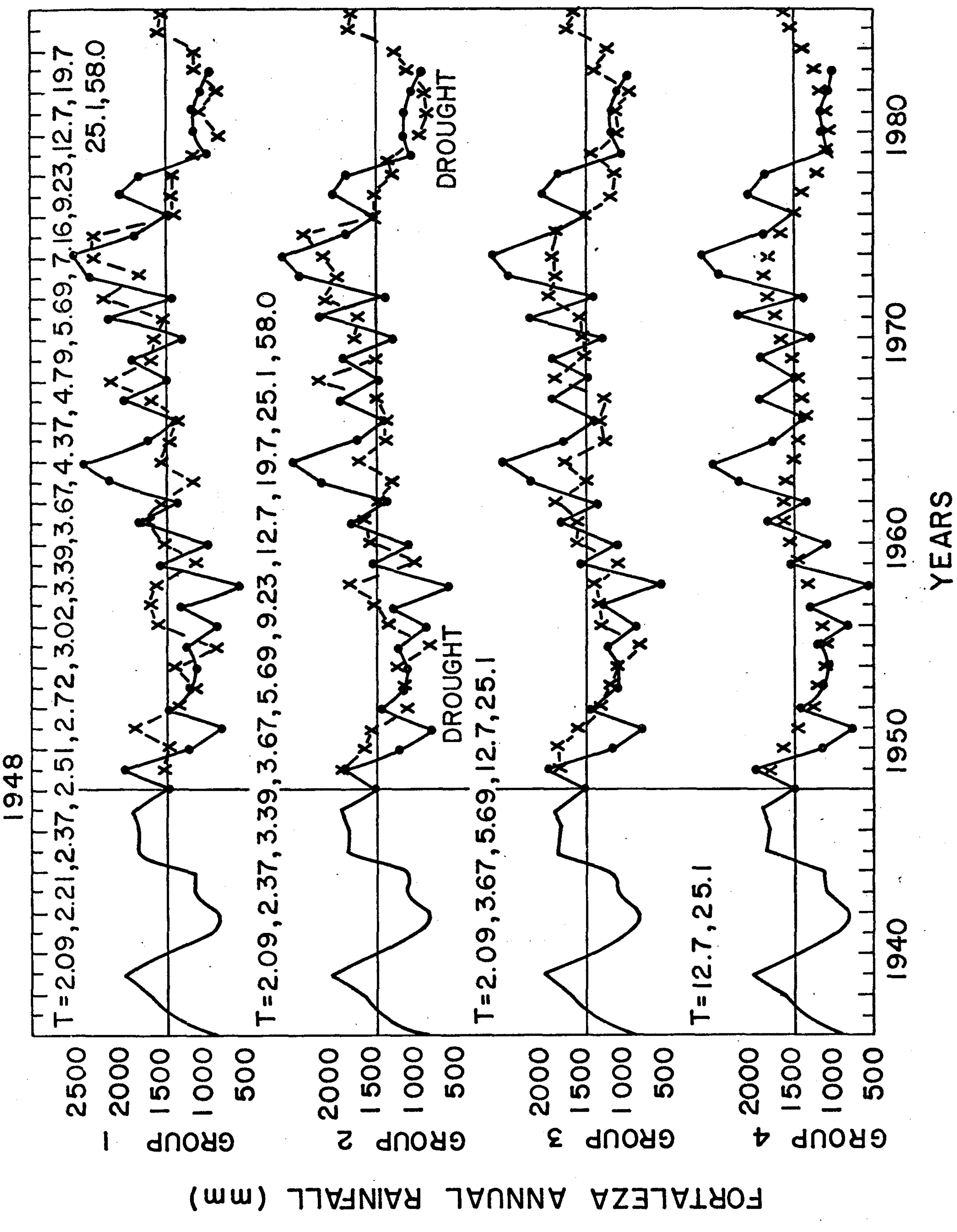

1944
1976
T=2.07,2.24,2.37,2.77,3.02,3.39,3.63,4.42,4.84,5.69,8.71,10.1,12.9,18.0,25.1,61.0
T=2.07,3.63,4.84,5.69,10.1,12.9,18.0,25.1,61.0
T=2.07,10.1,12.9,25.1,61.0
T=12.9,25.1
DROUGHT
ANNUAL RAINFALL (mm) AT FORTALEZA
GROUP 1
GROUP 2
GROUP 3
GROUP 4
2500
2000
1500
1000
500
1950
1960
1970
1980
1990
YEARS

Fig. 7



FORTALEZA ANNUAL RAINFALL (mm)
GROUP 1
GROUP 2
GROUP 3
GROUP 4
2500
2000
1500
1000
500
1948
T=2.09,2.21,2.37,2.51,2.72,3.02,3.39,3.67,4.37,4.79,5.69,7.16,9.23,12.7,19.7
25.1,58.0
T=2.09,2.37,3.39,3.67,5.69,9.23,12.7,19.7,25.1,58.0
DROUGHT
T=2.09,3.67,5.69,12.7,25.1
T=12.7,25.1
1940
1950
1960
1970
1980
YEARS

Fig. 8

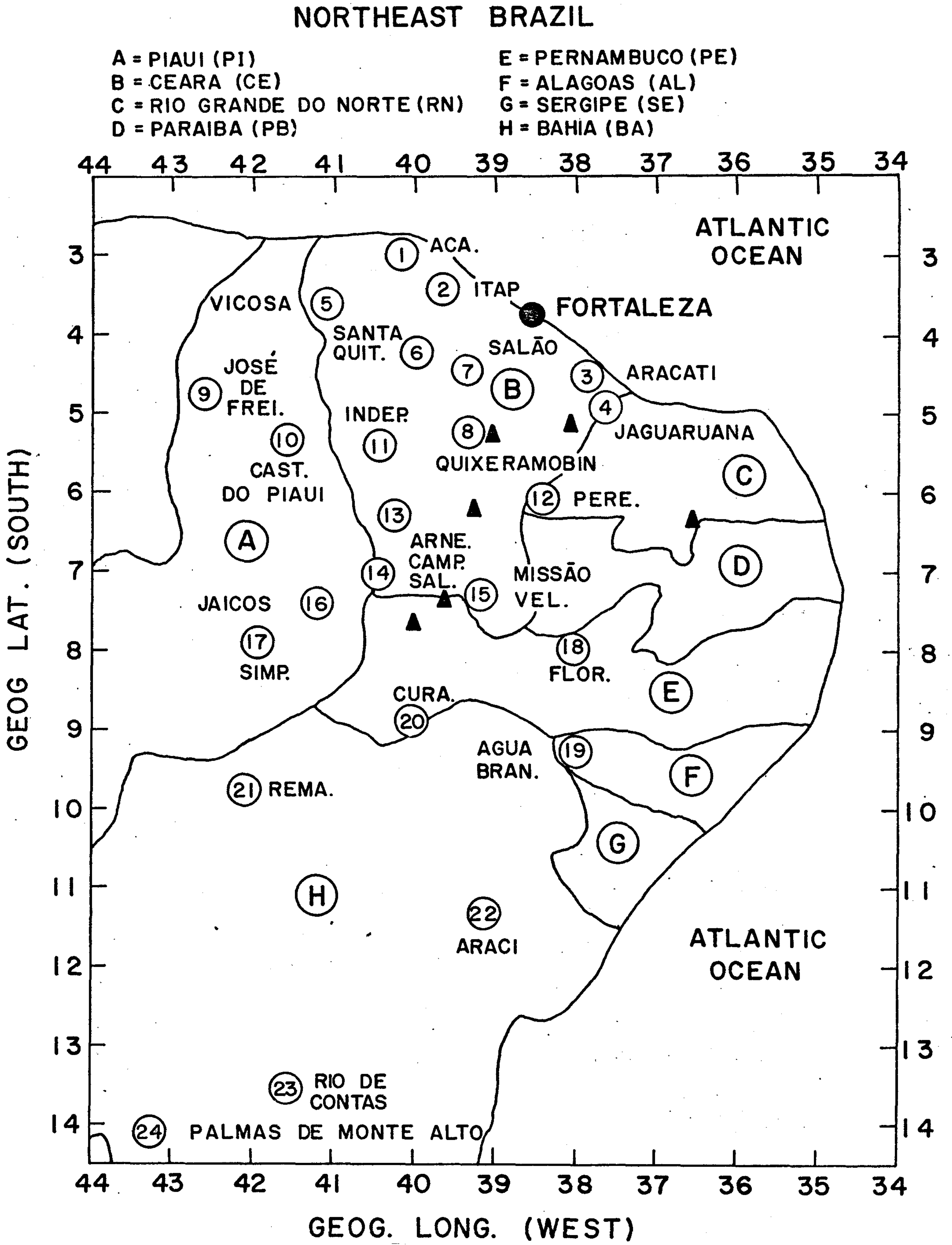

NORTHEAST BRAZIL
A = PIAUI (PI)
B = CEARA (CE)
C = RIO GRANDE DO NORTE (RN)
D = PARAIBA (PB)
E = PERNAMBUCO (PE)
F = ALAGOAS (AL)
G = SERGIPE (SE)
H = BAHIA (BA)
ATLANTIC OCEAN
FORTALEZA
1 ACA.
2 ITAP
3 ARACATI
4 JAGUARUANA
5 VICOSA
6 SANTA QUIT.
7
8
9 JOSÉ DE FREI.
10 CAST. DO PIAUI
11 INDER.
QUIXERAMOBIN
SALÃO
12 PERE.
13
14
ARNE. CAMP. SAL.
15 MISSÃO VEL.
16 JAICOS
17 SIMP.
18 FLOR.
19 AGUA BRAN.
20 CURA.
21 REMA.
22 ARACI
23 RIO DE CONTAS
24 PALMAS DE MONTE ALTO
ATLANTIC OCEAN
GEOG LAT. (SOUTH)
GEOG. LONG. (WEST)

Fig. 9

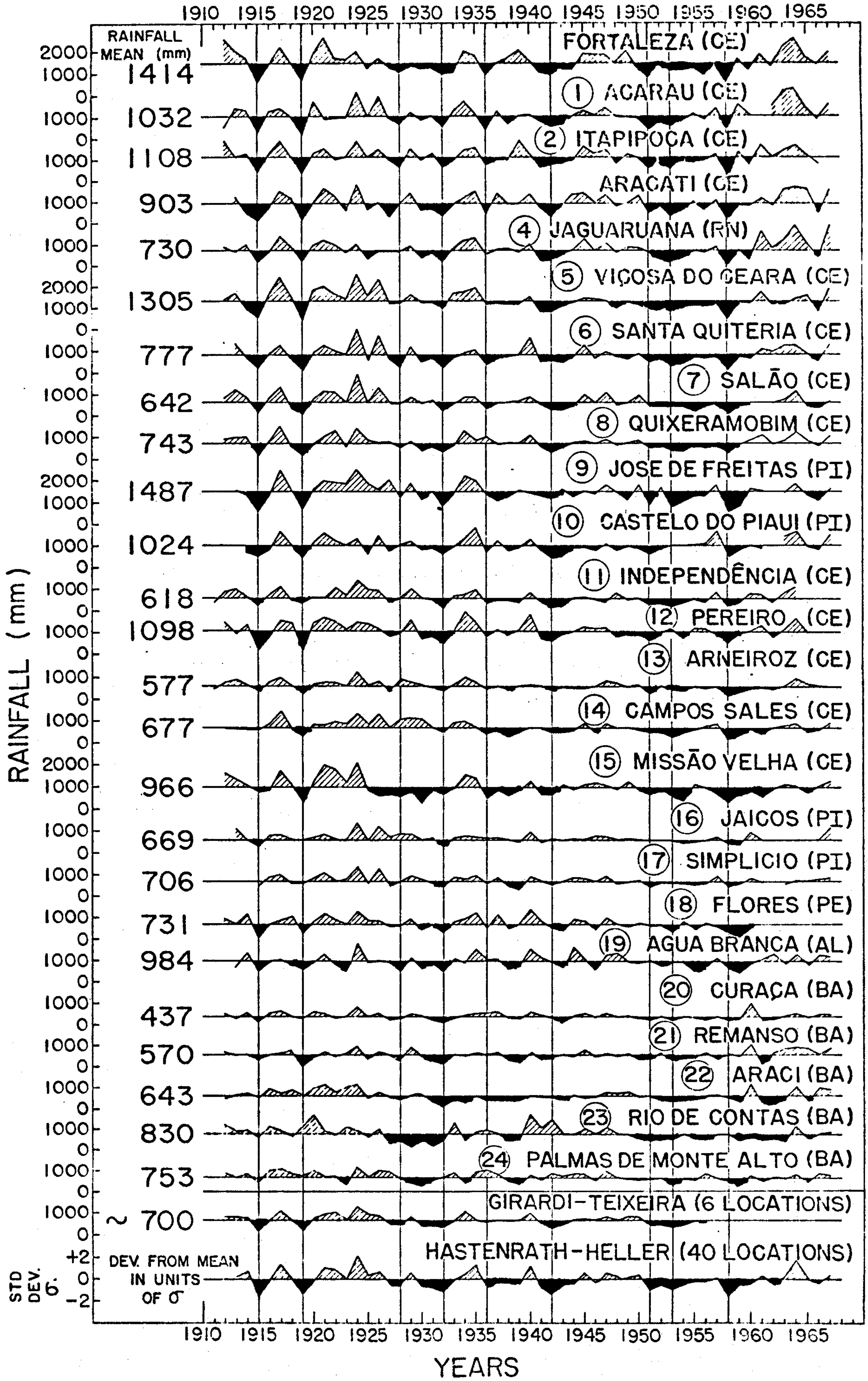

1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965
RAINFALL MEAN (mm)
FORTALEZA (CE)
1414
① ACARAU (CE)
1032
② ITAPIPOCA (CE)
1108
ARACATI (CE)
903
④ JAGUARUANA (RN)
730
⑤ VIÇOSA DO CEARA (CE)
1305
⑥ SANTA QUITERIA (CE)
777
⑦ SALÃO (CE)
642
⑧ QUIXERAMOBIM (CE)
743
⑨ JOSE DE FREITAS (PI)
1487
⑩ CASTELO DO PIAUI (PI)
1024
⑪ INDEPENDÊNCIA (CE)
618
⑫ PEREIRO (CE)
1098
⑬ ARNEIROZ (CE)
577
⑭ CAMPOS SALES (CE)
677
⑮ MISSÃO VELHA (CE)
966
⑯ JAICOS (PI)
669
⑰ SIMPLICIO (PI)
706
⑱ FLORES (PE)
731
⑲ AGUA BRANCA (AL)
984
⑳ CURAÇA (BA)
437
㉑ REMANSO (BA)
570
㉒ ARACI (BA)
643
㉓ RIO DE CONTAS (BA)
830
㉔ PALMAS DE MONTE ALTO (BA)
753
GIRARDI-TEIXEIRA (6 LOCATIONS)
~ 700
HASTENRATH-HELLER (40 LOCATIONS)
DEV. FROM MEAN IN UNITS OF σ
RAINFALL (mm)
STD DEV. 6
+2
0
-2
2000
1000
0
YEARS

Fig. 10

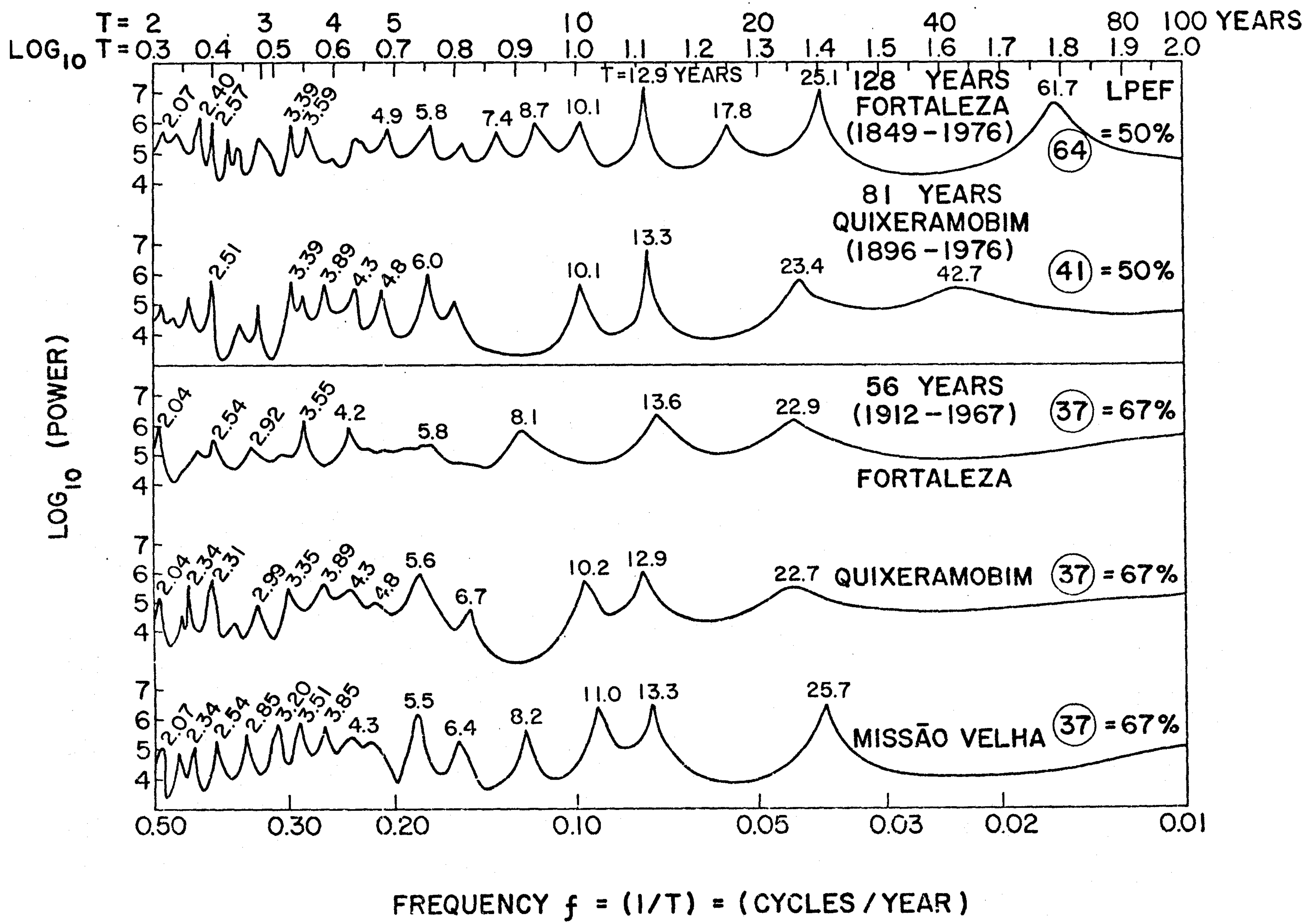

T = 2 3 4 5 10 20 40 80 100 YEARS
LOG10 T = 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
T=12.9 YEARS
128 YEARS
FORTALEZA
(1849-1976)
LPEF
64 = 50%
81 YEARS
QUIXERAMOBIM
(1896-1976)
41 = 50%
56 YEARS
(1912-1967)
37 = 67%
FORTALEZA
QUIXERAMOBIM
37 = 67%
MISSÃO VELHA
37 = 67%
LOG10 (POWER)
0.50 0.30 0.20 0.10 0.05 0.03 0.02 0.01
FREQUENCY f = (1/T) = (CYCLES / YEAR)

Fig. 11

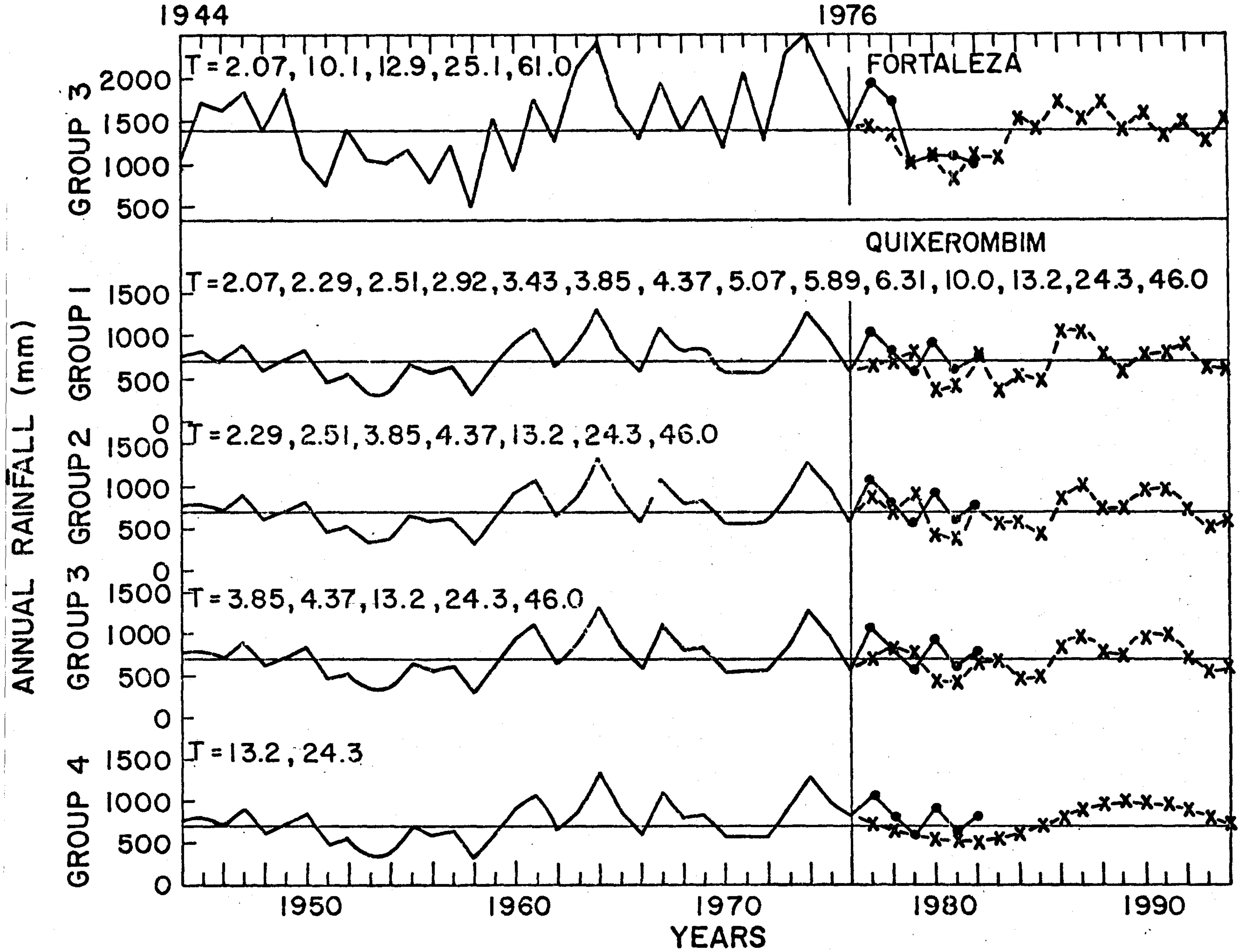

1944
1976
T = 2.07, 10.1, 12.9, 25.1, 61.0
FORTALEZA
QUIXEROMBIM
T = 2.07, 2.29, 2.51, 2.92, 3.43, 3.85, 4.37, 5.07, 5.89, 6.31, 10.0, 13.2, 24.3, 46.0
T = 2.29, 2.51, 3.85, 4.37, 13.2, 24.3, 46.0
T = 3.85, 4.37, 13.2, 24.3, 46.0
T = 13.2, 24.3
GROUP 3
GROUP 1
GROUP 2
GROUP 3
GROUP 4
ANNUAL RAINFALL (mm)
2000
1500
1000
500
0
1950
1960
1970
1980
1990
YEARS

Fig. 12

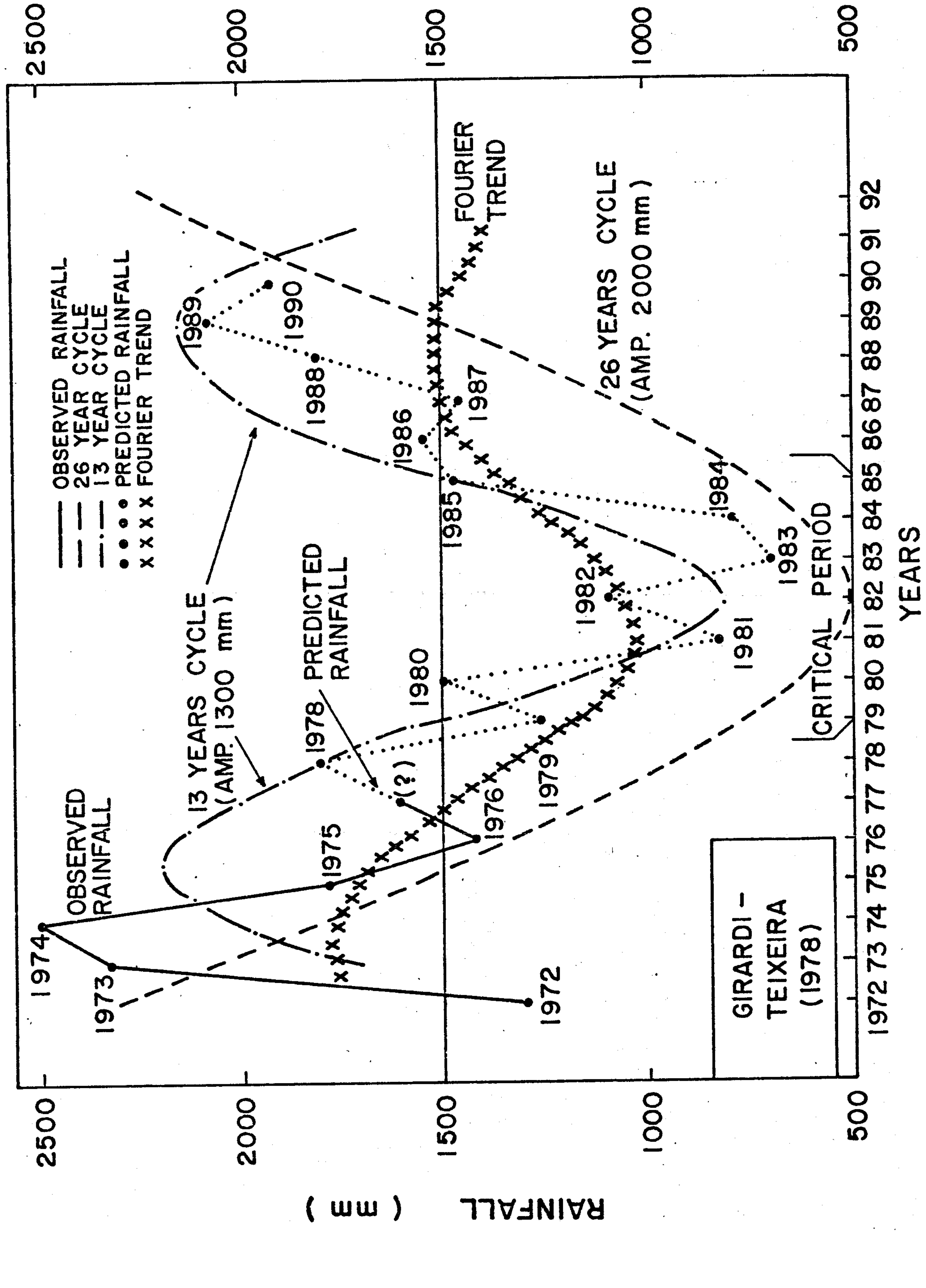

RAINFALL (mm)
YEARS
OBSERVED RAINFALL
26 YEAR CYCLE
13 YEAR CYCLE
PREDICTED RAINFALL
FOURIER TREND
13 YEARS CYCLE (AMP. 1300 mm)
26 YEARS CYCLE (AMP. 2000 mm)
PREDICTED RAINFALL
FOURIER TREND
CRITICAL PERIOD
GIRARDI - TEIXEIRA (1978)
1972 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92
2500
2000
1500
1000
500

Fig. 13

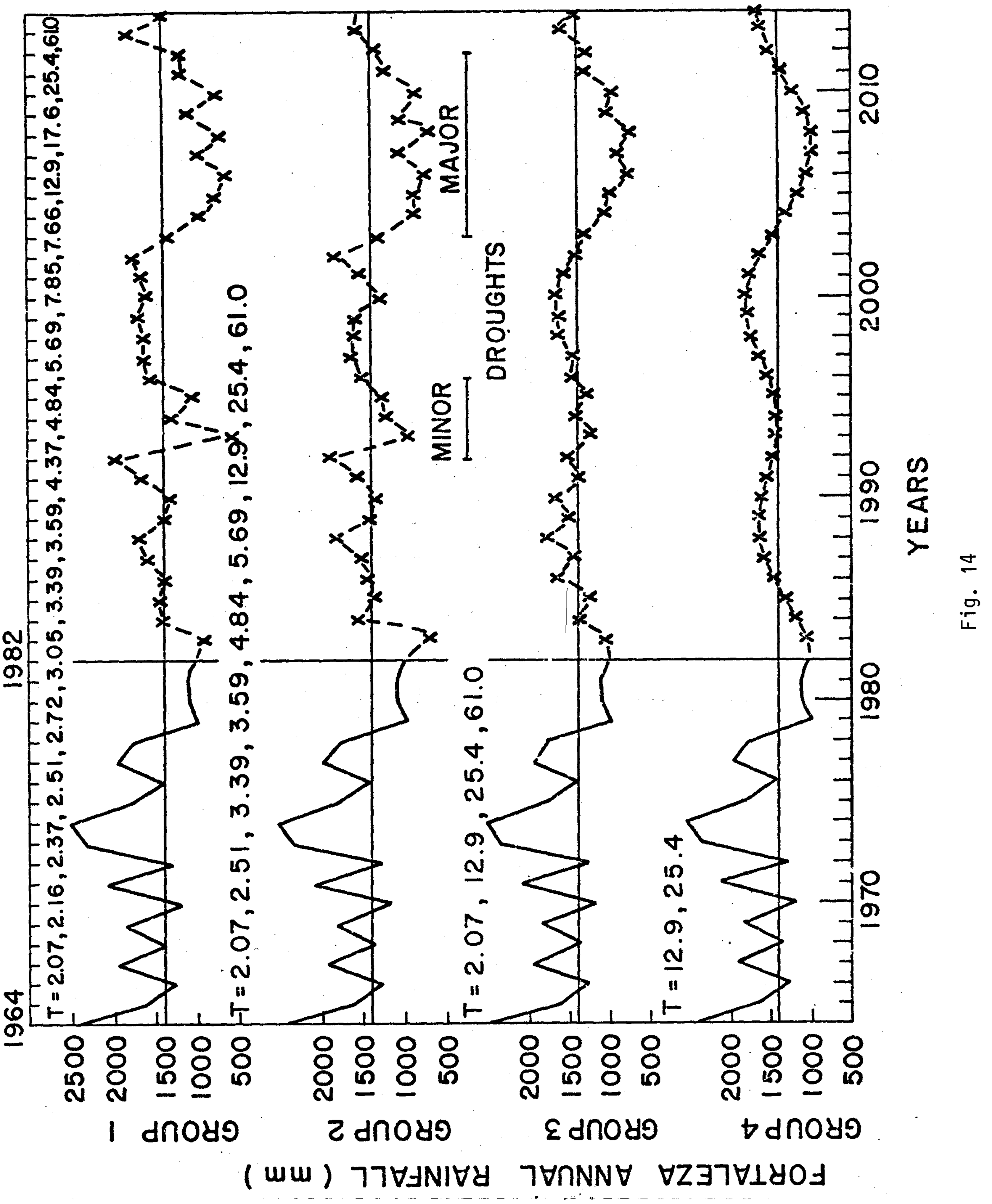

FORTALEZA ANNUAL RAINFALL (mm)
GROUP 1
GROUP 2
GROUP 3
GROUP 4
T = 2.07, 2.16, 2.37, 2.51, 2.72, 3.05, 3.39, 3.59, 4.37, 4.84, 5.69, 7.85, 7.66, 12.9, 17.6, 25.4, 61.0
T = 2.07, 2.51, 3.39, 3.59, 4.84, 5.69, 12.9, 25.4, 61.0
T = 2.07, 12.9, 25.4, 61.0
T = 12.9, 25.4
MINOR
MAJOR
DROUGHTS
1964
1982
1970
1980
1990
2000
2010
YEARS

Fig. 14

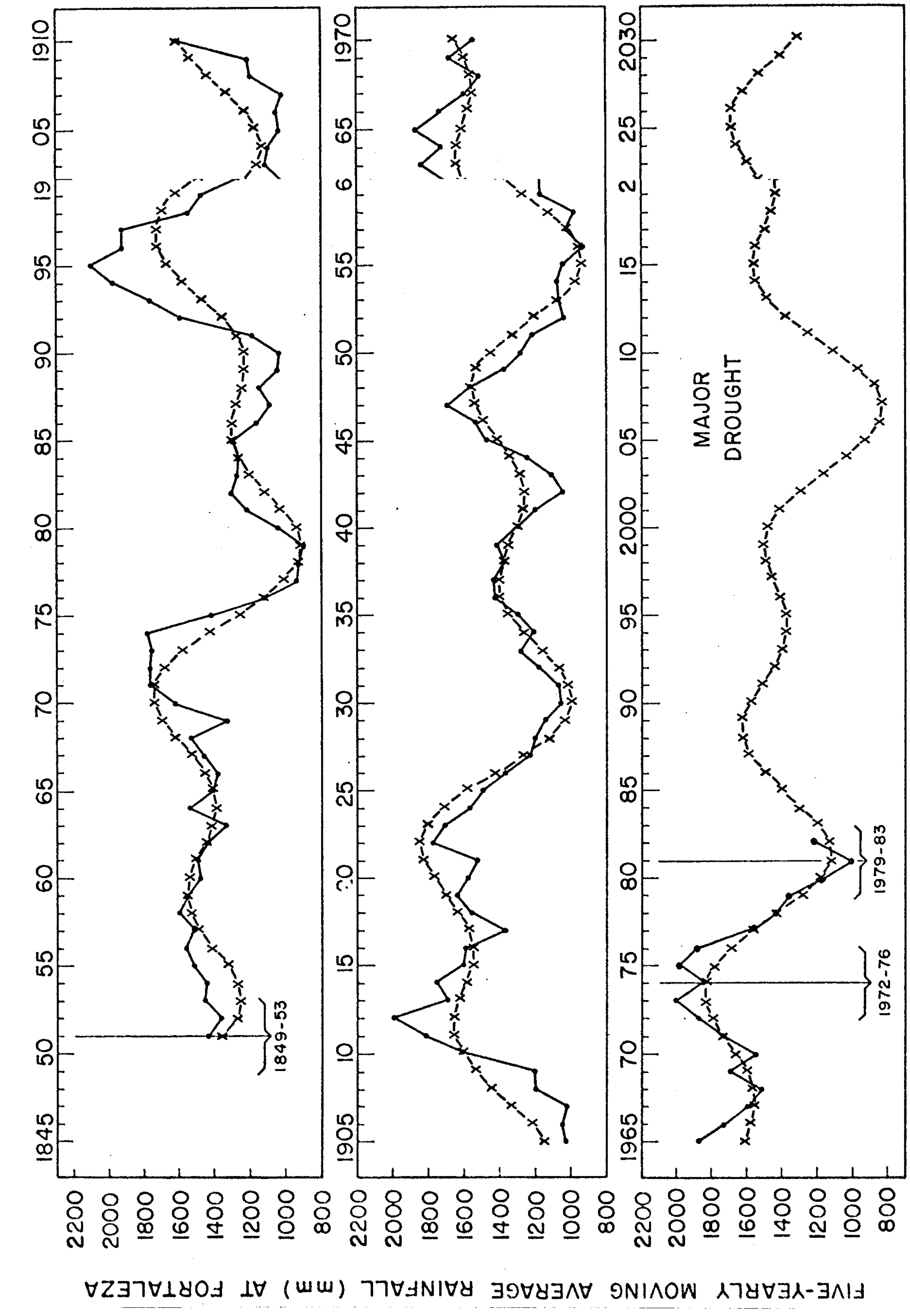

FIVE-YEARLY MOVING AVERAGE RAINFALL (mm) AT FORTALEZA
2200
2000
1800
1600
1400
1200
1000
800
1845
50
55
60
65
70
75
80
85
90
95
19
05
1910
1905
10
15
20
25
30
35
40
45
50
55
6
65
1970
1965
70
75
80
85
90
95
2000
05
10
15
2
25
2030
1849-53
1972-76
1979-83
MAJOR
DROUGHT

Fig. 15