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THE SPATIAL AND TEMPORAL PATTERNS OF THE EAST AFRICAN SEASONAL RAINFALL DERIVED FROM PRINCIPAL COMPONENT ANALYSIS

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1

ABSTRACT

this study, rotated principal component analysis (RPCA) was used to study the spatial and temporal characteristics of ısonal rainfall over East Africa during the period 1922–1983. The RPCA solutions were derived from both spatial and nporal correlation matrices. The spatial correlation matrices described intercorrelation between pairs of stations, while e temporal matrices gave correlations between pairs of map patterns.

Results obtained with the spatial correlation matrices indicated seasonal shifts in the patterns of the dominant RPCA odes which closely resembled the seasonal migration patterns of the rainfall belts induced by the Inter Tropical onvergence Zone (ITCZ). The influence of the large water bodies, especially Lake Victoria and the Indian Ocean, were owever, outstanding throughout the year. Twenty-six homogeneous regional groups were delineated from the spatial aracteristics of the dominant eigenvectors.

Solutions based on the temporal correlation matrices clustered together some of the wet and dry episodes. Some of e map patterns clustered together could be associated significantly with the El-Niño/Southern Oscillation events.

Y WORDS　East Africa　Inter Tropical Convergence Zone　Rotated principal components analysis　El Niño/Southern Oscillation

INTRODUCTION

he region of the study is located within latitudes 5°N–12°S and longitudes 28°E–42°E, and consists of three ates (Kenya, Uganda and Tanzania). Although the area lies within the Equatorial zone, there are large ıatial and temporal variations in the rainfall characteristics due to the complex topographical patterns, the istence of many large inland lakes, together with several other regional factors (Ogallo, 1983).

Several attempts have been made to study the spatial and temporal characteristics of rainfall over East frica (Johnson, 1962; Potts, 1971; Griffiths, 1972; Atwoki, 1975; Rodhe and Virji, 1975; Ogallo, 1980, 1983).

Johnson (1962) examined the seasonal march of daily rainfall patterns over East Africa using a daily rainfall las. Large-scale systems developing and persisting for several days were clearly discernible from his ıalyses. Griffiths (1972) used mean seasonal rainfall patterns from various locations in East Africa to classify e region into climatic zones. Over 50 regional divisions were delineated by the method. The regional itterns were quite complex in many areas.

Harmonic analysis has also been used to study rainfall characteristics over East Africa (Potts, 1971; Ogallo, 983). Potts (1971) used the patterns of the dominant harmonics to group East Africa into climatological visions. The regional divisions were not realistic over some areas. This was partly due to the substantial ısonal variance accounted for by higher harmonics over such areas (Ogallo, 1983).

Atwoki (1975) subjected 10-day rainfall for Uganda for the period 1949–1968 to factor analysis (FA) in der to determine the dominant spatial modes. The use of 10-day rainfall can introduce several errors in the A solutions since the 10-day records have many zero records during the dry months. The existence of many ros will introduce spurious values in the correlation or covariance matrix which is used in the FA solutions.

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Another problem with FA is the determination of the unique component of the variance for a complex variable like rainfall. The climatological stability of the FA results obtained from the 20 years data (1949–1968) was not examined by Atwoki (1975).

Ogallo (1980) subjected East African annual rainfall records for the period 1931–1975 to principal component analysis (PCA). It can be seen from Figure 1 that many parts of East Africa have more than one rainy season, and there is no month in a year when all parts of East Africa are dry. The use of annual rainfall records by Ogallo (1980) therefore filtered out seasonal rainfall characteristics over many parts of East Africa.

In this study an attempt was made to study the dominant spatial and temporal modes of the seasonal rainfall over East Africa using rotated principal component analysis (RPCA). The study was divided into three parts. The first two parts investigated the characteristics of the dominant spatial and temporal modes of the seasonal rainfall which were derived from RPCA, while the final part concentrated on the stability of the derived RPCA patterns.

The data used in the study were monthly rainfall records from the 90 stations shown in Figure 2, within the period 1922–1983. The homogeneity and other statistical properties of the monthly records have been discussed by Ogallo (1981), among many others. The monthly rainfall records were used to generate seasonal rainfall records for the standard seasons (summer, winter, autumn, and spring). The mean rainfall patterns for the four seasons are shown in Figure 1 for some representative stations. Their patterns generally reflect the influence of the Inter Tropical Convergence Zone (ITCZ) which migrates with the overhead sun. The northern summer peak, which is common over some western parts, is however, associated to moisture influx from the Atlantic and the moist Congo/Zaire basins.

All seasonal rainfall records were normalized by subtracting the long-term average and dividing with the corresponding standard deviation in order to have zero mean and unit variance.

ROTATED PRINCIPAL COMPONENT ANALYSIS (RPCA)

Principal component analysis (PCA) has been widely used to study the spatial and temporal characteristics of many climatological variables. Some of the recent applications include the work of Horel (1981, 1984), Richman and Lamb (1985), Barnston and Livezey (1987), and Janowiak (1988). Detailed accounts of PCA are available in many standard references and only a brief description of the method will be included in the text.

The basic principles of PCA are derived from the concept of variance. The first step usually involves the computation of some measures of association between the set of variables used. This is usually followed by the construction of a linear set of orthogonal vectors (eigenvectors), that are finally used to represent the various variables. Under PCA, the eigenvectors are scaled by the square root of the corresponding eigenvalue.

The PCA model for any variable j may take the form:

$$z_j = a_{j1}F_1 + a_{j2}F_2 + \dots + a_{jm}F_m \qquad (j = 1, 2, \dots, m) \tag{1}$$

$F_1, F_2, \dots, F_m$ represent the principal components, z_j the normalized rainfall records, a_{jk} the regression weight (loading) on the kth principal component. The regression weights can be obtained from the correlation and covariance matrices of the variables (Harman, 1967). The correlation matrix was used in this study.

The advantages and disadvantages of the correlation matrix have been discussed by Richman (1981). The advantages include equal weighting of all stations or grid points to avoid bias positioning of the 'synoptic centres'. They can also be used to assign perfect position correlation between a variable and itself by setting the diagonal of the input correlation matrix to unity.

The data used to generate the spatial correlation matrix for the various seasons consisted of seasonal rainfall records obtained from the 90 stations shown in Figure 2. The data covered the period 1922–1983 (62 years). The ij element of the initial data matrix corresponded to normalized seasonal rainfall records for the ith year at the jth station. These records were used to generate the 90 by 90 spatial correlation matrix which gave correlations between pairs of stations during the period of study (1922–1983).

The 90 by 90 correlation matrices describing the inter-station correlations for the individual seasons were independently subjected to PCA in order to derive the eigenvectors for the individual seasons. The S-mode

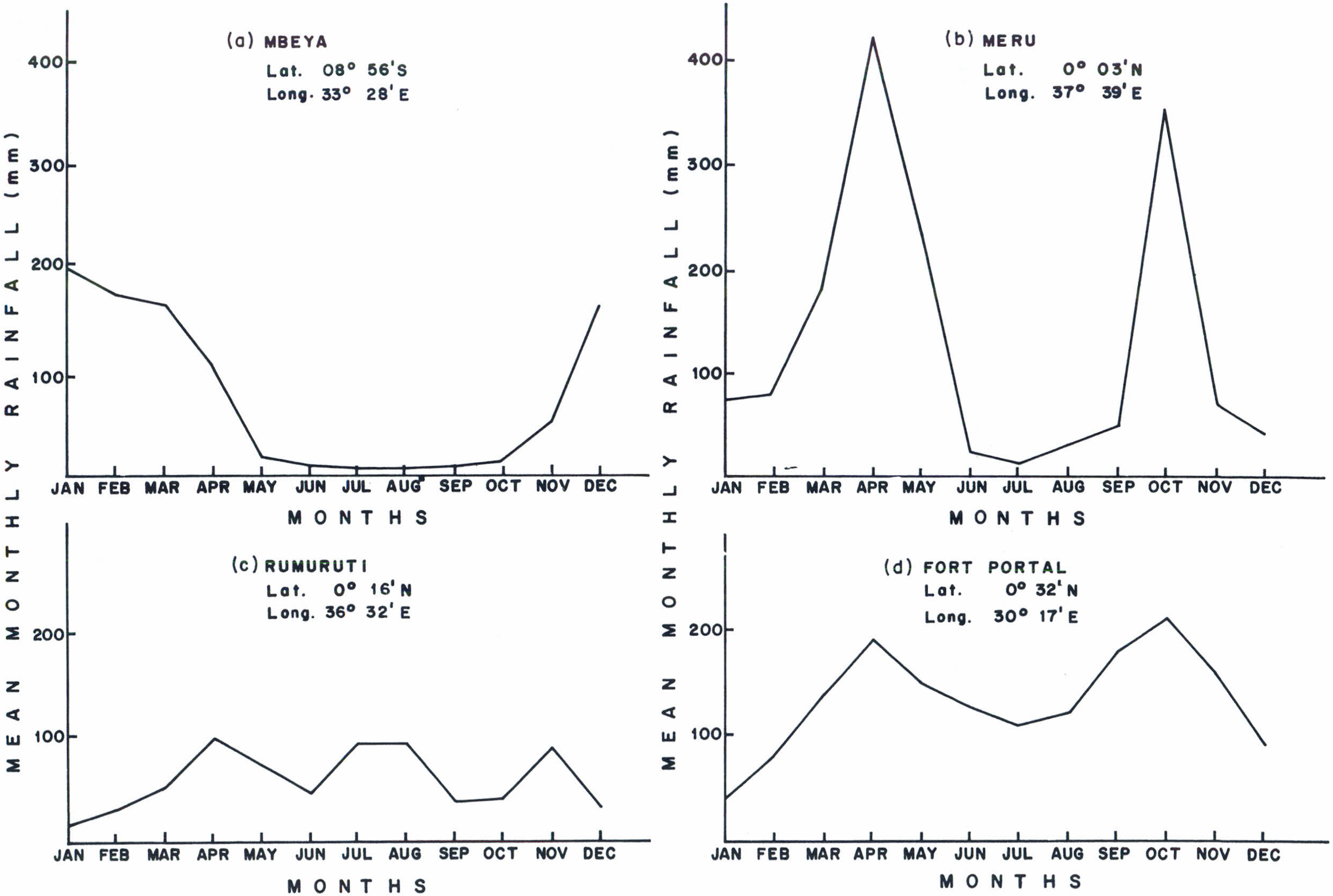


Figure 1. Mean seasonal patterns of rainfall over East Africa

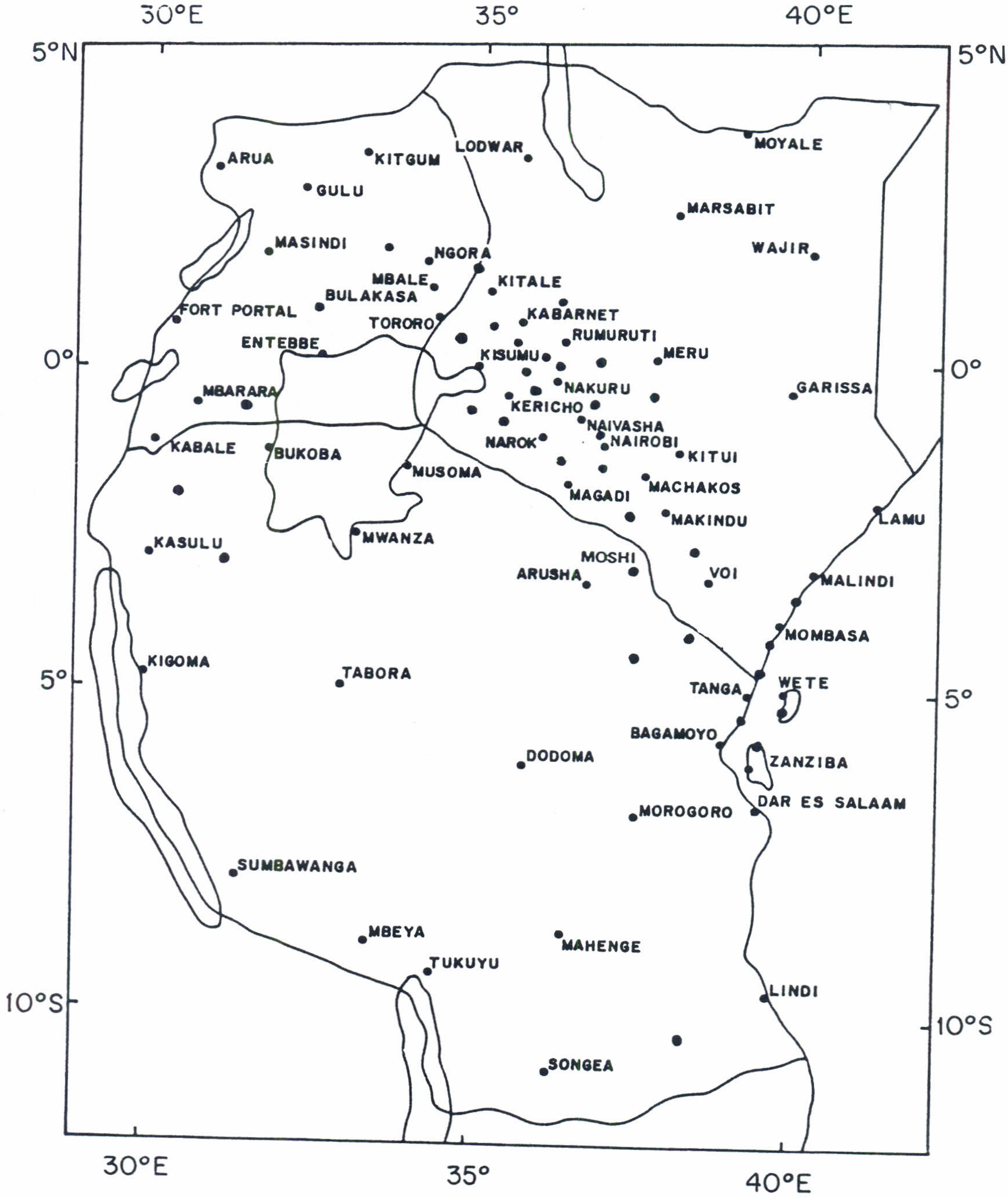


Figure 2. Network of the stations used

solutions from the PCA were used here to describe the dominant spatial modes for the individual seasons. Under this method, the major eigenvectors for each station were first identified. The patterns of the loadings of the dominant eigenvectors can be used to delineate spatial variables into homogeneous categories (Gregory, 1975; Dyer, 1977). The approaches by Gregory (1975) and Dyer (1977) were adopted in the classification of the 90 stations into categories. The inter seasonal changes in the patterns of the eigenvectors dominating at each f the locations were also considered during the classification of the stations. Thus, only stations with identical CA patterns during the four seasons were lumped together.

Eigenvectors are mathematically orthogonal while the underlying physical processes associated with the ariables are generally not orthogonal. In order to reduce some ambiguities which often accompany the direct olutions, several methods have been used to adjust the frames of references of the eigenvectors through otations (Kaiser, 1958; Harman, 1967; Richman, 1986). It has been noted by Horel (1981, 1984), Hsu and Vallace (1985), Richman (1981, 1986), and Barnston and Livezey (1987), among many others, that rotated olutions give better descriptions of the interrelations between variables. Kaiser's orthogonal (varimax) otation method (Kaiser, 1959), was adopted in the rotation of the significant eigenvectors. The final grouping f the stations was based on solutions derived from rotated PCA (RPCA).

Determination of the number of the eigenvectors to be rotated is one of the major problems in the rotation f the eigenvectors. The various methods which have been used in determining the number of significant genvectors can be obtained from Kaiser (1959), Anderson (1963), Catell (1966), Craddock (1973), Richman 981), Overland and Preisendorfer (1983), and North *et al.* (1982), among many others.

The three methods which were included in this study were the Kaiser's criterion (Kaiser, 1959), the scree test Catell, 1966) and the use of sampling errors in the eigenvalues (North *et al.*, 1982). Comparison of the three nethods is, however not a major objective of this study.

The Kaiser's criterion retains all eigenvectors with eigenvalues greater than one for the rotations, while nder the scree test the eigenvalues are plotted against the corresponding ordinate eigenvector numbers. The runcation value is near the point where the graph becomes almost a straight line.

Craddock (1973) noted that meteorological noise may be in geometric progression and suggested the plot of he logarithms of the eigenvalues in determining the 'scree' portion of the curve. North *et al.* (1982), among thers, have suggested the use of sampling errors in the determination of the number of significant igenvectors. The sampling errors test by North *et al.* (1982) is based on the comparison of the sampling errors or the eigenvalues and the separation in the neighbouring eigenvalues. The test states that 'If the sampling rror in the eigenvalues is comparable to the distance to the nearby eigenvalue, then, the sampling errors in he EOF will be comparable to the "nearby EOF". The sampling error [$\lambda(2/N)^{\frac{1}{2}}$] therefore indicates whether a sample eigenvalue is a faithful representation of the eigenvectors. Here, λ and N refer to the igenvalue and the total number of records, respectively.

Finally, for each season, the 90 stations were mapped on to the vector spaces of pairs of the significant igenvectors. The loadings of any station on to the pair of significant eigenvectors were used to map the ocations of the stations on the vector space of the two eigenvectors. The cluster of the 90 stations on to these ector spaces were compared to the spatial modes derived from the Gregory (1975) and Dyer (1977) pproaches.

Attempts were made finally to compare the spatial modes derived from RPCA with the known seasonal limatology of rainfall over the region. The influence of the major factors which control East African rainfall n the regional clusters were also investigated.

MAP PATTERNS

Many attempts have been made to compare map patterns. The methods which have been used in such studies have ranged from regression and cluster analyses to more complex methods like the principal component analysis (Lund, 1963; Blasing, 1979; Gregory, 1979; Walsh and Mostek, 1980; Richman, 1981; Nicholson, 986; Obled and Creutin, 1986).

In this study an attempt was made to compare seasonal map patterns for the 62 years (1922–1983), by ubjecting the temporal correlation matrix of the individual seasons to RPCA. Under this method, the 90 by 0 seasonal correlation matrices which were described under the S-mode analyses were replaced by the 62 by 2 temporal correlation matrices for the individual seasons. Some relationships between the initial data natrices have been discussed by Hirose and Kutzback (1969), and Storch and Hannoschock (1984), among nany others.

The element ij of the 62 by 62 temporal correlation matrix described correlation between map patterns for the years i and j. This correlation value was computed from the rainfall anomalies at the 90 locations during the years i and j.

The method of RPCA discussed for the S-mode solutions was then repeated using the temporal correlation matrices for the individual seasons as the inputs. The unit diagonal value in the input temporal correlation matrix expresses here the correlation between map patterns of one year and itself. These were derived from rainfall anomalies observed at the 90 locations during that particular year.

Using the analogies discussed under the S-mode solutions, all years with similar map patterns will tend to cluster on to similar eigenvector(s) by having large loadings on to these eigenvectors. Years clustering on to similar eigenvectors were considered here to have almost identical map patterns (i.e. they have experienced almost similar spatial rainfall anomalies).

Time coefficients of the dominant eigenvectors together with several other RPCA-derived methods have also been widely used to compare map patterns (Johnson, 1980; Walsh and Mostek, 1980; Richman, 1981; Cohen, 1983; Obled and Creutin, 1986). The characteristics of the principal component scores for the time series of the dominant eigenvectors derived from the S-mode solutions were also investigated for the years clustered together in order to further compare the characteristics of the clustered map patterns.

Finally, areal rainfall averages during the individual years clustered together were also computed using rainfall records from the regional stations. The number of stations in each region were determined from the S-mode classification. Details of these will be given later in the text. An attempt was also made to relate some of the clustered map patterns to some climatic systems.

THE STABILITY OF THE RPCA PATTERNS

The question of whether the patterns derived from RPCA are physically realistic and climatologically stable has been raised by many investigators. Methods of determining the robustness and consistency of the RPCA patterns have been discussed by North *et al.* (1982), Richman (1986), Rinne and Simo (1986), and Barnston and Livezey (1987), together with many others.

In this study, the stability of the RPCA patterns was investigated by comparing the patterns of the RPCA modes derived from the following seasonal rainfall records: (i) odd years (1923, 1925, . . . , 1983); (ii) even years (1922, 1924, . . . , 1982); (iii) 1922–1952; (iv) 1953–1983; and (v) the monthly records for the period 1922–1983. The RPCA patterns derived from the listed periods were compared between themselves, and with those obtained from the seasonal records for the whole period (1922–1983).

The odd and even years were considered here as random samples of the rainfall records, since no particular rainfall events could be associated to the odd and even years.

If RPCA patterns are stable then the results obtained with the various groups of the records should be comparable during any given season. Similarly, the RPCA patterns derived from each of the three months composing the individual seasons should be comparable to those derived from the corresponding seasonal records. The highest degree of similarity should be observed with the peak of the rainfall month which generally accounts for over 50% of the total seasonal rainfall at some locations. The peak rainfall months for the four seasons correspond to the months of April, November, July, and January. The locations of the rainfall belts during these months were discussed earlier in the text. Some of these patterns are also given in Figure 1.

Finally, the stability of the RPCA patterns was further examined using inter-station correlations. Under this method, the station with the highest loading was identified for each eigenvector. These stations were used as reference points while plotting inter-station correlations. Thus the correlation between this (highest loading) station and itself is taken as a positive unit and plotted at the station location. The correlation between this station and all other stations during a given season are also plotted at the various locations. The spatial patterns of the mapped correlations were compared with the spatial patterns of loadings of the corresponding eigenvector.

SPATIAL COHERENCE IN THE SEASONAL RAINFALL CHARACTERISTICS

ome examples of the characteristics of the computed eigenvectors derived from the S-mode RPCA are given ı Figure 3 for the two seasons which had the highest and lowest number of significant eigenvectors (northern ımmer and autumn). The characteristics are displayed in the form of 'scree plots' for the seasonal rainfall ecords during the period 1922–1983.

The horizontal lines marked yC in Figure 3 represent unit eigenvalues, while CD is the portion of the scree lot which is close to a straight line. It is evident from this figure that the unit eigenvalue line (yC) crosses each f the scree plots almost at the beginning of the straight line (point C), indicating that both the Kaiser's riterion and the scree test retained almost the same number of eigenvectors for the varimax rotations during ıese seasons. Similar results were obtained for the other seasons.

The gradients of the graphs in Figure 3 give some indication on the rate of shifts between neighbouring igenvalues. The rate of separations (gradients) are very steep within the AB portion of the curves, and almost onstant along CD. The gradients were also relatively smaller towards the end of BC, signifying one of the ıajor difficulties in the determination of the cut-off values for the eigenvectors during the rotations.

For $N=62$ (i.e. 1922–1983), the $(2/N)^{\frac{1}{2}}$ component of the sampling error for any eigenvalue was $(2/62)^{\frac{1}{2}}$ $\simeq 0{\cdot}18$. This factor was used together with the individual eigenvalues to determine whether the computed igenvectors were faithful representatives of the true eigenvectors. The results were compared with those from he Kaiser's criterion and the scree test in order to determine the number of eigenvectors which could be etained for the orthogonal varimax rotations. More than one rotation was performed whenever the three ıethods truncated a different number of eigenvectors. In such cases, the stability of the eigenvector loadings vas also examined for the various truncations.

In general the results from the S-mode RPCA solutions indicated that a maximum of four eigenvectors ould be retained for the varimax rotations during three of the four seasons. For the monthly records and luring the summer season as many as seven eigenvectors were retainable by both the Kaiser's criterion and he scree test. The retainable eigenvectors accounted for at least 70% of the seasonal rainfall variance. It was, ıowever, noted that in all cases the spatial patterns of the first three eigenvectors were not significantly ıffected by some changes in the number of the eigenvectors retained for the rotations. The characteristics of hese eigenvectors will be the fundamental base for most of the discussions to follow.

Figures 4–7 give the spatial patterns of the first three eigenvectors during the various seasons. These ›atterns were obtained from the S-mode solutions of the seasonal records for the period 1922–1983.

The first eigenvector describes the mean characteristics of the variables. The seasonal migration patterns of ainfall over the region are clearly discernible from the seasonal patterns of the first eigenvectors (Figures 4a, ›a, 6a, and 7a). The dominant RPCA mode is centred furthest north and south in summer and winter seasons, espectively (Figures 5a and 7a), and around equatorial Kenya during spring and autumn seasons (Figures ła, 6a, and b).

Spring is generally the major rainy season over most parts. Figure 4 indicates that during spring the first eigenvector was dominant over many regions, apart from the coastal areas and southern highlands of Tanzania where the second and third eigenvectors dominated, respectively. During the northern summer seasons the overhead sun has shifted the ITCZ-induced rain belts northwards, outside the region. Most of the ains received within this period are restricted to near large water bodies, and the western areas which are ınder the moisture influx from the Atlantic Ocean and the moist Congo/Zaire basins. Similar patterns are displayed by the spatial patterns of the first three summer eigenvectors (Figure 5). The third summer eigenvector dominated over some western parts (in the neighbourhood of Lake Victoria). Autumn is the second rainfall season for many parts of East Africa due to the southerly shift of the overhead sun, bringing ITCZ-related rainfall systems over the region. It can be observed from Figure 6 that the spatial patterns of the first three dominant eigenvectors were quite close to those observed during the first rainy season (Figure 4). The coastal region, however, accounted for the maximum seasonal rainfall variance during the autumn season. Along the northern coast the first eigenvector could explain over 70% of the autumn rainfall variance. Autumn season is locally known as the short rainy season due to the relatively shorter duration and lower

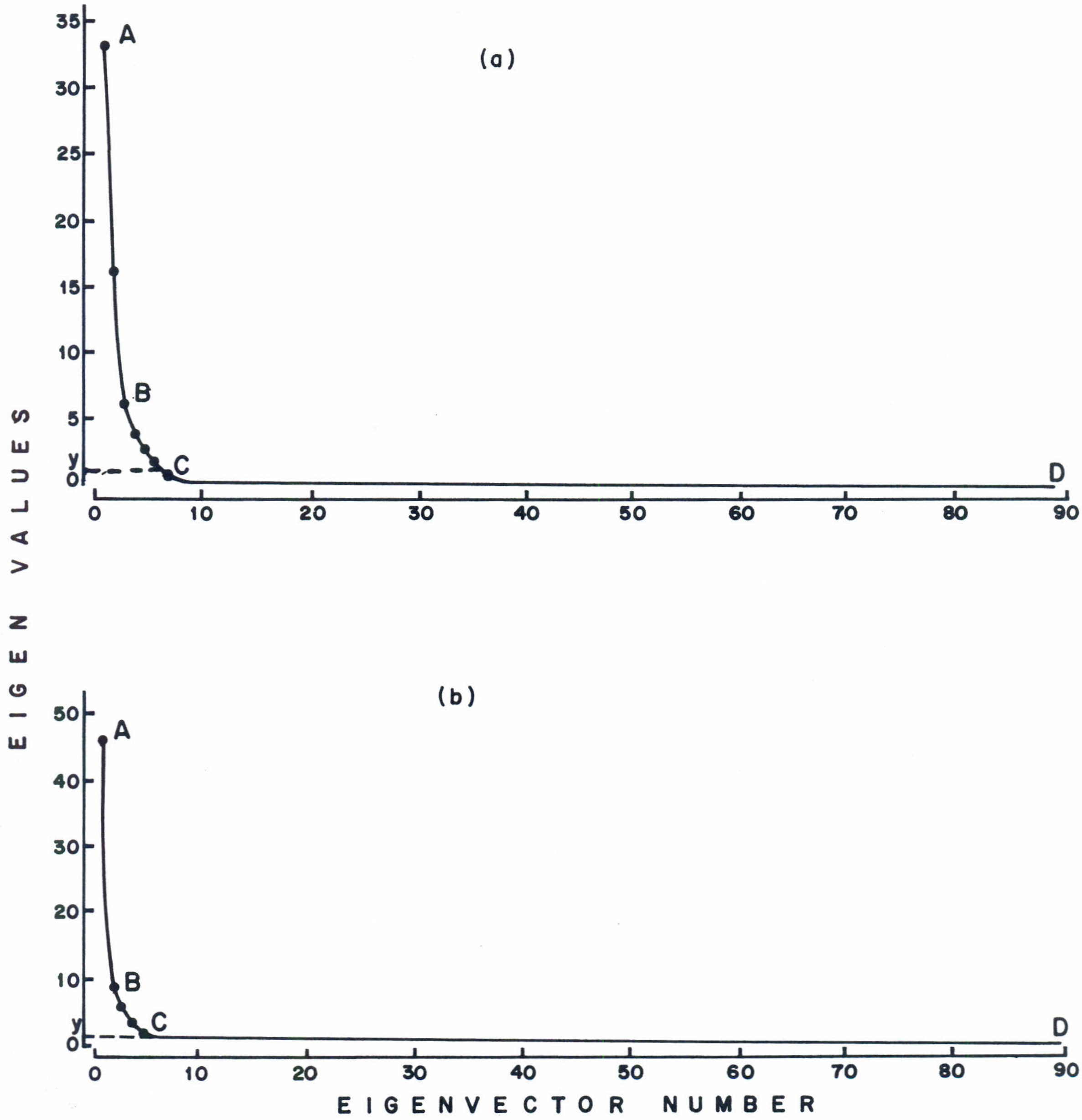


Figure 3. Scree plot of the eigenvalues for (a) summer and (b) autumn rainfall, 1922–1983

magnitudes over most of the region. Interannual rainfall variance is generally larger during the autumn season than in spring, especially to the east of the central highlands. During the months of December–February, the overhead sun is located in the southern hemisphere. The ITCZ-related rainfall systems are now restricted over southern parts of Tanzania during most of this season. Other wet areas are concentrated around the Indian Ocean and the large inland lakes. Similar characteristics can be observed from the spatial patterns of the three dominant eigenvectors for the season (Figure 7).

While RPCA gave good spatial description of seasonal rainfall characteristics over most of East Africa, it was noted that the seasonal rainfall characteristics around Lake Victoria could not be adequately described

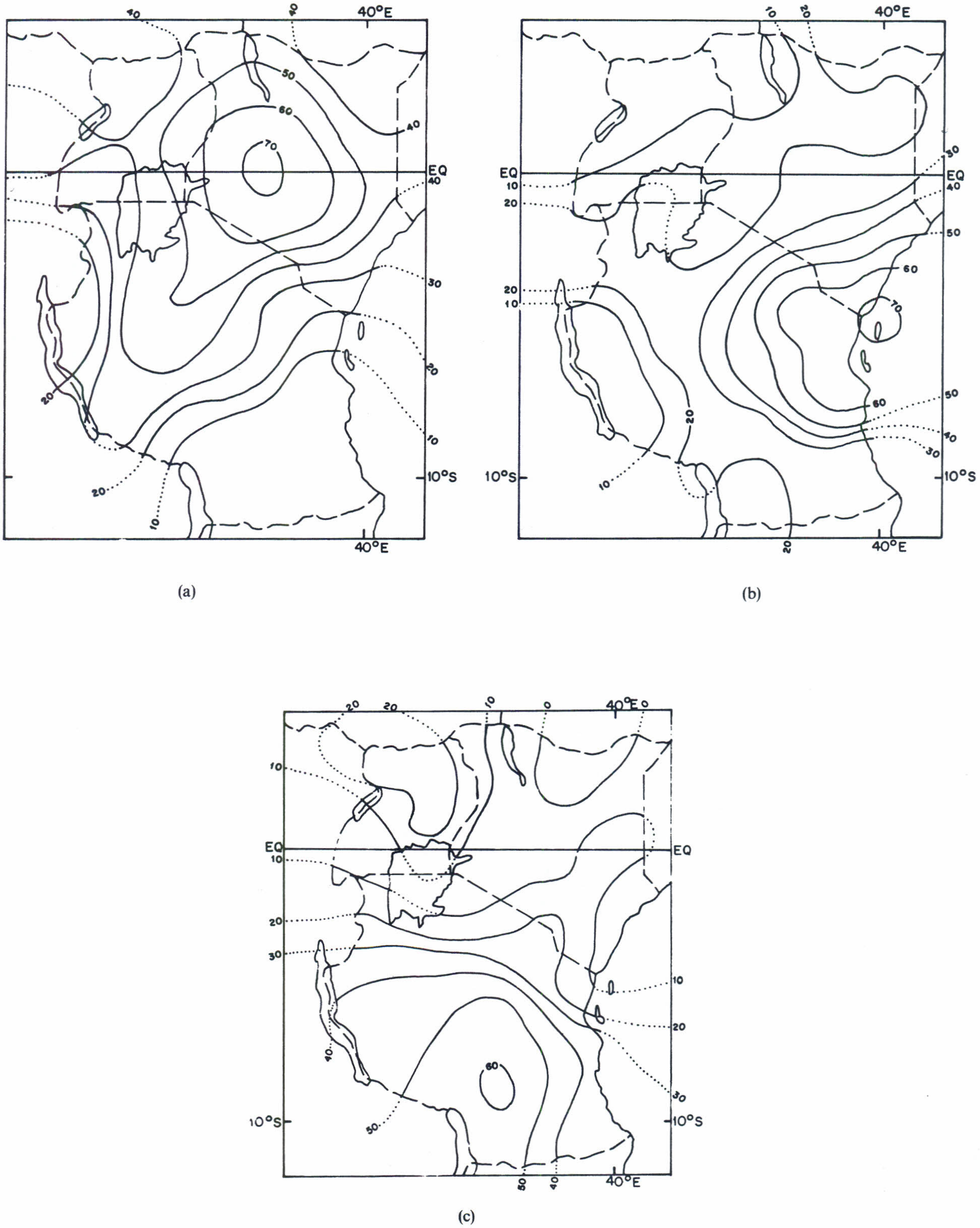
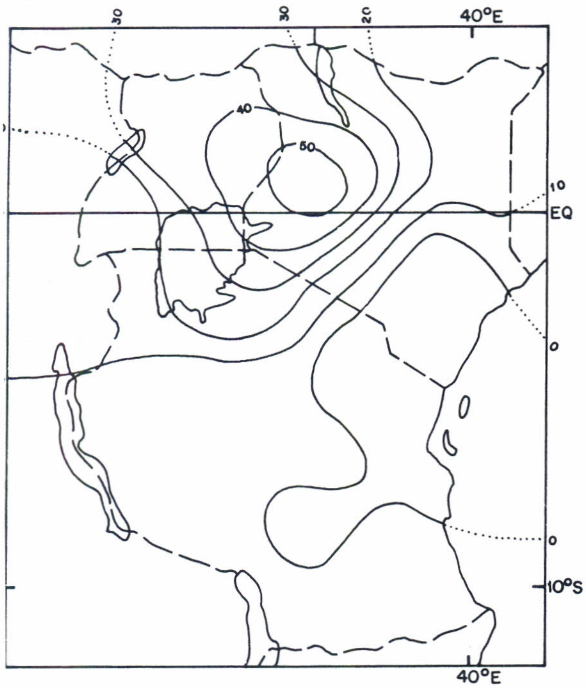
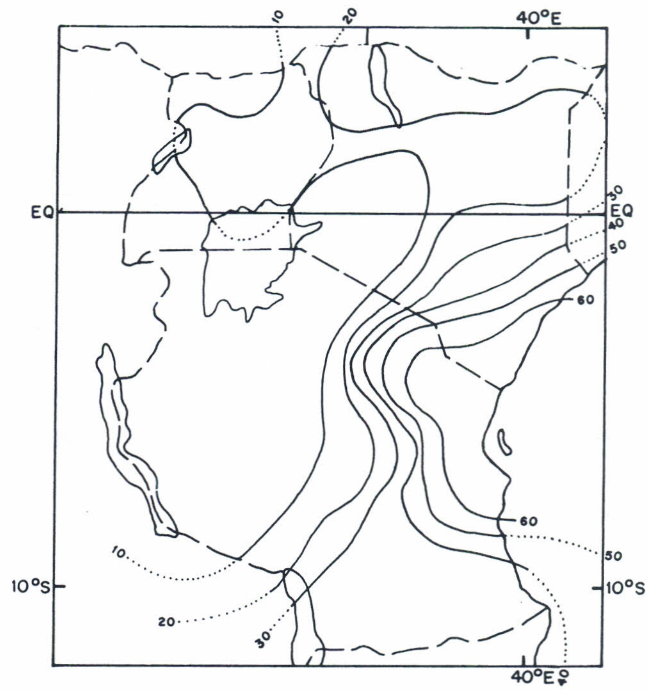


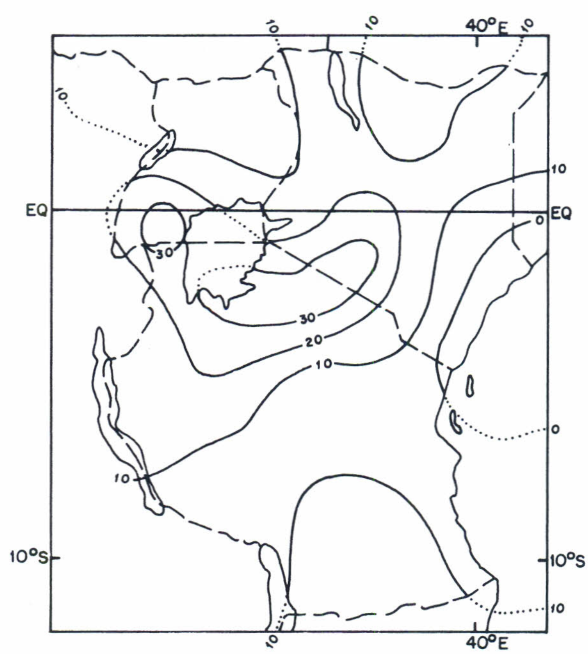
Figure 4. (a) First, (b) second and (c) third eigenvectors during northern spring seasons



(a)



(b)



(c)

Figure 5. Spatial patterns of the rotated (a) first, (b) second, and (c) third eigenvectors during northern summer season

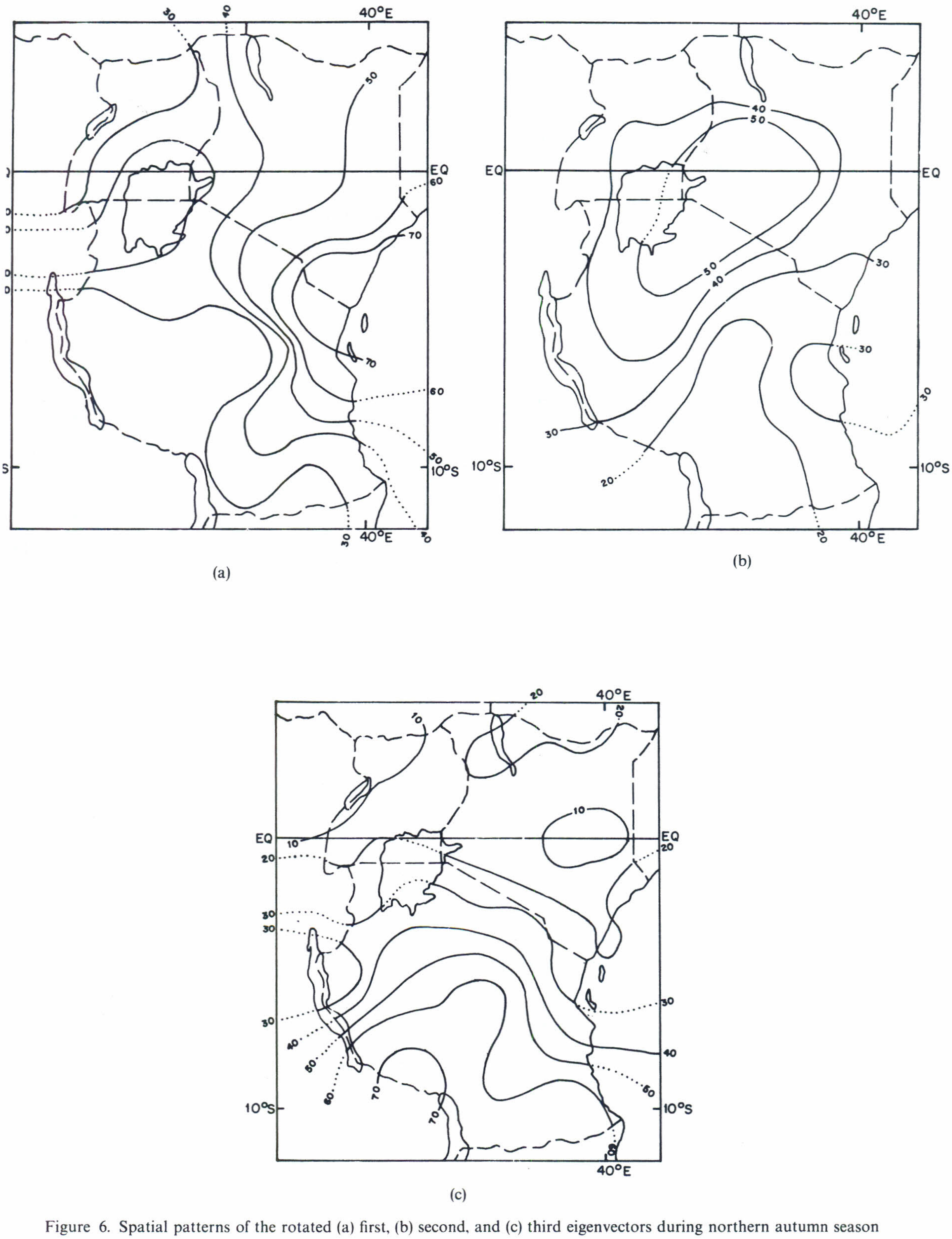


Figure 6. Spatial patterns of the rotated (a) first, (b) second, and (c) third eigenvectors during northern autumn season

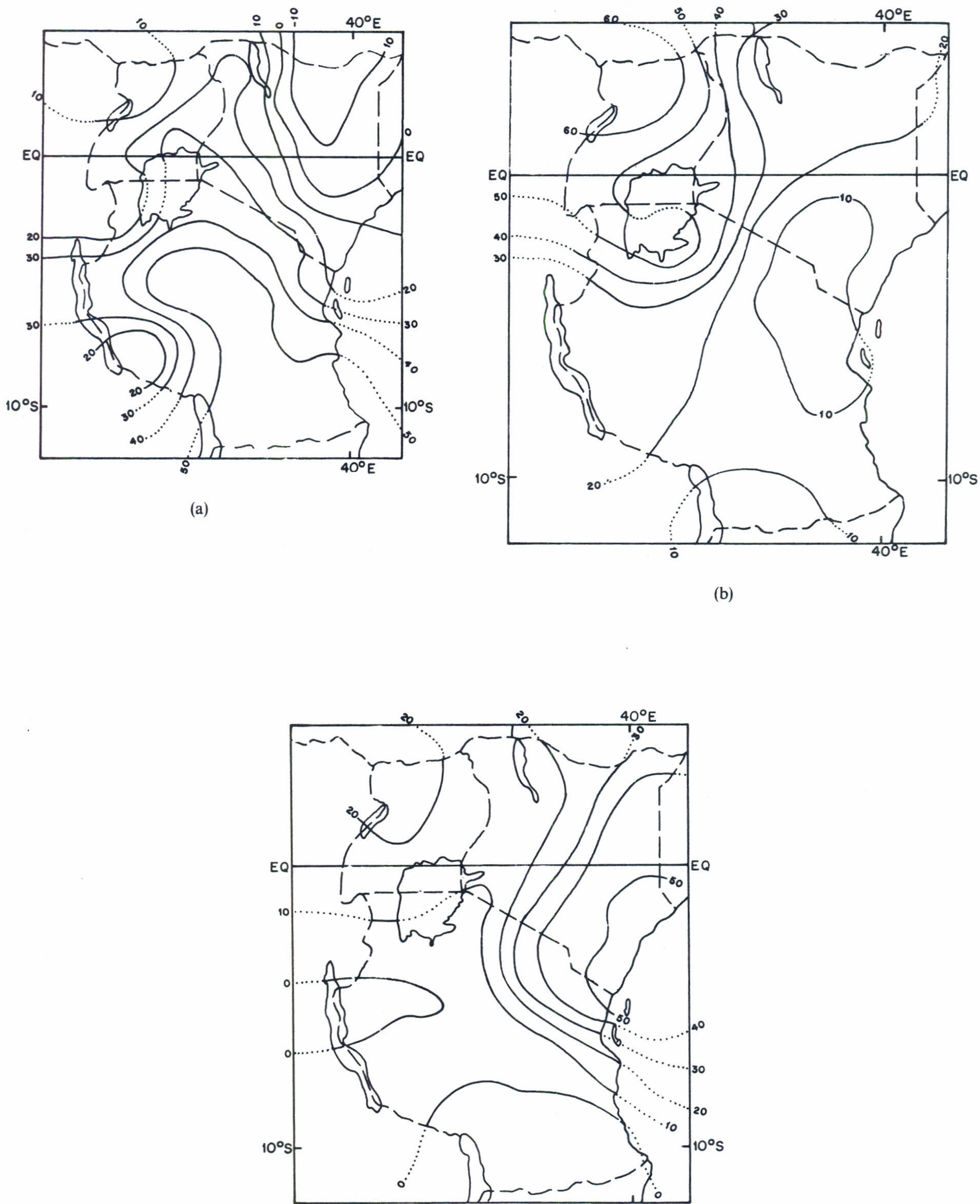


Figure 7. Spatial patterns of the rotated (a) first, (b) second, and (c) third eigenvectors during the northern winter season

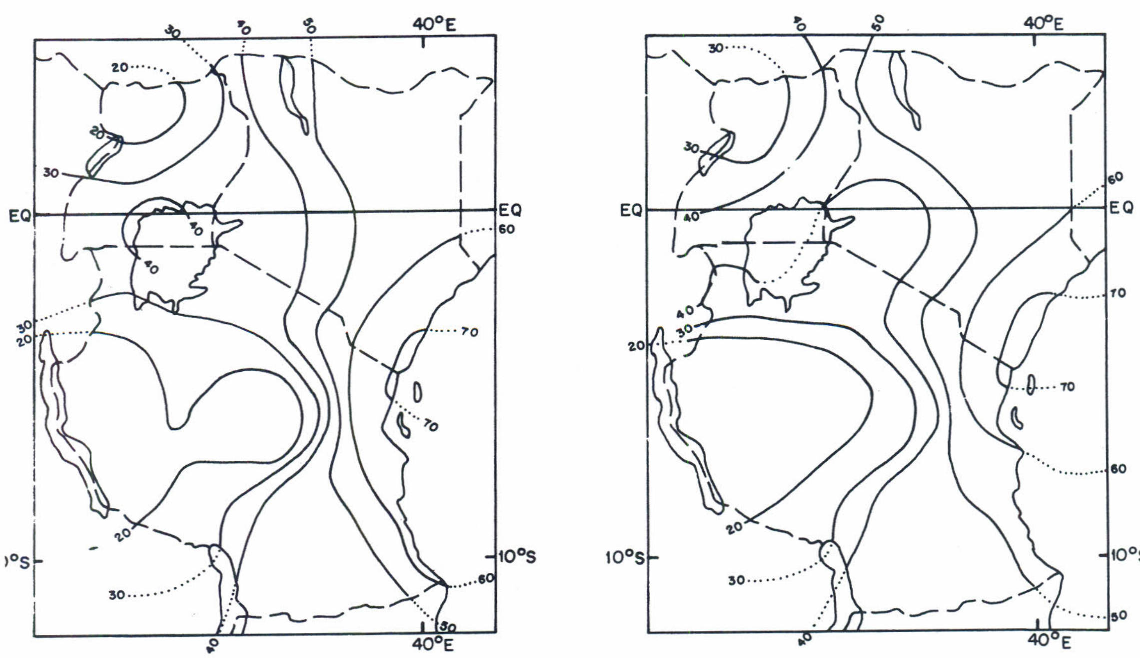
/ith the network of the rainfall stations used. Lake Victoria is one of the largest freshwater lakes in the world, nd it has a very strong circulation of its own (Asnani and Kinuthia, 1979). No single eigenvector dominated ver the lāke region in any given season. The influence of the Indian Ocean was, however, adequately ɜpresented by a single eigenvector throughout all seasons (Figures 4b, 5b, 6a, and 7c).

Results from stability tests indicated that the first three eigenvectors were generally stable, especially during ıe major rainfall seasons (spring and autumn). Some indications on the stability of the RPCA patterns are resented in Figures 8 and 9. Figure 8 gives the spatial patterns of the first rotated autumn eigenvector ›adings for the various groups of rainfall records used under the stability tests. Only the patterns of the first utumn eigenvectors were presented here due to the large number of maps involved.

It is evident from Figures 8 and 6a that the patterns of the first autumn eigenvector loadings were quite ose for the periods 1922–1983(v), 1922–1952(iii) and 1953–1983(iv), together with those derived from the dd(i) and even(ii) observations. In all cases, the first autumn eigenvector dominated over the coastal areas. It ıould, however, be noted from Figures 8c and d that the degree of persistence was relatively lower for the odd ıd even records, as can be seen from the relatively lower values of the loadings over the coastal region.

In Figure 9, the stability of the autumn rainfall records are further presented in terms of inter-station ›rrelations. The central stations used in the plotting of the inter-station correlations given in Figure 9 were ar-Es-Salaam, Nairobi, and Songea. These stations are located within the coastal region, eastern highland ıd southern highland of Tanzania, respectively. The high degree of spatial coherence in the seasonal rainfall ıaracteristics over the regions dominated by the individual eigenvectors are quite evident from Figures 4–9. may therefore be concluded from these results that the patterns of the first three eigenvectors were imatologically stable and will remain stable if the future rainfall records are homogeneous and stationary ımples from the same statistical distribution with constant mean and variance).

Regional classification based on the seasonal characteristics of the dominant eigenvectors are given in gure 10a. These patterns were further confirmed using the vector plots of the various stations on to the ctor spaces of the dominant eigenvectors. The loadings of the station on the two eigenvectors were used to termine the location of the station on these vector spaces.



(a) (b)

ıre 8. Autumn patterns of the first rotated eigenvector for (a) 1922–1952, (b) 1953–1983, (c) odd years, (d) even years, and (e) monthly (November) for the record 1922–1983

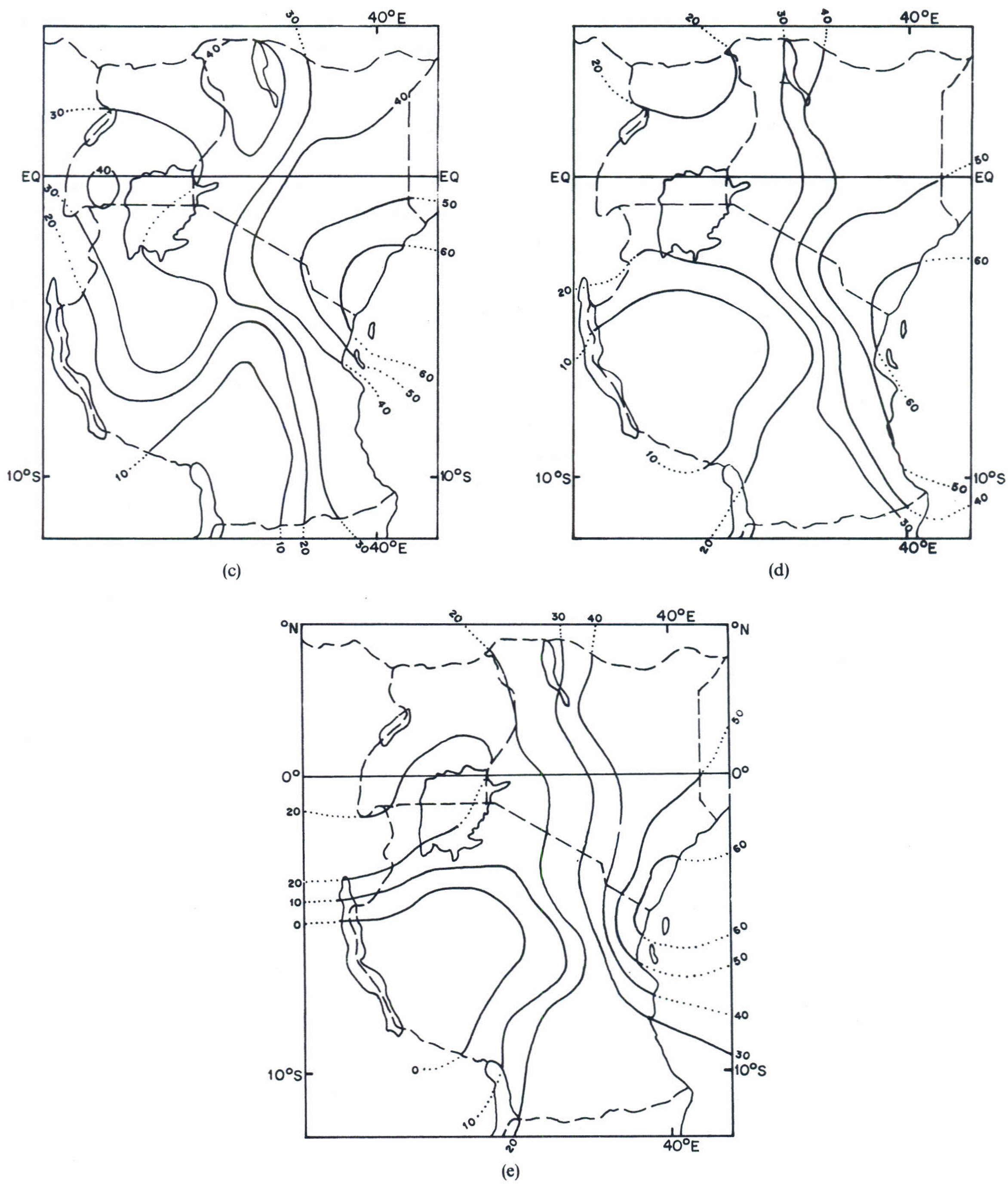


Figure 8 (*continued*)

When the 90 stations were plotted on to the vector spaces of the first two eigenvectors, two distinct clusters of stations were evident from the two groups of stations which had large single loadings on the first and second eigenvectors. Other clusters were also discernible from other pairs of the dominant eigenvectors. The seasonal patterns of the station clusters during the four seasons of the year were considered in the final classification of the stations into homogeneous categories.

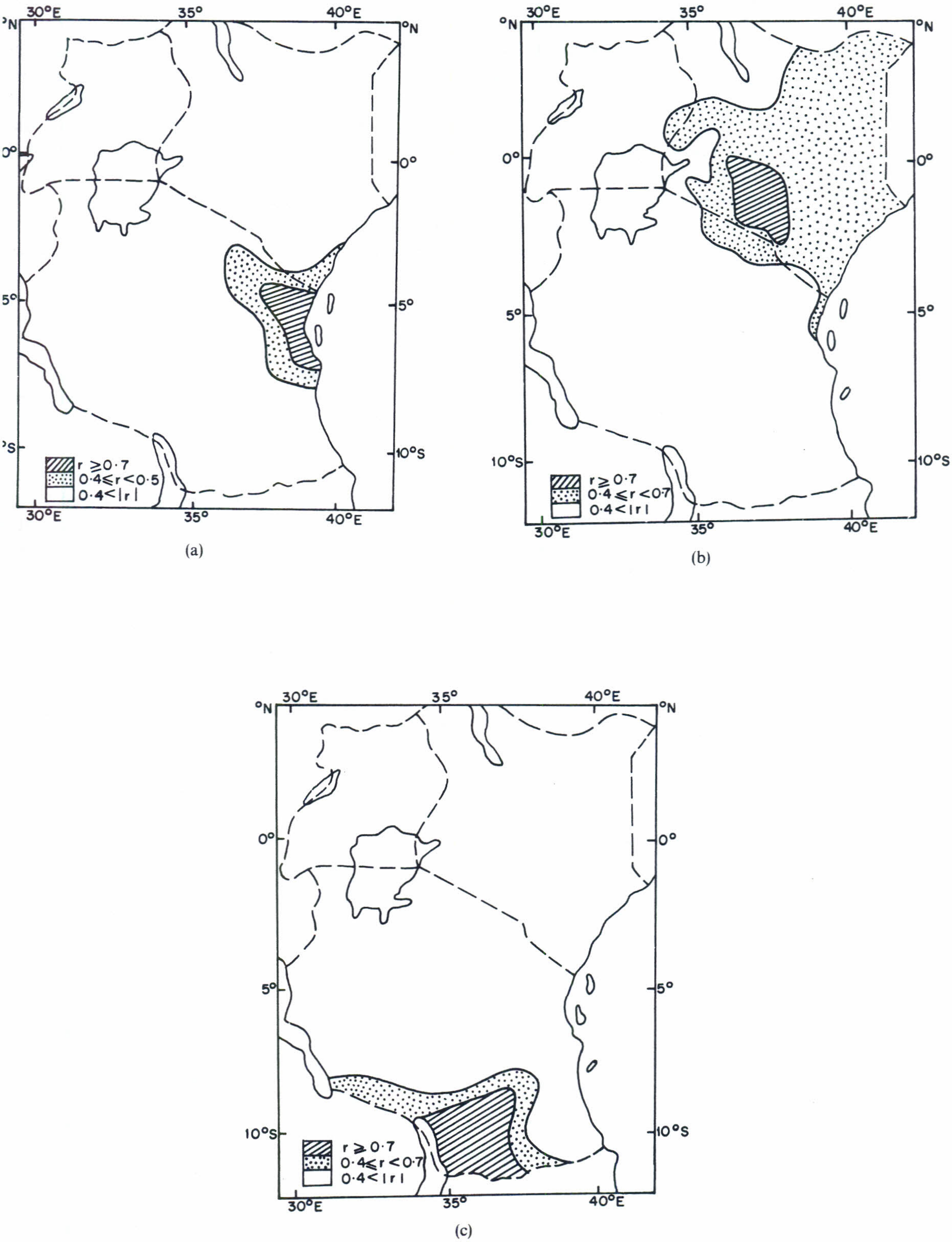


Figure 9. Spatial patterns of the inter-station correlations with reference stations (a) Dar-Es-Salaam, (b) Nairobi, and (c) Songea

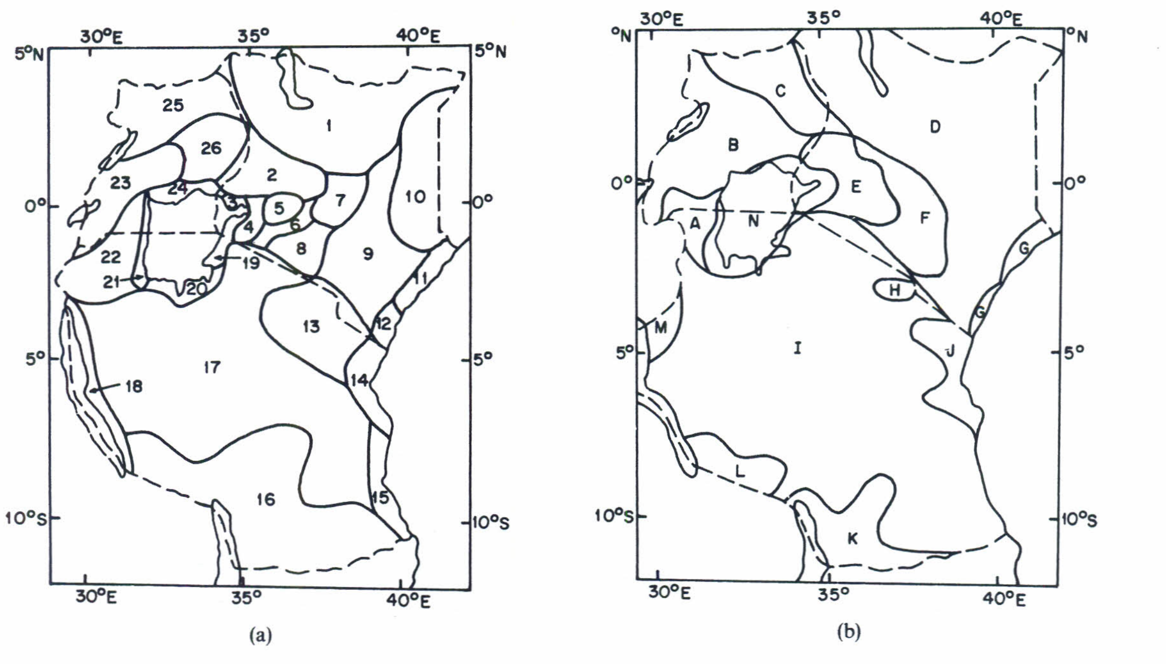
It was evident from Figure 10a and b that the seasonal clusters of the 90 stations were significantly different from those which had been derived from the annual records. This is dominantly due to the high degree of seasonality in the rainfall characteristics over most parts of East Africa (Figure 1). The seasonal clusters look more realistic compared to the climatology of the regions (Pant and Rwandusya, 1971), apart from some regions around Lake Victoria. The relatively poor classification around Lake Victoria may be attributed to poor data coverage around the lake. Large variations in the rainfall characteristics around the lake have been noted by Asnani and Kinuthia (1979), among many others. The regional classification around the lake can be improved by the inclusion of more rainfall stations.

It is evident from the regional classification that the ITCZ, monsoonal winds, westerly moisture incursions, large water bodies, topography and other rain-dependent factors had significant influence in the seasonal patterns of the inter-station correlations which were used in RPCA. The seasonal influence of some of these factors are shown in Figures 1 and 9.

MAP CLUSTERS

Under this section the temporal correlation matrices were subjected to RPCA in an attempt to examine similarities between the map patterns. When the temporal correlation matrix for the individual seasons were subjected to RPCA using the orthogonal varimax rotations, two eigenvectors were outstanding throughout the four seasons. As many as seven eigenvectors, however, had eigenvalues greater than one in some seasons, but the separation between these eigenvalues was relatively quite small compared to the separation between the first two eigenvectors. A maximum of up to seven eigenvectors was therefore retained for the varimax rotations. The first two dominant eigenvectors accounted for a maximum of 58% of the total variance of the map patterns, while all seven eigenvectors with eigenvalues greater than unity explained a maximum of 80% of the total variance of the maps.

Some of the map patterns which were clustered together using the characteristics of the loadings of the first two eigenvectors derived from the temporal correlation matrices are given in Tables I and II for the two major



(a) (b)

Figure 10. (a) Homogeneous divisions of the 90 stations derived from the seasonal RPCA patterns, and (b) homogeneous divisions with the annual records (Ogallo, 1980)

Table. I. Spring seasons clustered together

'et years	1923	1926	1932	1937	1940	1942	1951	1963, 1964	1967	1970	1978
.me*	1·66	1·37	1·37	0·60	1·02	0·72	1·51	1·90 0·76	1·73	1·80	0·92
ɜg. anom†	2·83	1·81	0·70	2·52	1·73	2·50	2·73	3·33 0·42	2·23	2·11	1·72

ry years	1928	1933	1950	1953	1955	1965	1969	1976	1979
me	−0·98	−1·53	−0·46	−1·04	−1·11	−0·53	−0·55	−0·18	−1·67
:g. anom†	−1·44	−3·31	−1·92	−1·63	−2·30	−1·83	−1·31	−2·34	−1·50

ʾrincipal component scores for the time series of the first rotated eigenvector.
ɩormalized regional rainfall anomalies for region 2(A) in figure 10.

Table II. Autumn seasons clustered together

et years	1925	1926	1937	1944	1946	1951	1953	1957	1965	1967	1972	1977
:ne	1·46	1·21	0·83	0·43 0·32	1·16	1·29	1·32	1·27	1·00	2·58	1·29	2·17
g. anom†	2·21	1·83	1·44	3·31 1·32	4·33	2·03	1·90	1·70	1·53	4·35	4·03	4·61

'ears	1922	1927	1928	1934	1936	1943	1950	1955 1956	1958 1959	1962	1964	1970	1974 1975	1983
	−1·12	−1·42	−0·82	−0·76	−0·14	0·76	−0·81	−1·23 −0·40	−1·07 −1·41	−1·66	−0·88	−0·94	−1·09 −1·55	−1·32
ınom†	−1·57	−2·13	−0·89	−2·03	−1·18	−1·33	−0·47	−2·43 −1·12	−2·58 −2·50	−2·23	−2·29	−1·87	−1·90 −1·63	−1·58

ons 11 and 12 (Figure 10).

nfall seasons. Examination of the patterns of the corresponding time coefficients derived from S-mode ʾCA solutions, the areal rainfall anomalies, the other climatologically derived rainfall-anomaly indices licated that the maps clustered together using the first two dominant eigenvectors were representative of : dominant periods of the positive and negative rainfall anomalies which have been observed in East Africa ring the period 1922–1983.

Γhe time coefficients of the S-mode first eigenvector and the representative areally averaged rainfall ɔmalies are also included in Tables I and II for the spring and autumn seasons. Figures 4a and 6a indicate ıt the first eigenvector for the spring and autumn seasons dominated over the inland and coastal regions, pectively. It is evident from the two tables that the two clusters represent map patterns of some identical t and dry episodes. These are confirmed from the values of the regionally averaged rainfall anomalies given :he two tables. The areal regional anomalies for regions A and B were obtained by arithmetic averaging of normalized monthly rainfall anomalies using all stations enclosed within the individual regions. The first ɜnvector for the spring and autumn seasons dominated over regions A and B, respectively (Figures 4a and . These determined the use of regions A and B in Tables I and II. The regional rainfall anomalies given in ɔles I and II were expressed in terms of monthly cumulative anomalies during the three months of the pective seasons.

₹ainfall anomaly maps for some of the periods clustered together in Tables I and II are given in Figure .–f. Similarities in the map patterns for the periods clustered together are quite evident from these maps.

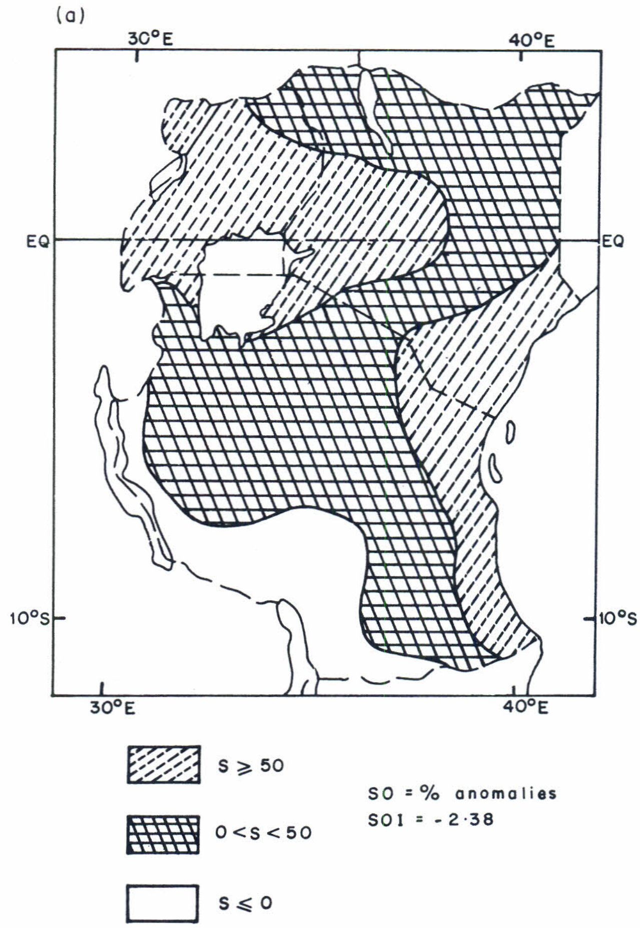
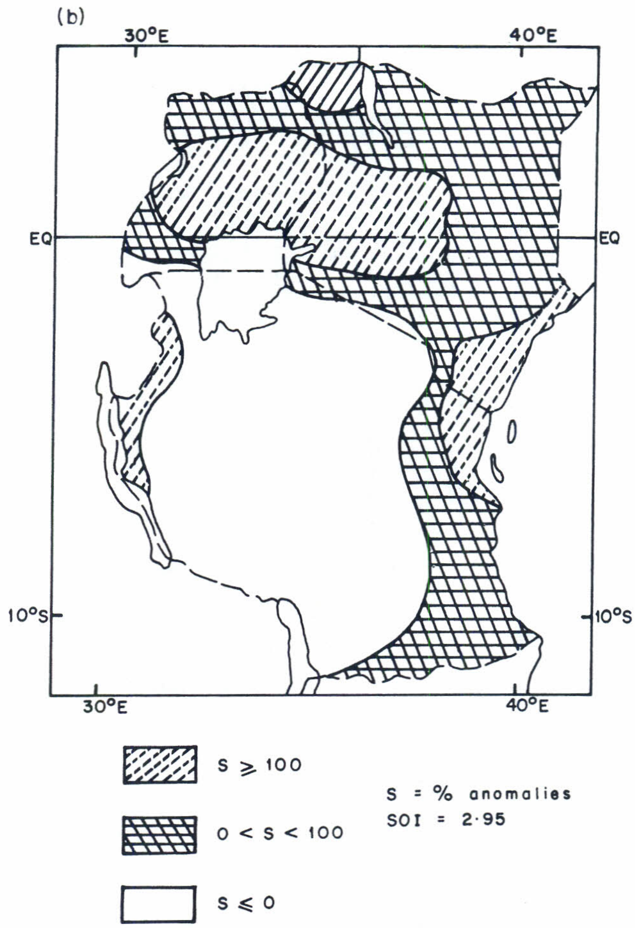


Figure 11. Examples of the map patterns for some of the periods clustered together
11(a) Rainfall anomalies, autumn 1977

Distinct spatial patterns can be connected to the individual clusters. Figure 11 (a) and (b) indicates large positive anomalies over the coastal areas, western Kenya and most of Uganda. In Figure 11 (c) and (d), most parts of Kenya and Tanzania recorded negative anomalies. Peak negative anomalies were concentrated along the coastal regions. Similar tendencies were evident from the other maps within the same clusters.

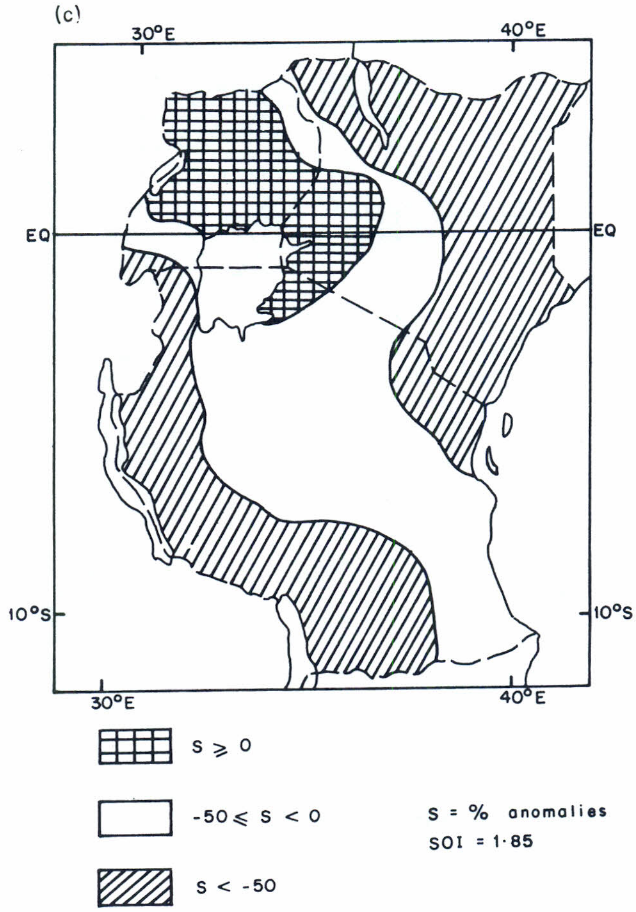
Historical records show that not all wet and dry years were included in the clusters given in Tables I and II, indicating that the first two eigenvectors could not effectively classify all of the 62 maps used during the individual seasons. Some of the 62 map patterns were noted to be significantly associated with higher eigenvectors. These could be due to large spatial anomalies observed in the seasonal rainfall characteristics during some years. Some good examples include 1949 and 1961 (Figure 11f and e) when abnormally dry and wet conditions, respectively, extended over most of the region. Such extreme spatial anomalies come out as outliers from the RPCA solutions derived from the temporal correlation matrices. Such episodes individually clustered on to eigenvector(s) which were not common to the other maps.

It was observed from the list of the warm episodes by Rasmusson (1984) that some of the rainfall anomalies listed in Tables I and II occurred during the warm and cold episodes over the eastern Pacific Ocean. Since El Niño indices were not available, the closely related Southern Oscillation indices (SOI) were examined for the years clustered together. The SOI used were obtained from the Climate Analysis Center (Washington). The SOI are given in Figure 11 for some of the clustered periods.



11(b) Rainfall anomalies, autumn 1965

Table III gives a summary of the conditional probabilities associated with the warm and cold episodes over : eastern Pacific Ocean and the delineated map patterns during the various seasons. The maximum nditional probabilities are centred around the northern summer and autumn seasons. It was, however, dent from Rasmusson (1984) that not all warm and cold episodes were included in Tables I and II. This uld be due to large variations in the factors which have been associated with the rainfall anomalies over the ;ion. Such factors range from synoptic to regionally induced meso-scale systems. The factors controlling isonal rainfall over East Africa include the position, orientation, and intensity of the ITCZ, subtropical ticyclones, Indian Ocean cyclones, monsoonal winds, sea-surface temperatures, the jet streams, and several iers including regional factors like topography and large water bodies. Some links between these systems d the El Niño/Southern Oscillation (ENSO) episodes have been discussed by Cadet and Diehl (1984), det (1985), Wright (1985), and Ogallo (1987). Cadet (1985) noted the strengthening/weakening of the itheasterly monsoon wind systems during the warm/cold ENSO episodes. These monsoonal winds are the jor source of moisture, especially along the coast and east of the Central Highlands. The large ;ative/positive rainfall anomalies observed over these areas may be closely linked to the akening/strengthening of easterly and south-easterly components of the monsoonal wind systems over the stern part of the Indian Ocean, together with other related phenomena.



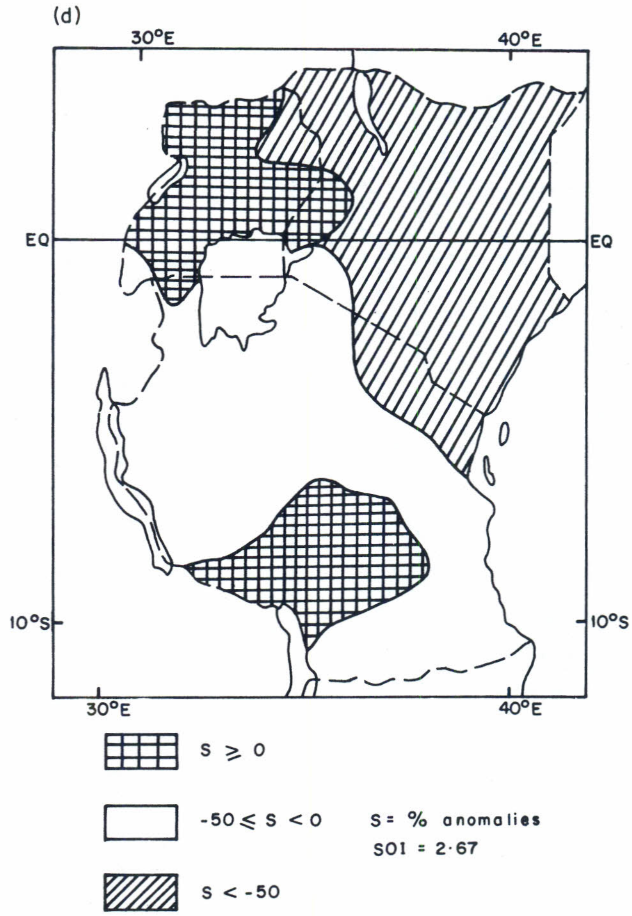
11(c) Rainfall anomalies, autumn 1964

Table III. Conditional probabilities associated with the Southern Oscillation and El Niño events: D = dry; W = wet; LSI = below normal SOI; HSI = above normal SOI (Normalized Tahiti–Darwin sea-level pressure); P(W/LSI) = probability of above normal rainfall given that seasonal SOI is below normal, etc.

Season	Largest	Probability ($\times$ 100)
Winter	P(W/LSI) = 31	P(D/HSI) = 38
Spring	P(W/LSI) = 40	P(D/HSI) = 35
Summer	P(W/HSI) = 53	P(D/LSI) = 43
Autumn	P(W/LSI) = 70	P(D/HSI) = 63

CONCLUSIONS

By subjecting the spatial and temporal correlation matrices to RPCA using orthogonal varimax rotations, some spatial and temporal characteristics of the East African seasonal rainfall have been determined.

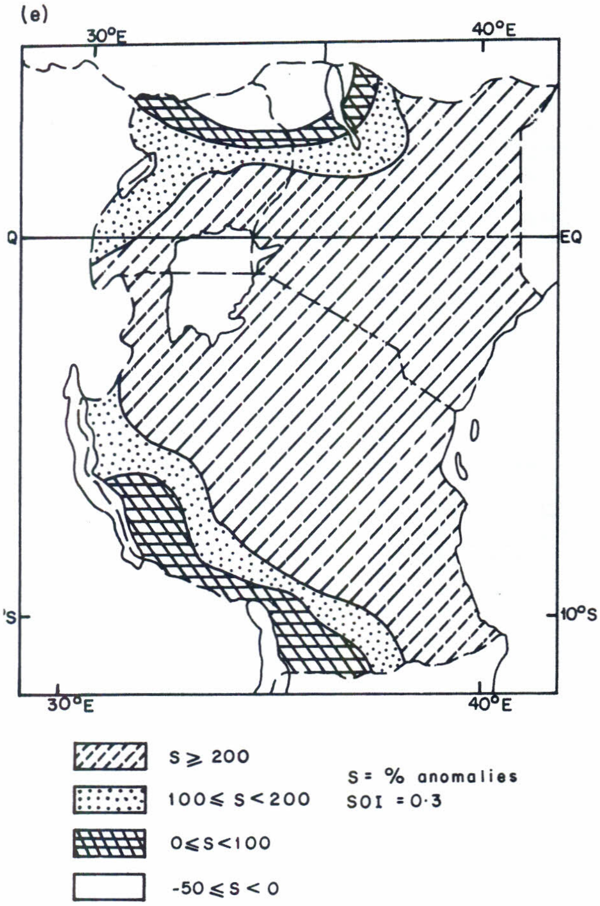


11(d) Rainfall anomalies, autumn 1970

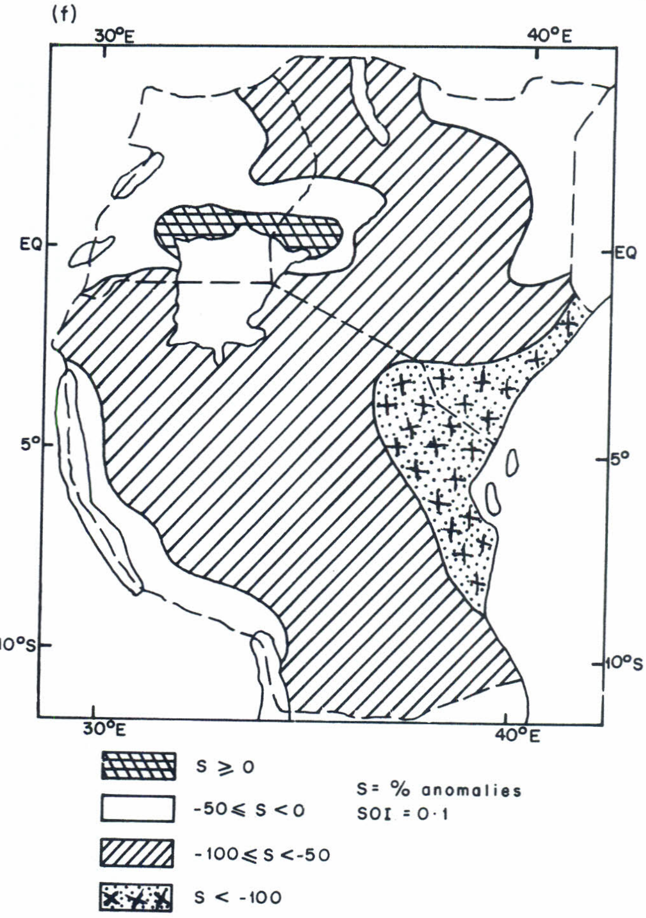
The results from the S-mode solutions indicated significant seasonal shifts in the patterns of the dominant ;genvectors which closely resembled the seasonal migration patterns of the East African rainfall belts duced by the ITCZ systems. The influences of the large water bodies especially Lake Victoria and the Indian cean were outstanding throughout the year by producing two dominating significant eigenvectors over ese regions throughout the year. Twenty-six regional groups were delineated from the seasonal character-ics of the major eigenvectors within the four seasons of the year. The regional divisions were quite close to e climatological expectations over many areas, apart from some areas near the large inland lakes.

It was also observed from the study that the RPCA solutions derived from the temporal correlation atrices accounted for a maximum of 80% of the total variance of the map patterns. The first two ;envectors, which generally represented the dominant wet and dry episodes, accounted for a maximum of % of the variance.

It was also noted that some of the map patterns could be associated with the warm and cold episodes over : eastern Pacific. Such links were, however, highly seasonal with a maximum conditional probability of out 0·7 during the autumn season. It would be of great interest to examine whether solutions derived from lique rotations would give better representation of the spatial and temporal patterns of the East African ısonal rainfall.



11(e) Rainfall anomalies, autumn 1961



11(f) Rainfall anomalies, autumn 1949

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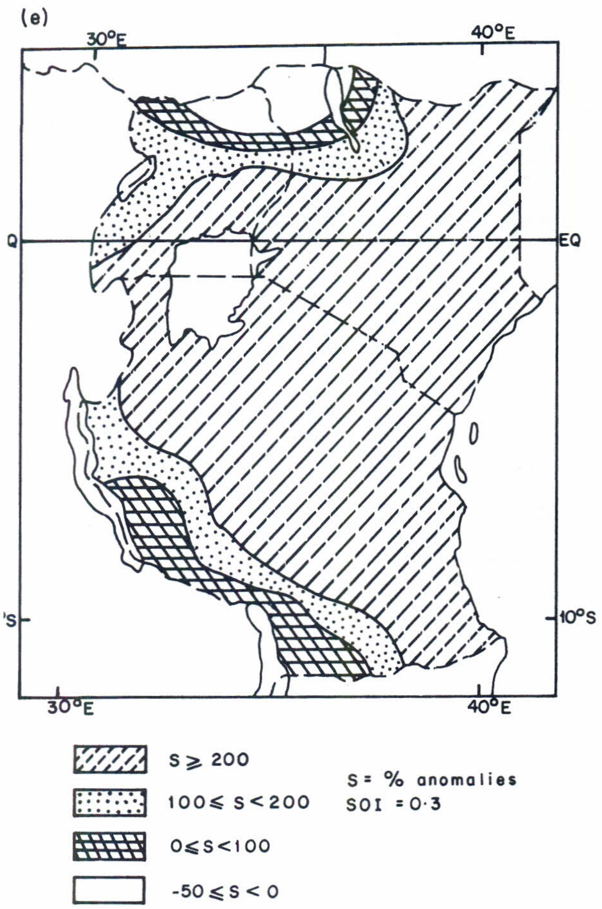
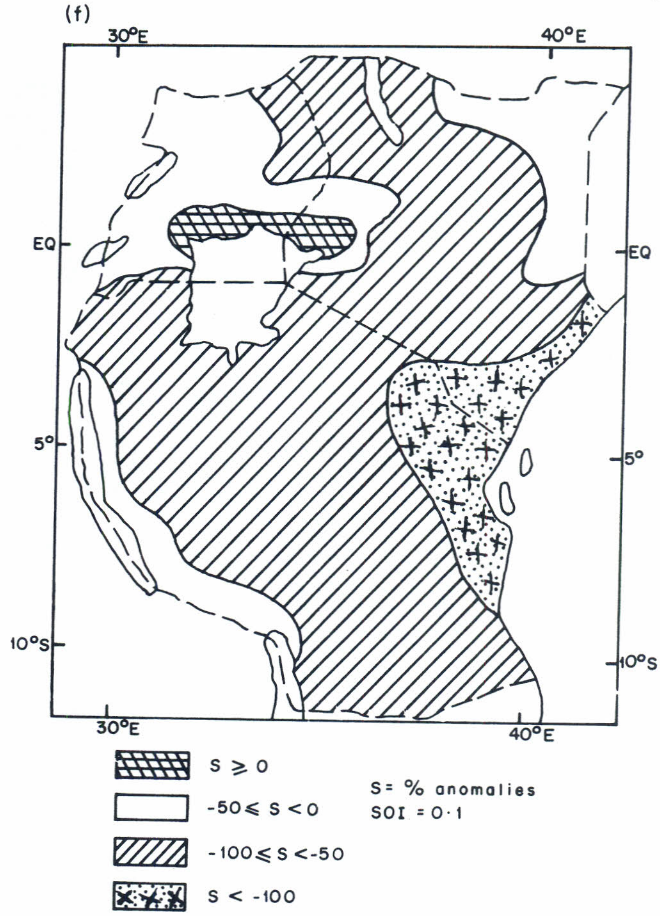


11(e) Rainfall anomalies, autumn 1961



11(f) Rainfall anomalies, autumn 1949

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