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A METHOD FOR PREDICTING MONTHLY RAINFALL PATTERNS *

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ABSTRACT

A brief survey is made of previous methods that have been used to predict rainfall trends or drought spells in different parts of the earth. The basic methodologies or theoretical strategies used in these methods are compared with contents of a recent theory of Sun-Weather/Climate links [Njau, 1985a; 1985b; 1986; 1987a; 1987b; 1987c] which point towards the possibility of practical climatic predictions. It is shown that not only is the theoretical basis of each of these methodologies or strategies fully incorporated into the above-named theory, but also this theory may be used to develop a technique by which future monthly rainfall patterns can be predicted in further and finer details. We describe the latter technique and then illustrate its workability by means of predictions made on monthly rainfall patterns in some East African meteorological stations.

1. INTRODUCTION

There is no doubt that any technique which can produce reasonable predictions upon rainfall one or more years in advance will greatly benefit not only Agricultural Sectors (especially in as much as food storage and planting policies are concerned), but will also benefit power and fuel industries, water supply authorities, Insurance industries and International Trading Strategists. There have been two most common methods for predicting rainfall. The first method is essentially "physical" in the sense that it involves reasonable mastery of the physical processes which control rainfall variations and the subsequent use of knowledge regarding the latter processes to chart out future rainfall variations. The second method is statistical in that it involves a statistical analysis of past rainfall records and the significant characteristics of these records are used to predict future rainfall on the assumption that future and past rainfall records have similar statistical characteristics.

At least up to the mid-1980's, the "physical" method had not been developed to a level whereby reasonable predictions could be made basically because the physical processes involved were not yet well understood [Pittock, 1978; 1983; Oguntoyinbo, 1986; Hastenrath, 1987a; Cevolani et al., 1987]. However, the situation may change in view of the recent theory on Sun-Climate/Weather relationship [Njau, 1985a; 1985b; 1986; 1987a; 1987b; 1987c] which has been successful in explaining all the observed climatic variations at periods from 2 years to 110 years [see Njau, 1987b]. The statistical method, on the other hand, has been used for several years as far as rainfall or drought prediction is concerned [e.g. Mitchell, 1964; Wilhite, 1978; Kane and Trivedi, 1986]. The procedure often adopted in this case is that significant periodicities would be established in past records and thereafter used for future predictions on the basis of simple extrapolation or extension techniques. This procedure, however, has been criticized for not attaching physical mechanisms to the periodicities used [Friedman, 1950; Mitchell, 1964; Pittock, 1978; 1983] and also on the view that the statistics of the past may not be adequate for prediction of future events [Schneider, 1978].

The question of whether rainfall can be predicted has drawn a diversity of opinions from atmospheric scientists and other scientists whose main fields

are related to meteorology. Carroll (1986) has remarked that rainfall is one of the most difficult climatic parameters to predict and Oguntoyinbo (1986) has concluded that there is as yet no fool-proof technique for predicting rainfall accurately. Pessimism was added to the picture by Tapp (1984) who noted that since the available climatic database is too limited in time (i.e. it hardly exceeds about 100 years), it is impossible to make accurate climatic predictions purely based upon the statistical method before we extend the database by at least 1,000 years. However, according to Lamb (1977), the possible scientific methods for making long-term climatic predictions may be summed up as follows:

(a) Predictions may be made by extrapolating or extending cycles or quasi-cycles detected in past climatic records.

(b) Predictions may be made by initially assuming that climatic changes are essentially random and then using probability theory to work out the probability of a given climatic change recurring within a given length of time.

(c) Predictions may be made through elaborate physical and dynamical models.

(d) Predictions may be made on the basis of statistical characteristics of past climatic records with substantial backing from sufficient knowledge of the physical processes responsible for climatic variations as a whole.

In as far as reliable climatic prediction is concerned, each of methods (a) to (d) mentioned above has had both criticism against it as well as some practical limitations [e.g. Lamb, 1977; Schneider, 1978]. Method (a) has been criticized mainly for failure to attach physical significance to the periodicities used while method (b) is mainly criticized on the grounds that climatic changes may not be purely random events after all. Besides, both methods (a) and (b) are also criticized on the basis that raw statistics of past climatic changes may not necessarily apply to future changes. Predictions based upon method (c) are limited to few days at most because the atmospheric circulation cannot be predicted accurately by models beyond two weeks (Houghton and Houghton, 1987]. Finally as regards method (d), the main criticism has been the apparent lack of adequate knowledge regarding the physical processes that control climate variations.

Recent findings, though, have increased the hope of ultimately attaining at least a reasonable rainfall prediction method. According to Kane and Trivedi (1986), approximate but meaningful rainfall predictions may be made using a statistical approach provided that the region involved has rainfall series with prominent periodicities (of large amplitude) in the long periodicity region (about 10 years or more) and that the patterns of the series do not change abruptly and drastically. We shall comment on these conditions later on in the paper. In another development, Bah (1987) has shown that summer rainfall in the Sahel may be predicted either by using sea surface temperature data in the immediate warm water areas and the Equatorial upwelling zone 1-2 months earlier or by using previous quarterly rainfall data in the Sahel. Clearly this approach, though suitable for short-term predictions, cannot be used to predict rainfall one or more years in advance unless parallel predictions are made upon sea surface temperature values. Another rainfall prediction method has been reported by Nicholls (1981) and Hastenrath (1986, 1987a, 1987b). These authors have shown that a substantial part of interannual rainfall variability in certain tropical regions may be predicted from antecedent departures in the large-scale circulation. Again while the method appears satisfactory for short-term predictions, its use for long-term prediction critically hinges upon corresponding prediction of departures in the large-scale circulation.

The background information given above clearly exposes significant gaps that still exist in the methodology for long-term rainfall prediction. This paper incorporates our attempts to fill some of these gaps. It contains a presentation of our method, partly based upon the new theory on Sun-Weather/Climate links mentioned earlier and partly based upon some statistical analysis of past rainfall records, which apparently may be used to make reasonable rainfall predictions one or more years in advance. The validity and workability of this method is ascertained by prior predictions on rainfall in East Africa which were made in 1985 for the period 1981-1990. According to some earlier papers [e.g. Njau, 1987a; 1987c] and as will be elaborated in the text, the predictions made for the years 1986 and 1987 have already agreed with real observations to at least 70% for all the 27 stations considered.

2. DESCRIPTION OF THE PREDICTION METHOD

2.1 Theoretical and physical basis

The rainfall prediction method described in the paper is based mainly upon recent work on Sun-Climate/Weather links by the author [e.g. Njau, 1985a; 1985b; 1986; 1987a; 1987b; 1987c]. The latter references collectively explain how the Sun (indirectly) controls climatic variations and one of them in particular [i.e. Njau, 1987b] presents a generalized theory that satisfactorily explains at least all the observed climatic variations with periods between 2 years and 110 years. A number of these periodicities have been detected in past rainfall records from all the continents (see Table 1) and some of them have already been used successfully to predict occurrences of dry spells in Africa and the USSR (see Table 2). In several other cases, significant periodicities (within the 2-110 years range mentioned above) were detected but then found unfit for rainfall prediction purposes on different accounts. For example, Rothe and Virji (1976) analyzed rainfall data from East Africa and established significant periodicities at 2.1-2.2 years, 3.3-3.6 year and 5.0-5.7 years. However, these periodicities were considered unsuitable for prediction purposes due to their relatively small variances.

The prediction method described in this paper initially involves a search for significant periodicities (and/or quasi-periodicities) in past rainfall records as in the method by Kane and Trivedi (1986). However, we go further than the former in that we take advantage of the new theory of Sun-Climate/Weather links mentioned earlier to achieve relatively more detailed and finer rainfall predictions. In fact it is shown in Section 3 that the conditions attached to the method by Kane and Trivedi (1986) are incorporated "inter alia" into our method but fully dressed up in descriptions of their causative physical mechanisms.

2.2 Prediction methodology

All previous and successful predictions of drought spells (or significant rainfall drops) were, to the best of my knowledge, based upon dominant periodicities detected in past rainfall data. For each of these prediction cases, significant periodicities were first detected in past rainfall records and thereafter either the most dominant periodicity was used for a prediction [e.g. Tyson and Dyer, 1978] or more than one of the dominant periodicities were used for a prediction [e.g. Kane and Trivedi, 1986]. It appears that in the process of making any of the previous drought/rainfall predictions, no attempt was made to establish and use any physical linkage that might exist among the significant periodicities detected in the respective past rainfall data. Prior search for physical links among periodicities detected in past data before using some or all of the periodicities to mould up a prediction is of paramount importance mainly because variations impressed upon, say, monthly rainfall by a certain signal always give rise to periodicities in the corresponding frequency spectrum which are more numerous than those which characterize the signal itself and the rainfall pattern without the latter's influence. Implicitly the frequency spectrum of the influenced rainfall pattern will display more periodicities than are actually required for making an accurate prediction on the rainfall pattern. Proper identification of these particular periodicities that are by themselves enough to mould an accurate prediction requires full knowledge of the physical relationship(s) binding the periodicities in the frequency spectrum of the influenced rainfall pattern together. In fact, any attempt to make a prediction that does not involve the latter physical relationship(s) tacitly assumes physical independence of each periodicity from the others and will most likely make use of only the most dominant periodicities in which case some substantial loss of prediction accuracy may be risked. For example a simple sinusoid at a single period T may impress variations on monthly rainfall (say at a given frequency), but the frequency spectrum of the disturbed monthly rainfall pattern will have seven different finite periodicities including T (see the next paragraph for further details). Now, if one realizes that all the seven periodicities are physically related together, then one will easily conclude that the monthly rainfall variations were caused by a simple sinusoid signal whose periodicity and amplitude may be deduced from the corresponding frequency spectrum and used for prediction purposes. On the other hand, if one is unaware of the physical relationship binding the seven periodicities, one may assume that they are all physically independent from each other and hence use one or few of the dominant ones for prediction purposes. Obviously, since the latter prediction is based upon an incomplete

or incorrect physical process, it is likely to yield less realistic results than the former one which is based upon a complete and correct physical process. This point is clarified and illustrated further by the following examples.

Linear plots of monthly rainfall data for many a region that has a single dry season in a year apparently consist of a time-dependent series of distorted positive portions of sinusoids or quasi-sinusoids (e.g. see Figs.7(b) and 10(a) of Section 3). Let us assume that in a specific case, these portions are undistorted so that a monthly rainfall record at frequency w_c which is amplitude-modulated by a sinusoidal signal at frequency w_m may be represented by Fig.1(a). In order to extend this pattern into the future (i.e. make a prediction) accurately, all we need to know are the frequencies w_m and w_c together with the corresponding amplitudes. In this case, we would expect to pick the two frequencies and the two amplitudes from the locations and heights of only two peaks in the frequency spectrum of the record in Fig.1(a). However, an accurate form of the latter spectrum has a total of 8 peaks with the most dominant one located at zero frequency (Fig.1(b)). Obviously the corresponding 8 periodicities are physically related together, and we only need to uncover this relationship in order to realize that only two of the 8 peaks in Fig.1(b) (i.e. one at $w = w_c$ and one at $w = w_m$) are to be used for an accurate prediction. Of the remaining 6 peaks, two are simply extra signatures of the modulation process while the other four primarily result from the non-negative nature of rainfall records. Now of the two peaks, which are the ones required for an accurate prediction, one is the second most dominant and the other is the fourth most dominant. This indicates that peak dominance is not the only criterion for choosing periodicities from frequency spectra to be used for prediction purposes. Suppose that we are to make a prediction upon the record in Fig.1(a) on the basis of the spectrum in Fig.1(b) but without knowledge of the physical link among the 8 periodicities in this spectrum. If we base our prediction on the three or less most dominant periodicities in Fig.1(b), then our prediction will correctly reveal variations at frequency w_c but would have incorrect amplitudes because the variations at frequency w_m have been left out. Thus some significant accuracy would be lost just because we did not seek and use the physical relationship among the 8 periodicities in Fig.1(b). It should be mentioned that although this example has been modelled upon rainfall patterns for regions with only one dry season per year, it could easily be modified and adapted to suit rainfall patterns in any region of the world. Yet the ultimate results would be fairly comparable to the ones already presented.

The example just discussed involves a single amplitude-modulation process on regular rainfall variations at frequency w_c. If the latter variations are subjected to a double amplitude-modulation process, then the resultant record would have a frequency spectrum with a total of 44 peaks at different frequencies including a most dominant one at zero frequency. Yet the physical relationship(s) among the 44 periodicities imply that only three (out of the 44) periodicities are needed in order for an accurate prediction upon the record involved to be made. Of course, an accurate prediction would certainly be difficult to make in the absence of the physical relationship(s) even if the most dominant periodicities are selected and used for this purpose. What happens if a triple amplitude-modulation process was involved? In such a situation, the resulting record would have a frequency spectrum with a total of 260 different periodicities all having certain physical relationships among them. Full awareness of these relationships would simply lead into the realization that only four of the 260 periodicities are needed in order to make an accurate prediction. On the other hand, unawareness of these relationships may tempt one to base predictions on only the most dominant periodicities and may, in doing so, risk some significant inaccuracy in the predictions. Triple (or even higher order) amplitude-modulation processes should not at all be considered uncommon in actual rainfall variations. For example, the annual rainfall cycle may be simultaneously amplitude-modulated by the quasi-biennial oscillation, the sunspot cycle as well as the double sunspot cycle. This is a typical example of a possible triple amplitude-modulation process upon rainfall. Of course, relatively higher order processes are quite possible especially over large spans of time. In fact, the analysis described later in this Section has shown that each of the rainfall patterns illustrated in Figs.4(a), 4(b), 6(a), 7(a) and 8(a) are predominantly characterized by at least a triple amplitude-modulation process.

There is no doubt, at this point, that the examples given above have served to emphasize the usefulness of attempting to establish any physical relationships among significant periodicities detected in rainfall records before using them to mould up predictions. As already explained, the physical relationships do not only simplify the prediction processes, but they also increase the accuracy of the predictions.

The new prediction method which we propose in this paper is summarized in Fig.2. This method mainly differs from previous ones proposed and used by other colleagues [e.g. Tyson and Dyer, 1978; Kane and Trivedi, 1986] only in that we essentially search for any physical relationships among the significant periodicities detected in past rainfall records and use these relationships in the prediction process. This move tunes up the resultant predictions and also increases their accuracy as already explained. Now, how do we practically identify these physical relationships? First of all it would be worth noting that most (if not all) of the variation processes which interact with monthly rainfall patterns do so in two main ways. Firstly they may directly amplitude-modulate the rainfall patterns, and secondly they may add conventionally onto the rainfall patterns. However, since rainfall patterns are always positive (i.e. there is normally nothing like negative rainfall), both of these processes manifest themselves in rainfall records in a similar manner. We may clarify this point through the following example. Consider two sinusoidal signals labelled "signal C" and "signal M" with frequencies w_c and w_m, respectively, such that $w_m < w_c$. We assume that the amplitude of signal C is greater than the amplitude of signal M. If signal M amplitude-modulates signal C, the resultant waveform is as illustrated in Fig.3(a), and the frequency spectrum of the latter is illustrated in Fig.3(b). On the other hand, if signal M simply adds up to signal C, the resultant waveform is shown in Fig.3(c) and the frequency spectrum of the latter is illustrated in Fig.3(d). Note that although the spectra in Figs.3(b) and 3(d) are clearly different from each other, elimination of the nagative portions of Figs.3(a) and 3(c) will in either case result in a similar pattern which is identical to that formed through amplitude-modulation and illustrated in Fig.1(a). This shows that if a given physical process amplitude-modulates rainfall patterns, the resultant variations will be similar to those which would be formed if the same process was simply added to the rainfall patterns. Therefore, in searching for amplitude-modulation processes (which physically relate some periodicities) in rainfall records, we also simultaneously identify phenomena by which physical processes were simply added onto monthly rainfall patterns (e.g. see step 2 of Fig.2). These phenomena also create some physical links among periodicities detected in the respective rainfall patterns. We have developed a computer program that seeks and identifies physical relationships among periodicities detected in past rainfall records [Njau, 1987c].

According to Fig.2, there are four main conditions which make prediction impossible or difficult to make. The first condition (i.e. condition 2.1 in Fig.2) is lack of significant periodicities in past rainfall data. The second condition is a situation whereby the significant periodicities detected in the past rainfall data do not constitute any systematic amplitude-modulation. This implies that the past rainfall process was neither amplitude-modulated systematically nor did it interact systemtically with other processes via additive mechanisms. The third condition is that each of the systematic amplitude-modulations detected has a modulation index greater than 1. The rationale behind this condition is that if the modulation index for a given pattern is greater than 1, the pattern will at certain intervals undergo 180° phase shifts and hence abrupt and rapid changes in overall rainfall as has apparently been the case with Sahelian rainfall patterns. Obviously, such abrupt and rapid changes do make accurate prediction rather difficult. This particular condition seems to coincide with one of the conditions outlined by Kane and Trivedi (1986) that "meaningful predictions of drought-prone intervals are possible only for regions where .... the (rainfall) patterns do not change abruptly and drastically". The fourth condition is that although systematic amplitude-modulations (with modulation indices $\leqslant 1$) and periodicities are detected, none of these conforms to Eqs.7(a), 8(b) or 8(c) in Njau (1987b). Since the latter equations were derived from natural atmospheric processes as we know them, then non-conformity to these equations by the significant periodicities and amplitude-modulations detected in past rainfall records implies that these records were significantly influenced by "abnormal" physical processes (e.g. man-made ones like those that would be associated with a global nuclear war) other than the ones known to exist normally in the atmosphere. In this case, the lifetimes of these abnormal physical processes and the extent to which they overshadow the normal atmospheric processes will have to be known before an accurate (long-term) prediction is attempted.

We would like to stress that the method summarized in Fig.2 puts enormous weight upon detection of systematic amplitude modulation(s) in the respective past rainfall records. An amplitude modulation process is rendered unsystematic if its modulation index is greater than 1. This point has already been discussed. Besides, an amplitude modulation process is rendered unsystematic if its carrier frequency is not high enough compared to its modulating frequency. In this case, the resultant wave-form pattern incorporates what is known as "foldover distortion" wherein some of the frequencies in the pattern add onto some neighbouring frequencies and hence cause distortion. The ultimate effect is that some of the lower frequency components in the pattern are amplified to levels higher than the normal or expected ones. Therefore, unless this artificial amplification is appropriately taken care of, some inaccuracy will be introduced into any prediction based upon periodicities detected in the pattern.

3. TESTS ON THE PREDICTION METHOD

The method described in the preceding section has been used to predict the peaks of monthly rainfall patterns in several East African meteorological stations from 1981 up to 1990. By 'peaks of monthly rainfall patterns" we specifically mean the series of points each of which represents the highest monthly rainfall in a year. Monthly rainfall records for each station stretching from before 1930 up to 1981 were spectrally analyzed using the Maximum Entropy Method (MEM) of spectral analysis. The periodicities in the resultant MEM spectrum whose peaks towered over the 95% confidence level were selected out and fed into the prediction procedure outlined in Fig.2. The final results with respect to fifteen representative stations are illustrated in Figs.4 to 11 wherein actual rainfall measurements (only from 1967 onwards) are represented by solid lines while discontinuous lines represent the peak monthly rainfall patterns predicted using our method.

Each discontinuous line in Figs.4 to 11 has been discretely fitted with vertical lines that indicate the corresponding lower and upper 95% confidence limits. These limits were computed as already described elsewhere [Njau, 1987b].

It is worthwhile mentioning that the predictions indicated in Figs.4 to 11 were made and finalized in 1985, the year in which the theory described in Njau (1987b) had just been partly evolved from earlier publications [Njau, 1985a; 1985b]. Interestingly, not only is there a good agreement (at least 70% for all the stations except one i.e. Moshi in Fig.4(a)) between the predicted peak patterns of monthly rainfall in all the stations involved (e.g. see Figs.4 to 11) and the recorded patterns from 1981 to 1985, but also recently available data from these stations indicate that all the predictions made for 1986 and 1987 have also come true to at least 70% accuracy. Important features like the mini-drought predicted for Moshi for the current year (see Fig.4) and the sharp rainfall increase during the 1986/87 period for Singida (see Fig.7) have taken place precisely as predicted two years ago. On top of these successful predictions, the method described in the text has been used (in a slightly modified version) to make successful predictions upon climatic parameters other than rainfall [e.g. Njau, 1986]. Altogether, these results uphold and demonstrate the workability of our prediction method, which has already been successfully tested in at least 96% of the meteorological stations in Tanzania [Njau, 1987c]. This method is clearly guided by the theory given in Njau (1987b) which offers perhaps the first predictability theory for guiding the much needed research into climatic prediction. As remarked elsewhere [Somerville, 1987], no such predictability theory ever existed before.

4. CONCLUSION

We have described a method by which long-term predictions upon monthly rainfall patterns may be made. Although this method incorporates some statistical procedures used routinely in other previous techniques [e.g. Tyson and Dyer, 1978; Kane and Trivedi, 1986], it is significantly guided by the contents of a recently developed theory of Sun-Climate/Weather links [Njau, 1985a; 1985b; 1986; 1987a; 1987b]. Since peak variations in monthly rainfall patterns are positively correlated with the corresponding variations in annual

rainfall, at least for East African stations [Njau, 1987c], our prediction method may be used directly to predict occurrences of drought spells. In a slightly modified version, this method has been used to successfully predict variations in climatic parameters other than rainfall [e.g. Njau, 1986]. This symbolizes consistency with a recent conclusion by Mosetti (1987) that the various climatic parameters fluctuate at mostly similar periods but with different amplitudes and phases.

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TABLE 1

The most prominent periodicities obtained from analyses of various rainfall records from different regions of the world.

LOCATION	LENGTH OF RAINFALL DATA USED	MOST PROMINENT PERIODICITIES (IN YEARS)	SOURCE OF THE INFORMATION
INDIA (semi-arid part)	1911 - 1974	2.3, 2.9	Kraus (1977)*
NEW ZEALAND	1900 - 1979	2.2, 2.9, 9.6	Tomlinson (1980)*
CHINA (Beijing)	1870 - 1969	2.3, 3.5	Yao (1982)*
ARGENTINA	1910 - 1977	18.8	Compagnucci and Vargas (1983)*
SOUTH AFRICA (Southern part)	1910 - 1977	10.6	Vines (1980)*
SOUTH AFRICA (N.E. part)	1910 - 1977	18.0	Tyson and Dyer (1978)*
NORTH AFRICA	1911 - 1974	6.0	Krauss (1977)*
WEST AFRICA	1905 - 1980	30.0	Bunting *et al.* (1976)*
AUSTRALIA (Victoria)	1913 - 1978	2.1, 2.6, 8.0	Vines (1980)*
DIFFERENT PARTS OF THE WORLD	Long historical records	200	Winstanley (1973)*
ITALY (Padova)	1725 - 1980	2, 3, 4	Camuffo (1984)
U.S.A. (Eastern part)	1879 - 1960	16, 22	Vines (1984)
INDIA (whole country)	1871 - 1978	2.8, 14	Mooley and Parthasarathy (1984)
U.S.A. (N.E. part)	1851 - 1978	2.1, ∼ 20	McGuirk (1982)
CHINA (whole country)	1470 - 1979	2, 11, 22, 36	Shao-Wu and Zong-Ci (1981)

TABLE 1 (continued)

EUROPE	1760 - 1920	2.0 - 2.5,* ∼ 23, ∼ 35	Brunt (1925)
TANZANIA	1920 - 1980	2-3, 6-7, ∼ 11	Njau (1987c)
AFRICA (Equatorial and southern part)	1948 - 1972	2.0 - 2.5, 5.0, 6.2	Nicholson and Entekhabi (1987)
HAWAII	1939 - 1975	2.0 - 2.5	Lyons (1982)
ISRAEL (Jerusalem)	1846 - 1954	2.1, 3.0 - 3.3, 6.0	Zangvil (1979)
U.S.S.R.	1900 - 1963	∼ 2	V.A. Bugaev in Lamb (1977)

* In addition to Kane and Trivedi (1986)

TABLE 2

Rainfall predictions that have been made on the basis of the prominent periodicities shown in Table 1.

REGION FOR WHICH PREDICTION WAS MADE	PREDICTION	SUCCESS OR FAILURE OF PREDICTION	SOURCE OF THE INFORMATION
WEST AFRICA	Mild dry spell during 1983-84	Prediction came true	Bunting et al. (1976)
SOUTH AFRICA (N.E. part)	Dry spell in 1982-87	Prediction came true	Tyson and Dyer (1978)
SOUTH AFRICA (Southern part)	Dry spell in 1978-80	Prediction came true	Vines (1980)
NORTH AFRICA	Dry spell in 1976-79	Prediction barely came true	Kraus (1977)
NEW ZEALAND	Mild dry spell in 1983-86	Did not come true	Tomlinson (1980)
U.S.S.R.	Drought in 1972	Prediction came true	V.A. Bugaev in Lamb (1977)

FIGURE CAPTIONS

Fig.1 A rectified (i.e. wholely positive) sinusoidal signal at frequency w_c that is amplitude-modulated by another sinusoidal signal at frequency w_m. The resultant modulated waveform is illustrated in (a) and its frequency spectrum is illustrated in (b). Note that $w_1 = w_c - w_m$, $w_2 = w_c + w_m$, $w_3 = 2w_c - w_m$ and $w_4 = 2w_c + w_m$.

Fig.2 The summary of a new method by which predictions of monthly rainfall patterns may be made.

Fig.3 Two sinusoid signals, one a double-sided signal at frequency w_c and the other a signal at frequency w_m ($< w_c$) interact with each other in two ways. Firstly they form an amplitude-modulated waveform (see (a) above) whose frequency spectrum is shown in (b). Secondly they simply add to each other to form a waveform (see (c) above) whose frequency spectrum is shown in (d).

Fig.4 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for (a) Moshi and (b) Dar es Salaam.

Fig.5 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for (a) Musoma and (b) Tabora.

Fig.6 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for (a) Amani and (b) Mbeya.

Fig.7 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for (a) Mahenge and (b) Singida.

Fig.8 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for (a) Sumbawanga and (b) Morogoro.

Fig.9 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for Kigoma.

Fig.10 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for (a) Dodoma and (b) Songea.

Fig.11 A plot of recorded monthly rainfall data (solid line) from 1967 to 1985 and predicted peak variation of monthly rainfall pattern (discontinuous line) from 1981 to 1990 for (a) Bukoba and (b) Mwanza.

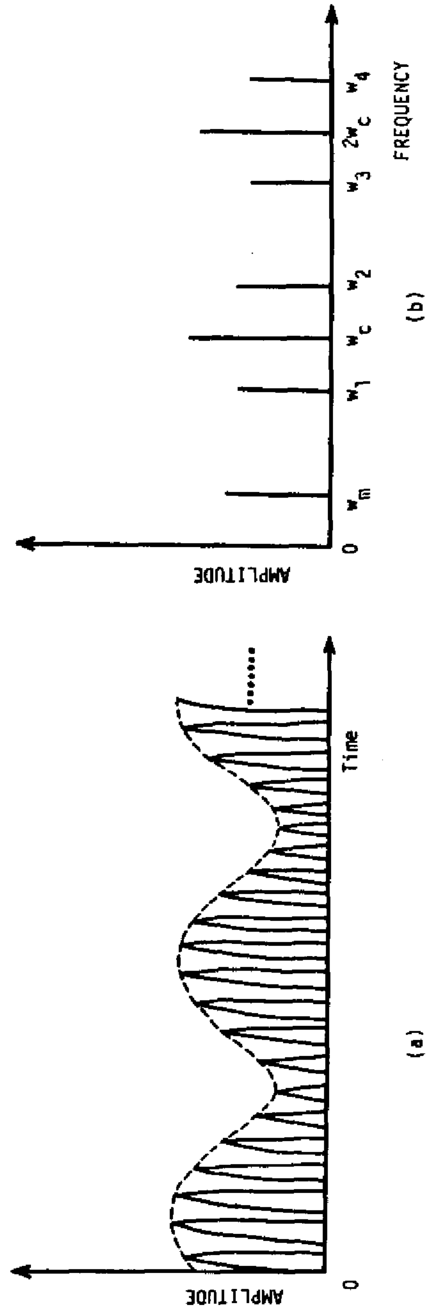
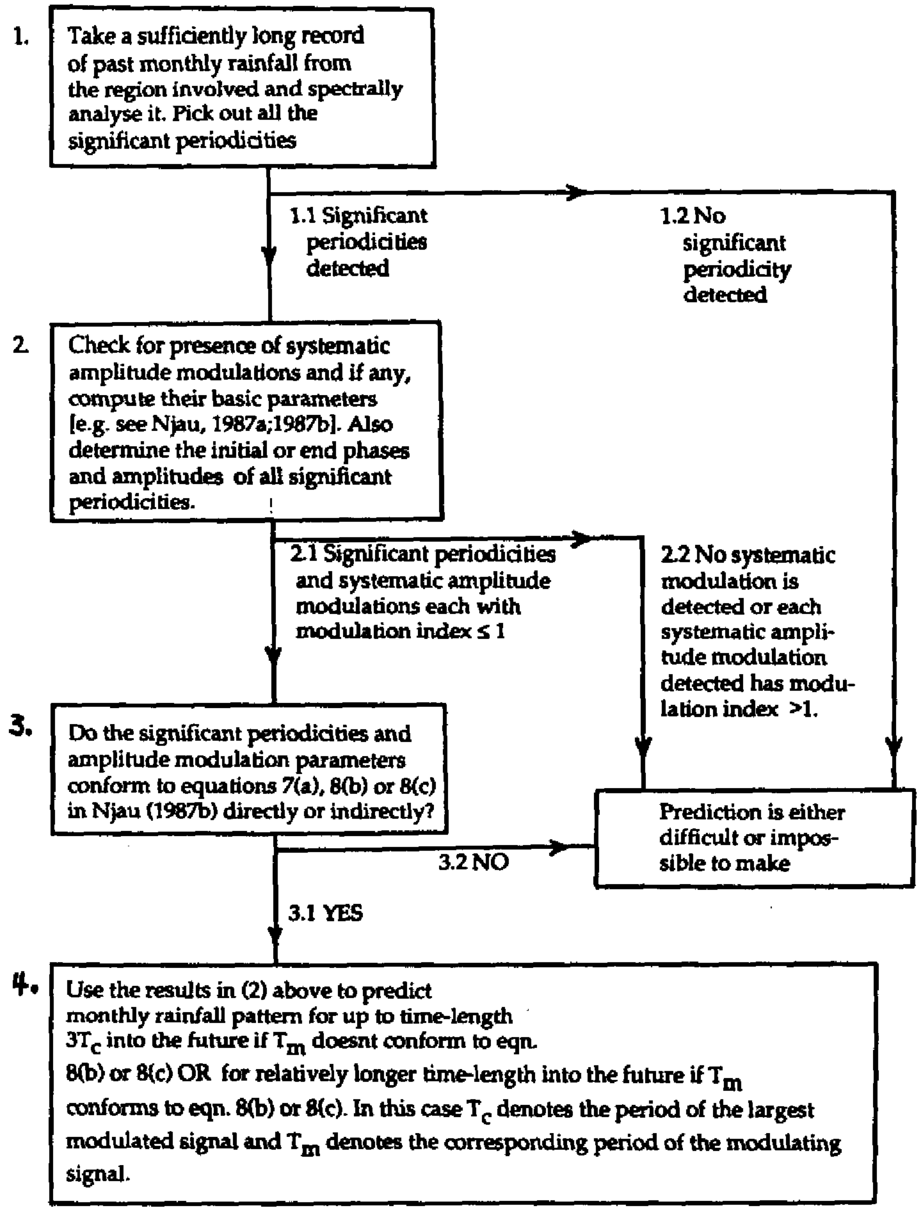


FIG. 1

FIG.2


1. Take a sufficiently long record of past monthly rainfall from the region involved and spectrally analyse it. Pick out all the significant periodicities
1.1 Significant periodicities detected
1.2 No significant periodicity detected
2. Check for presence of systematic amplitude modulations and if any, compute their basic parameters [e.g. see Njau, 1987a;1987b]. Also determine the initial or end phases and amplitudes of all significant periodicities.
2.1 Significant periodicities and systematic amplitude modulations each with modulation index ≤ 1
2.2 No systematic modulation is detected or each systematic amplitude modulation detected has modulation index >1.
3. Do the significant periodicities and amplitude modulation parameters conform to equations 7(a), 8(b) or 8(c) in Njau (1987b) directly or indirectly?
3.2 NO
3.1 YES
Prediction is either difficult or impossible to make
4. Use the results in (2) above to predict monthly rainfall pattern for up to time-length $3T_c$ into the future if T_m doesnt conform to eqn. 8(b) or 8(c) OR for relatively longer time-length into the future if T_m conforms to eqn. 8(b) or 8(c). In this case T_c denotes the period of the largest modulated signal and T_m denotes the corresponding period of the modulating signal.

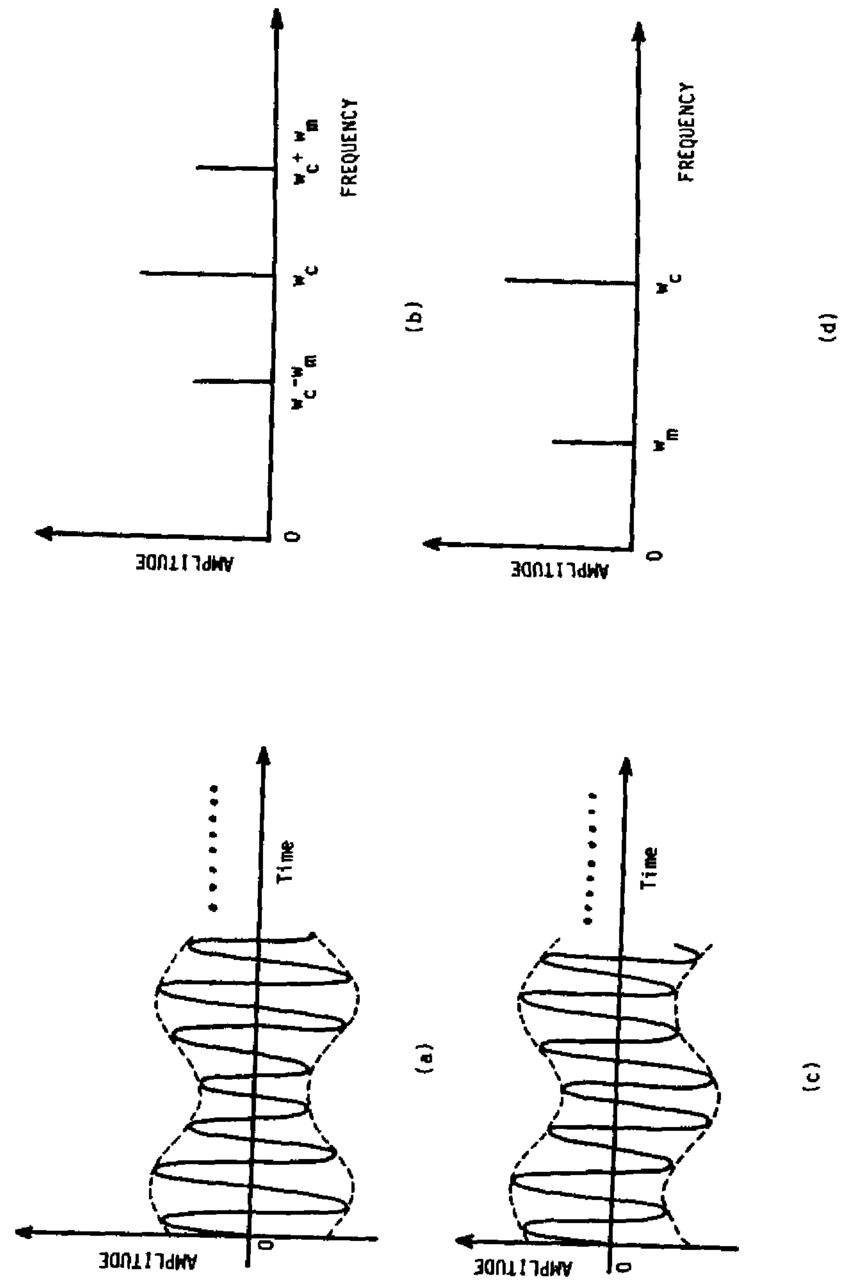
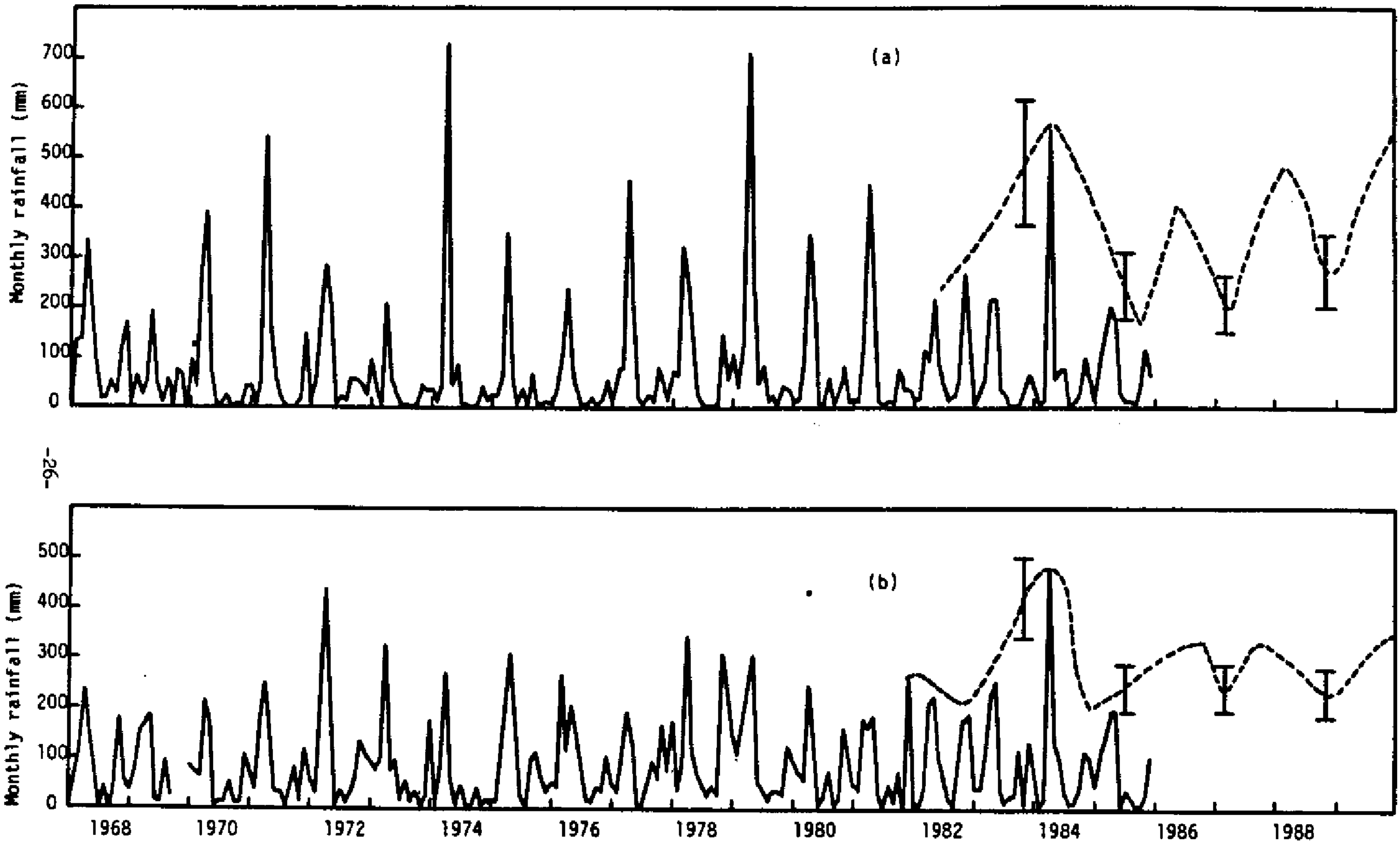
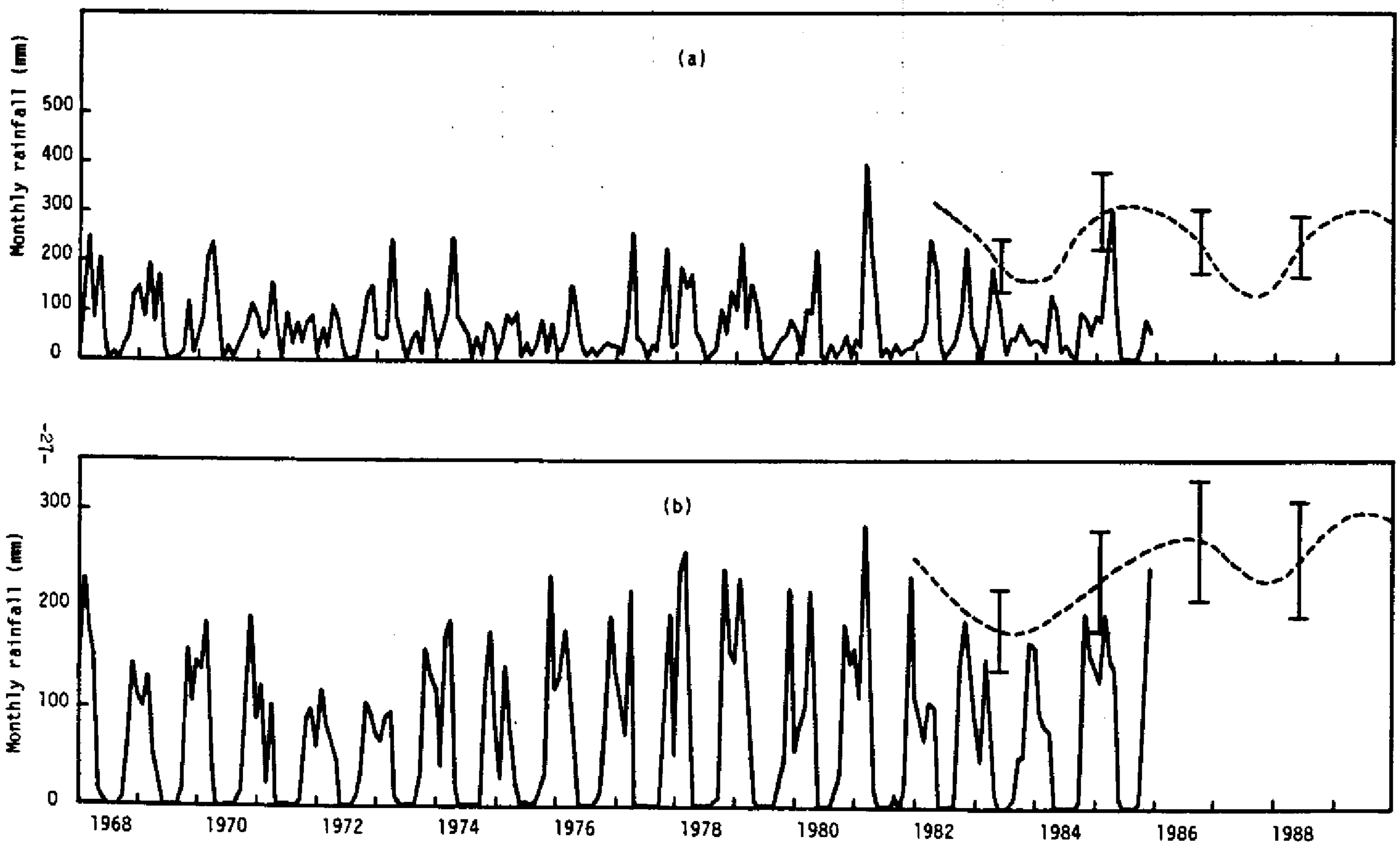

FREQUENCY
AMPLITUDE
Time
0
(a)
(b)
(c)
(d)

FIG. 3



(a)
Monthly rainfall (mm)
700
600
500
400
300
200
100
0
(b)
Monthly rainfall (mm)
500
400
300
200
100
0
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 4



(a)
Monthly rainfall (mm)
500
400
300
200
100
0
(b)
Monthly rainfall (mm)
300
200
100
0
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 5

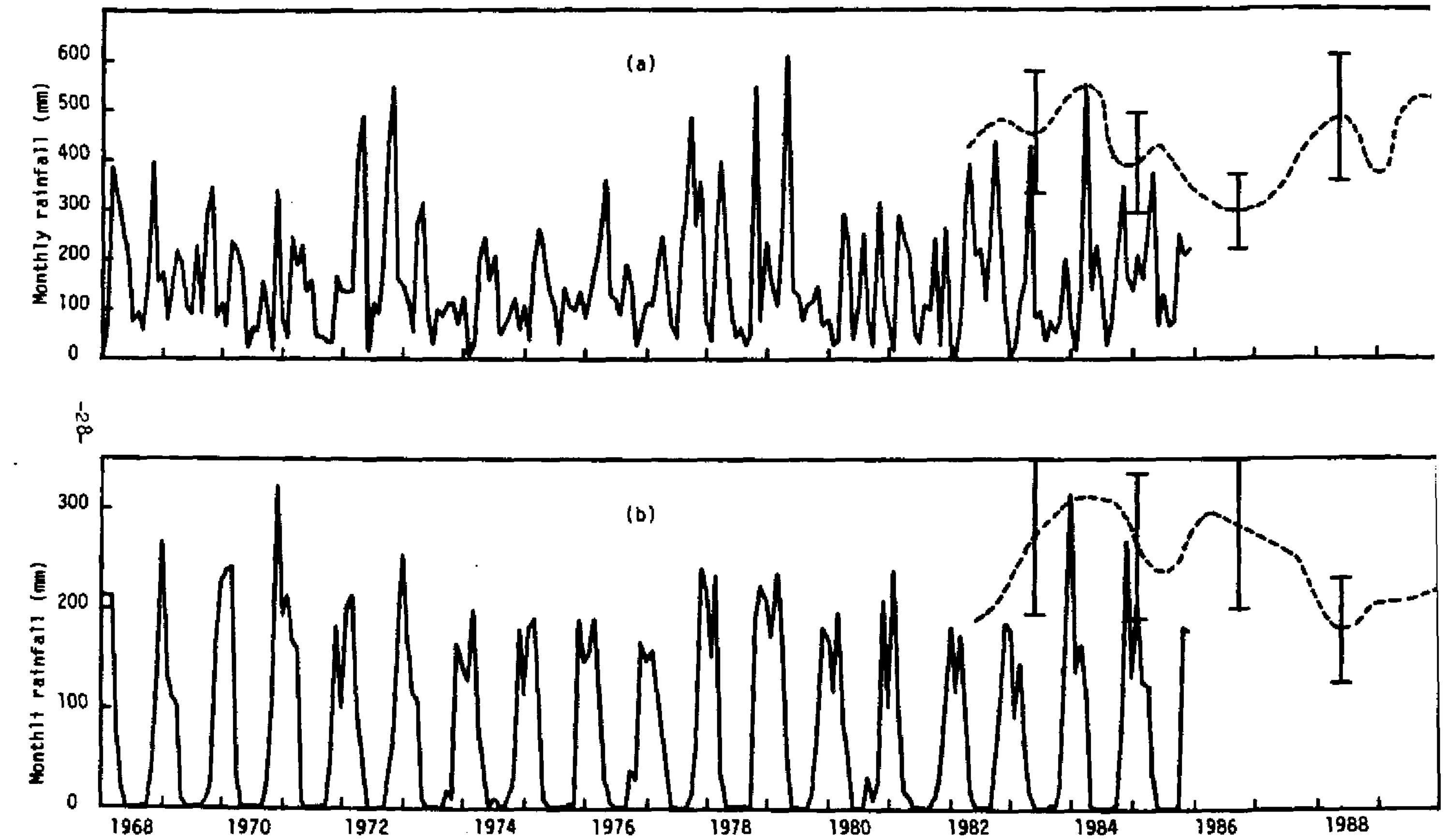

(a)
Monthly rainfall (mm)
0
100
200
300
400
500
600
(b)
Monthli rainfall (mm)
0
100
200
300
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 6

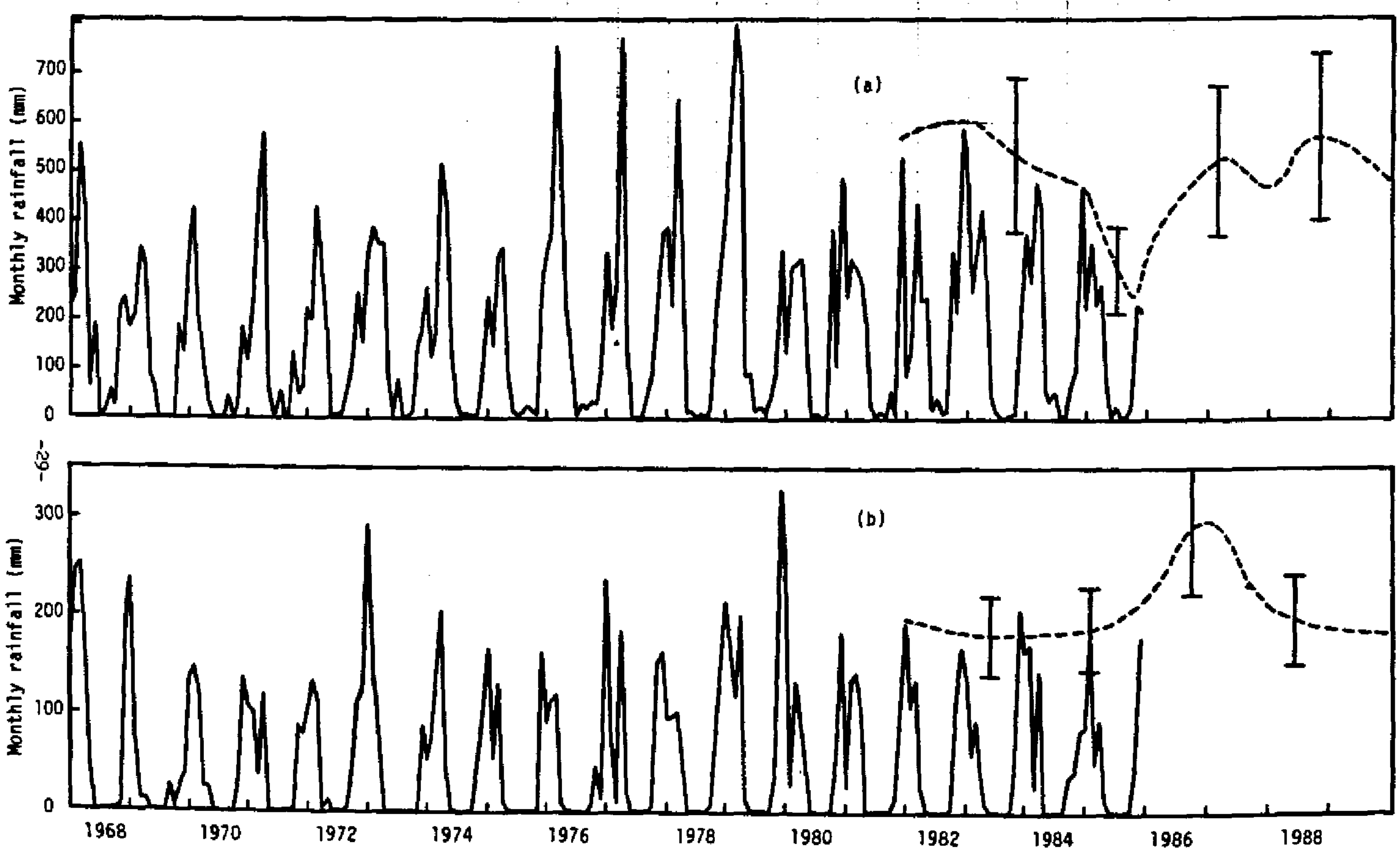

(a)
Monthly rainfall (mm)
0
100
200
300
400
500
600
700
(b)
Monthly rainfall (mm)
0
100
200
300
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 7

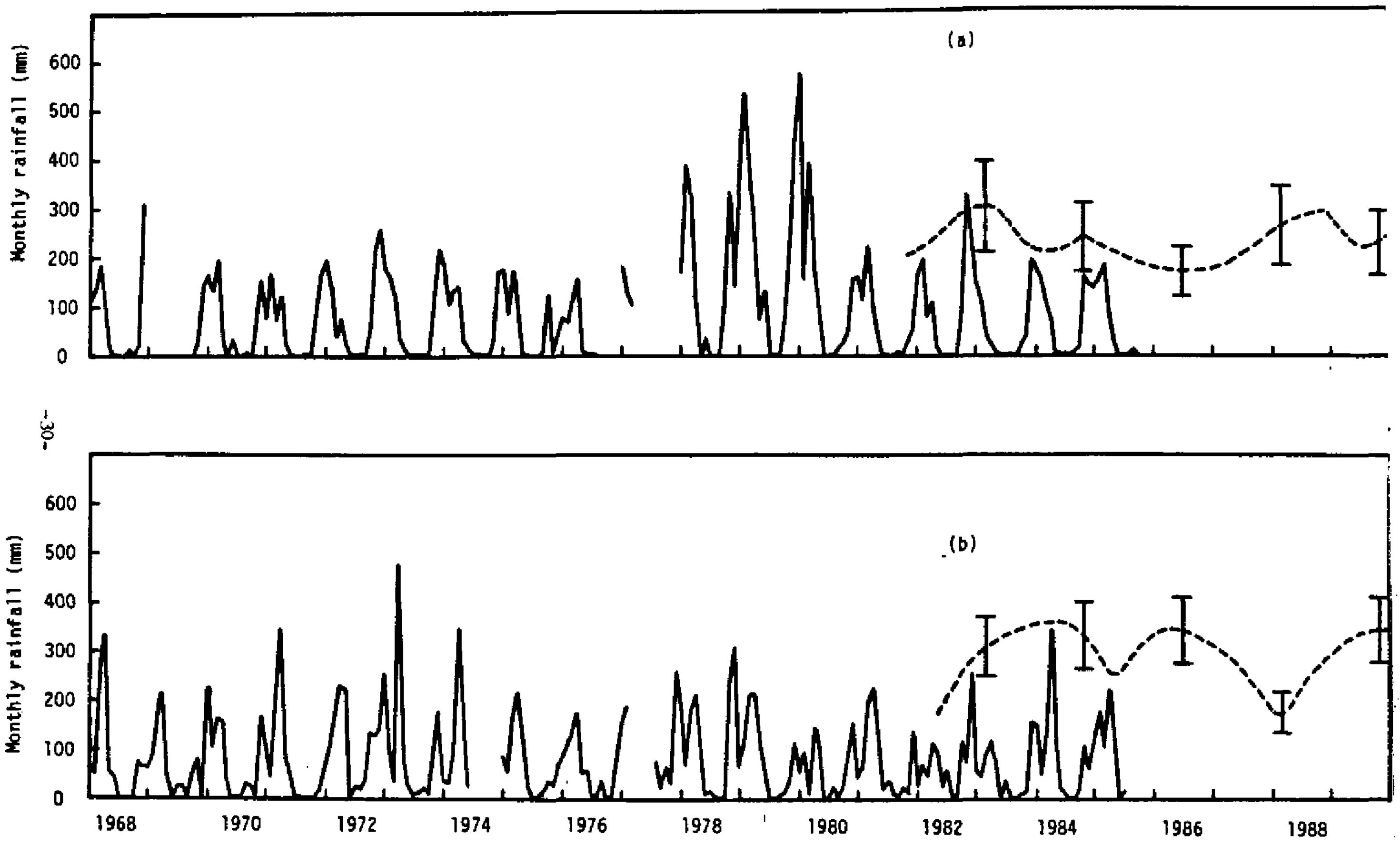

(a)
(b)
Monthly rainfall (mm)
Monthly rainfall (mm)
0
100
200
300
400
500
600
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 8

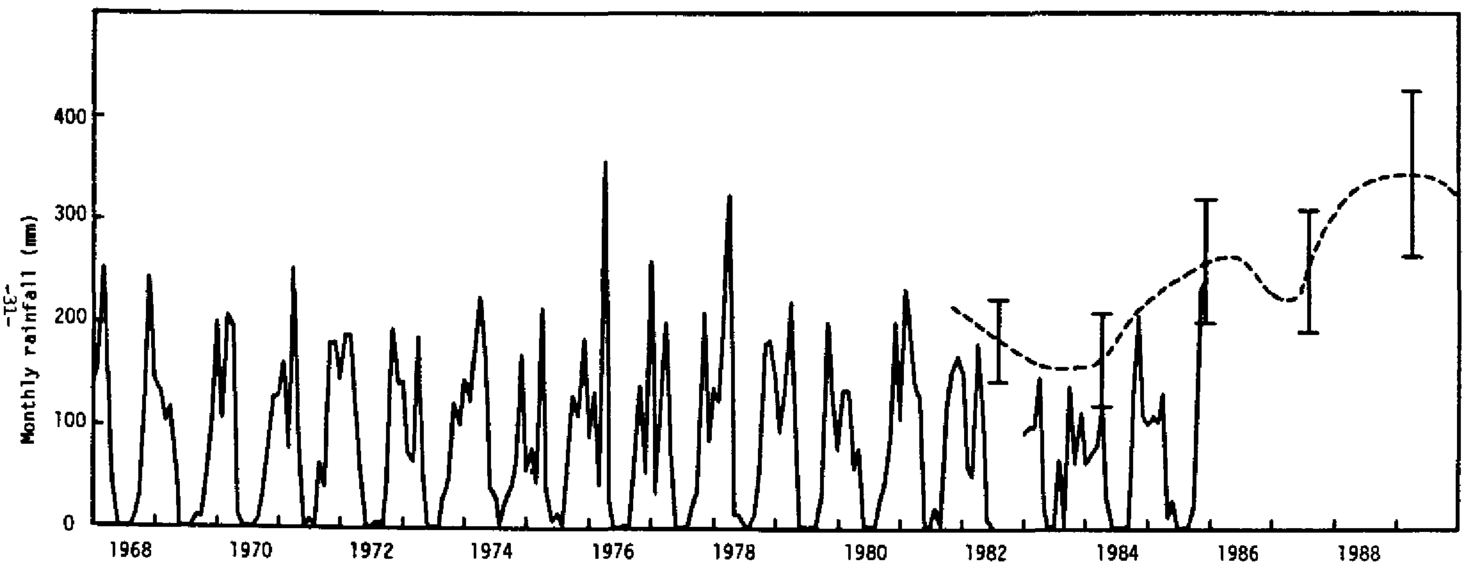

Monthly rainfall (mm)
0
100
200
300
400
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 9

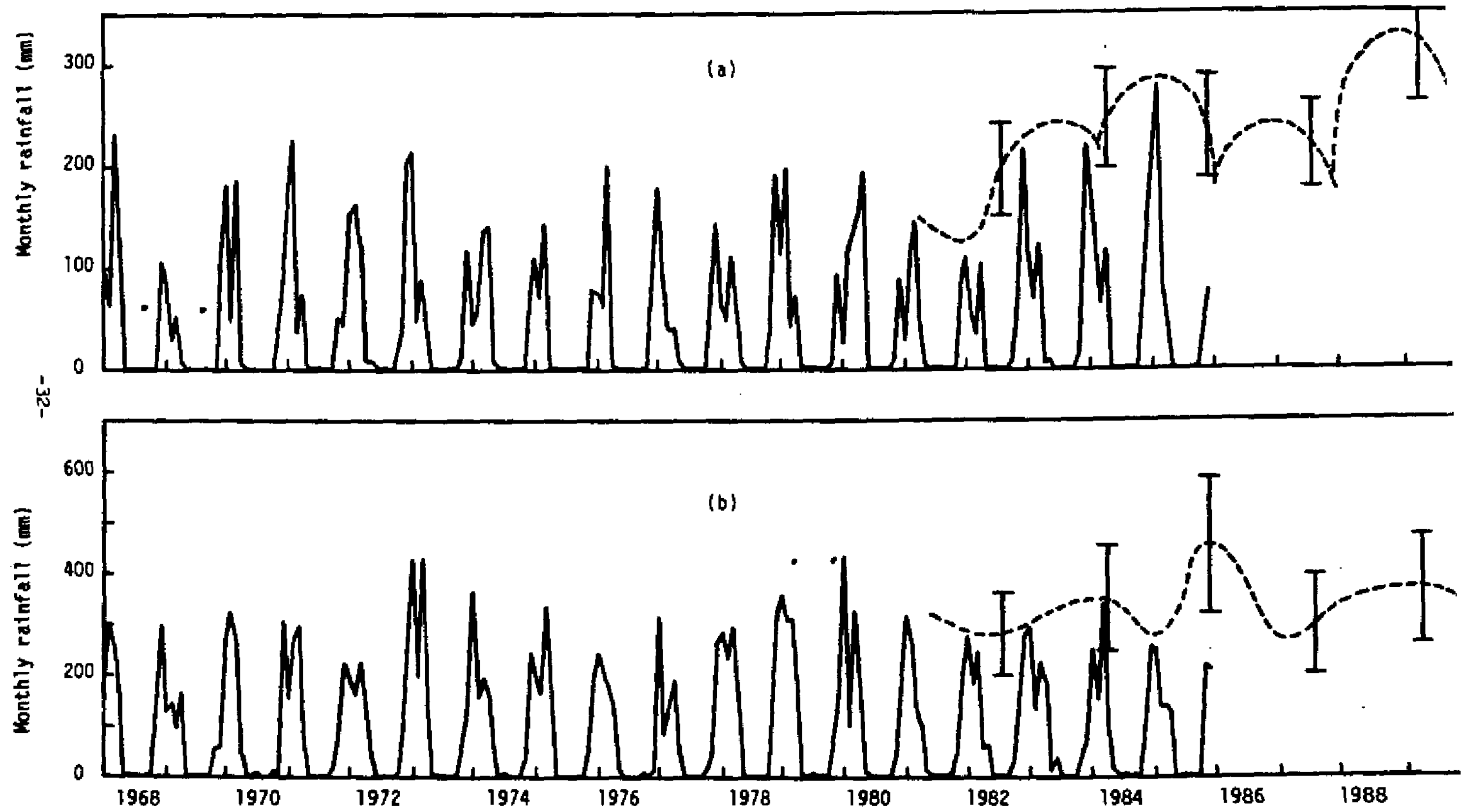

Monthly rainfall (mm)
(a)
300
200
100
0
Monthly rainfall (mm)
(b)
600
400
200
0
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 10

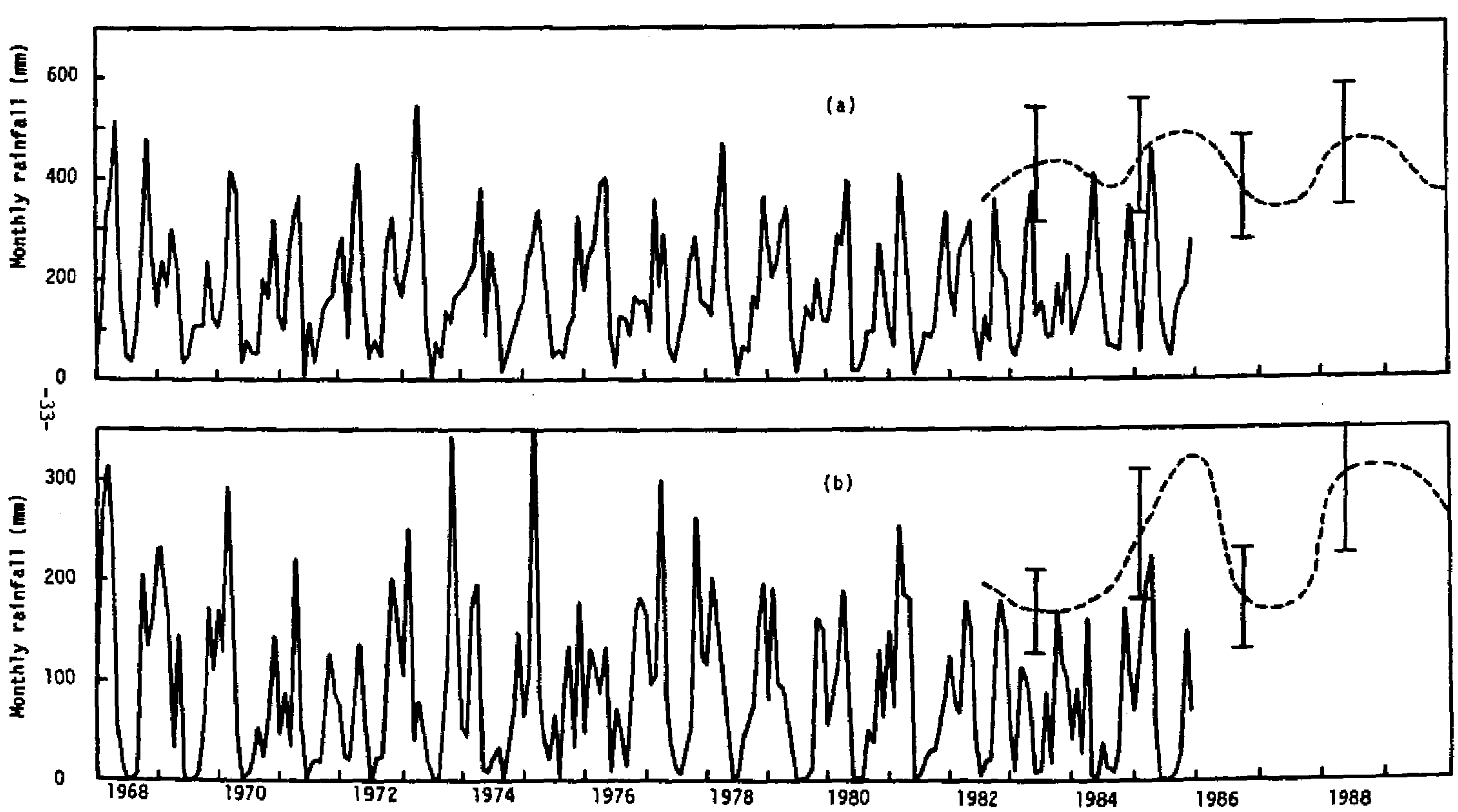

Monthly rainfall (mm)
(a)
600
400
200
0
Monthly rainfall (mm)
(b)
300
200
100
0
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988

FIG. 11

[illegible]