

INTERANNUAL VARIATIONS OF  
TROPICAL PRECIPITATION PATTERNS

by

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Submitted to the Department of Meteorology, 12 February 1980, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Seasonal and annual precipitation anomalies, normalized with respect to the standard deviations are computed for stations between 30°S and 30°N. It is established that the annual anomalies are normally distributed. Spatially averaged anomalies are computed for various regions and their representativeness confirmed. Correlations between the annual average normalized anomalies of the various regions are computed.

The results show that simultaneous variations of the zonally oriented circulations of the tropical troposphere occur which are in phase with variations of the Southern Oscillation. The concurrent variations of the intensity of the zonal cells account for most of the observed interannual rainfall variations. Interannual variations in the intensity and position of the meridional Hadley cell seem to play only a minor role.

Thesis Supervisor: Reginald E. Newell  
Title: Professor of Meteorology

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## I. Introduction

In the early 1970's, a severe and prolonged drought struck the region of Africa lying at the southern edge of the Sahara Desert. The cost in human suffering and animal life was enormous. Herds which had been built up during the previous years of relatively abundant rainfall could find little to feed on and the resulting food shortage focused international attention on the area (Krueger and Winston, 1975).

Nicholson (1979) presented a time series of rainfall anomalies for the region which agrees in its major features with those of other investigators. It shows several periods of drought having occurred prior to 1972, most recently around 1940. The 1950's showed above normal precipitation while the 1960's were close to normal with a gradual decline setting in around 1965 culminating in the extremely dry years of 1972 and 1973.

The causes of these large and important interannual variations in the Subsaharan rainfall record have as yet not been determined although several theories have been suggested. Winstanley (1973) claimed that from 1960 onward the major climatic zones of the Northern Hemisphere have been shifting southward resulting in increasing winter rainfall in the Mediterranean region and decreasing summer rains just south of the Sahara. He even went so far as to predict rainfall trends to the year 2030 based on past information. Bunting and his co-workers (Bunting, et. al., 1976) refuted the statistical basis of Winstanley's claims and showed that there are no statistically significant trends in the rainfall records of subsaharan Africa. Nicholson (personal communication, 1980) has analyzed precipitation data which shows that the droughts and floods are actually due to the expansion and contraction of the Sahara

in both northerly and southerly directions and that during wet years the ITCZ seems to be farther north than normal in the late summer while in the dry years it is close to its normal position but less intense. The winter rainfall in northern Africa does not increase when there is drought to the south as Winstanley's hypothesis would require. In addition, Tanaka, et.al. (1975) analyzed 700 mb heights around 50°N for January and August for the years 1961-73 and found no clear trends either, thus further refuting Winstanley's claims.

Kraus (1977a) noted that many subtropical stations all over the world were reporting below normal summer precipitation in 1940 and 1972 and suggested that such droughts were caused by a decrease of the pole to equator temperature gradient in the winter hemisphere. This, he reasoned, would lower the amount of heat transported across the equator, thereby requiring a reduced excursion of the ITCZ into the summer hemisphere. He presented some temperature data to support his hypothesis and developed a simple model to explain the dynamics of the mechanism (Kraus, 1977b).

Charney (1975) made some theoretical calculations which suggest that the apparent southward movement of the Sahara in the early 1970's could actually have been due to the anthropogenic increases in the surface albedo of the region just south of the desert due to over-grazing. His results have been confirmed by later numerical studies (Charney, et. al., 1977) which show that, despite the decreased cloudiness associated with the increased surface albedo, the net radiation absorbed by the ground decreases and this results in decreased precipitation. The lower precipitation in turn inhibits plant growth thereby further increasing the surface albedo. While it is not obvious that this



biogeophysical positive feedback mechanism is the most important one producing droughts in Subsaharan Africa, merely the fact that it exists is cause for concern for the future of this region.

The northeastern corner of Brazil is another region of the tropics which is subject to periods of severe drought (Trewartha, 1961). The region is effected at various times of the year by disturbances of different characteristics and the mechanism of drought and flood are not well understood (Kousky, 1979). Hastenrath and Heller (1977) have stratified wind and temperature data for the tropical Atlantic according to dry and wet years in northeastern Brazil. Their data shows that dry years occur when the South Atlantic high expands equatorward and the north Atlantic high retracts poleward, thus keeping the ITCZ further north than normal.

Hastenrath and Heller also found that rainfall in northeastern Brazil is negatively correlated with the sea surface temperature (SST) off of the Ecuador/Peru coast. The occurrence of anomalously warm water along the coast of Peru is known as an El Niño event. During such an event, the flow of nutrients normally brought up by cold upwelling waters is cut off resulting in drastically reduced fish catches. Since the Peruvian economy is heavily dependent on the fishing industry, such occurrences can be disastrous (Wyrтки, 1974).

The El Niño phenomenon is intimately associated with another important interannual variation in the tropics: the Southern Oscillation. The Southern Oscillation was first described by Walker (1924) as an aperiodic shifting of mass in the lower troposphere between the eastern South Pacific and western South Pacific - Indonesia region. Since Walker's discovery, a tremendous amount of observational and theoretical

work has been done concerning this intriguing large-scale phenomenon. Indices of sea level pressure values at various stations have been developed by numerous investigators and extensive areas of significant correlations of wind speed and direction, surface pressure, temperature and precipitation in the tropics have been found (see Julian and Chervin, 1978 for an excellent review).

The counterpart of the Southern Oscillation in the wind system is known as the Walker Circulation (Bjerknes, 1969). This thermally direct, zonally oriented cell has its ascending branch normally located over the eastern Pacific - Indian Ocean region while its descending branch is located over the cold water regions in the eastern South Pacific, the South American coast and out along the equator to about 170°W (Bjerknes, 1969). In the phase of the Southern Oscillation in which pressures over the eastern South Pacific are anomalously high and those over the western South Pacific - Indian Ocean region are anomalously low, the cell is driven more strongly than usual and we observe increased precipitation in the region of rising motion and decreased precipitation in areas where anomalous sinking motion is occurring (Walker and Bliss, 1932). Such rainfall anomalies are most marked over the central equatorial Pacific islands. Leighly (1933) noted a strong correlation of rainfall on the Marquesas Islands (9-10°S, 139-140°W) with the Southern Oscillation as measured by the difference in sea level pressure between Apia, Samoa and Port Darwin, Australia (see Julian and Chervin, 1978).

More recently, Bjerknes (1969) has noted the correlation of rainfall at Canton Island (2°48'S, 171°43'W) with the surrounding SST's and the Southern Oscillation. Times of abnormally heavy rains coincide

with abnormally low pressure in the eastern South Pacific and warm waters off the islands. Murakami (1975) has done a study of tropical cloudiness using satellite data which shows that cloudiness anomalies over the tropical eastern North and South Pacific are negatively correlated with the anomalies over western North and South Pacific, respectively. This lends further support to the existence of the Walker Circulation.

Kidson (1975), drawing on earlier works, has postulated the existence of similar circulations in zonal planes in the Atlantic sector. He performed an empirical orthogonal function (EOF) analysis of the surface pressure, temperature and rainfall in the tropics and showed that the first component of each does a good job of representing the Southern Oscillation patterns of these variables as described in previous investigations by Walker and Bliss (1932, 1937) and Berlage (1966). This indicates that the Southern Oscillation is a preferred mode of the tropical atmosphere (i.e. it explains the largest percent of the variance of sea level pressure, temperature and rainfall which is attributable to any one predictor). Significantly, Kidson's patterns also show a center of action over northern Brazil which is in phase with the Indian Ocean. This result lends support to the hypothesis that a thermally direct cell, with rising motion over the Atlantic, exists and varies in phase with the Walker Circulation. Calculation of atmospheric heating rates by Krueger (1970) and mean vertical motion fields by Boer and Kyle (1974) also show rising motion over central Africa with sinking on either side, as well as the first two cells mentioned above. Fig. 1 taken from Newell (1979) shows the approximate positioning of these cells. In what follows I will explore the evidence

in the rainfall data for the existence of these cells, their interannual variations and their interactions with the Southern Oscillation.

It is the purpose of this thesis to examine the interannual variations in the tropics of one very important variable: precipitation. This element of the weather is of obvious importance to agriculture, upon which many of the developing countries in the tropics depend heavily (Jackson, 1977). As I have endeavored to point out in the above discussion, rainfall is subject to large interannual variations in many key regions such as Subsaharan Africa, northeastern Brazil and the monsoonal areas of southeast Asia. At the present time, these variations are only partly understood and we are not able to forecast them.

As should be obvious from the above, a study of precipitation anomalies will also provide valuable clues as to how the tropical atmosphere behaves on interannual time scales. It is also important to note that, as pointed out by Bjerknes (1969), Newell, et. al. (1974), Rowntree (1972), Namias (1972) and Kidson (1975), interannual variations in the tropics seem to be connected with events in middle latitudes and thus are of importance to those regions as well.

## II. Data and Analysis

Most of the data used in this study was obtained from the National Center for Atmospheric Research in the form of world monthly surface station climatological data tapes (see Appendix for data sources). Additional data for Brazil was kindly provided by Carlos Nobre of the Massachusetts Institute of Technology (MIT). All precipitation data used was in the form of monthly totals in tenths of millimeters. Data for the Southern Oscillation index (SOI) was provided by Rennie Selkirk of MIT. This consisted of monthly departures from the mean of Easter Island minus Darwin, Australia sea level pressure for the years 1949-1975. Seasonal and annual values were obtained by averaging over the appropriate months.

Stations chosen for this study were those lying between 30°S and 30°N latitude for which data was available at least between 1951 and 1970. All available data for these stations between 1941 and 1975 was collected on a separate tape. Also included were the number of observations during each month and miscellaneous information about each station such as height above mean sea level, etc. The minimum time window of 1951-1970 was chosen because the greatest number of stations reporting during any one year occurred during this time (see Table 1), and it insures that all of the selected stations will have a reasonable temporal coverage. Data prior to 1940 was discarded because few stations are available before this time. A total of 568 stations fulfilled these requirements. Their distribution is shown in Fig. 2. Most regions are well represented with the obvious exception of the oceans and, unfortunately, the interior of Australia and Saudi Arabia.

After suitable reformatting of the data, a check for gross errors was made and any monthly totals found to be in error were considered to be missing. Mean monthly values were then computed for each station along with the standard deviations. From these results the mean annual values were obtained. Since maps of mean seasonal rainfall have been published elsewhere (Newell, et. al., 1974), they will not be repeated here.

Following Kraus (1977a), I defined the monthly normalized precipitation anomaly as

$$x_{ijk} = (r_{ijk} - \bar{r}_{ik})/\sigma_{ik}$$

where

$x_{ijk}$  is the normalized anomaly for month k of year or season j and station i,

$r_{ijk}$  is the total precipitation for month k of year or season j and station i,

$\bar{r}_{ik}$  is the mean total precipitation for month k, station i and

$\sigma_{ik}$  is the corresponding standard deviation.

As pointed out by Hastenrath (1976), this normalization is convenient since it gives direct information about the significance of the anomaly.

When the  $x_{ijk}$ 's were computed for each month, the unnormalized departures from the mean were also saved and used to calculate the normalized departures for the three month seasons December-February, March-May, June-August and September-November along with the annual departures. This was done using the easily derived expression

$$x'_{ij} = \left\{ \frac{J_i - 1}{J_i \sum_{j=1}^{J_i} \left[ \sum_k (r_{ijk} - \bar{r}_{ik})^2 \right]} \right\}^{\frac{1}{2}} \sum_k (r_{ijk} - \bar{r}_{ik})$$

where

$x'_{ij}$  is the normalized anomaly for the  $j^{\text{th}}$  season or year of station  $i$ ,

$J_i$  is the number of seasons or years for which data is available for station  $i$

and the other symbols are as defined above. In this expression, the summation over  $k$  is understood to mean the summation over all available months of the season or year which  $j$  represents.

Since the quantities  $(r_{ijk} - \bar{r}_{ik})$  are the unnormalized monthly deviation computed earlier, the quantity in the curly brackets is just the inverse of the variance of the seasonal or annual total precipitation. This is then divided into the total anomaly for the season or year to come up with the seasonal or annual normalized anomaly. Henceforth, in order to avoid confusion, "anomalies" will be taken to mean normalized anomaly and the two terms will be used interchangeably.

Months for which data was missing were not included in the calculation. Thus, some of the seasonal anomalies were computed on the basis of only one or two months of data while some of the annual anomalies were based on less than twelve months of data. If these anomalies are taken to be representative, we are in effect assuming that exactly the mean amount of precipitation fell during the missing months. If the number of missing months is large, this assumption could produce misleading results. In order to avoid this problem while at the same time not discarding any

data that is available, the number of months of data which went into each seasonal and annual anomaly was stored along with the anomaly. This number was then checked whenever the anomaly was used in a later calculation. In most cases, if the number of missing months was large (usually taken to mean one or more months of a season or more than one month out of a year) the anomaly was not used.

The annual and monthly anomalies were also reordered into "map" format where the principal ordering is by time rather than by station. This facilitates certain computations and allows for easy production of anomaly maps.

Because of the "noisy" nature of the normalized anomalies it is advantageous to take both spatial and temporal averages. Spatial averages were computed merely by taking the average normalized anomaly (ANA) of a regional group of stations. Note that this means that data gaps in any of the stations in the region will lead to a different group of stations being included in the ANA from one season or year to the next. This could conceivably lead to an inconsistent time series of ANA's. However, due to the limited amount of data available and because most regions dealt with are fairly homogeneous, I shall not be concerned with this problem.

Following Kraus (1977a), the question of whether or not such ANA's are representative of a region can be at least partially answered by testing the statistical significance of the ratio of the variance in time of the ANA to the average spatial variance of the individual anomalies within the region. Kraus obtains the following expressions for the variance in time,  $V_t$ , and the mean spatial variance,  $V_a$ :

$$V_t = (J - 1)^{-1} \sum I_j a_j^2$$



and

$$V_a = (N - \sum I_j a_j^2) (N - J)^{-1}$$

where

$I_j$  is the number of stations in the region reporting in year  $j$ ,

$a_j = (\sum x'_{ij})/I_j$  is the ANA of the region,

$N = \sum I_j$  is the number of station-years of data for the region and

$J$  is the number of years for which data is available.

Assuming that the individual anomalies are normally distributed (see the discussion of normality of the data below) this ratio will follow an F distribution and its significance can thus be tested. If the null hypothesis of equal variances can be rejected, then we at least know that the variance in time of the underlying distribution is greater than the average spatial variance in that region. Unfortunately this does not guarantee that the variance in time is much larger than the spatial variance which is the condition we need to have satisfied in order to insure that variations between the stations within the region are small compared to the seasonal or annual variations of the region as a whole. Only if this is the case can we confidently use the ANA as being representative of the entire region. This point was not mentioned by Kraus (1977a).

Nevertheless, the F-test does provide a necessary criterion for establishing the representativeness of the ANA of a region. In most cases other evidence such as correlations between stations will also be available and this will allow us to be reasonably sure about the validity of the ANA.

Annual ANA's were computed for each 5° latitude by 10° longitude

square for which data was available. This grid square size was chosen because it is the maximum convenient size for which the ANA will pass the F-test discussed above over most of the tropics while at the same time insuring an adequate number of stations within each square.

The results of the F-test for each of the grid squares are shown in Fig. 3. Note that most of the squares in the key regions of Sub-Saharan Africa, northeastern Brazil, Central America and India pass the F-test at at least the 95% level. Of the remaining squares only a few have more than 36 station-years of data and still fail the test. The most notable occurrences of this are around Madagascar, in Africa between the equator and  $10^{\circ}\text{S}$  and in Australia. In these areas, the available evidence does not allow us to state that the ANA's for the grid squares adequately represent the precipitation anomalies at the stations within the squares. Not enough data was available in the remaining squares to calculate the ratio of the variances. It is important to note that all of the multiple grid square regions I will discuss below do pass the test and can thus be adequately represented by their ANA's.

The advantages to using the ANA's as opposed to individual station anomalies is that they provide a simpler picture of the gross behavior of a region by smoothing over individual station anomalies which make maps of such individual anomalies difficult to interpret. Another advantage of using the ANA's is that they give us a much smaller set of numbers to work with when computing correlations.

After the ANA's were computed for each grid square and several larger regions as discussed below, a means of detecting connections in the anomalies between one or more regions was needed. The Pearson

product-moment correlation coefficient,  $r$ , provides a testable statistic whose square measures the percent of variance of one of the variables which can be explained by a linear function of the other variable. If the correlation coefficient is statistically significant, then we know that there is a very good chance that the two variables are related in some way. Since I am testing against a null hypothesis of independence ( $r=0$ ), a positive result of the test does not mean that one variable can explain a physically significant portion of the variance of the other variable, but merely that the two are not independent of one another (see Brooks and Carruthers, 1953, for more details of the meaning of  $r$ ).

In testing the significance of the Pearson product-moment correlation coefficient I have used the usual  $t$  statistic:

$$t = r(n - 2)^{\frac{1}{2}} \cdot (1 - r^2)^{-\frac{1}{2}}$$

where  $n$  equals the number of data points and  $t$  follows the students'  $t$  distribution with  $n-2$  degrees of freedom. The underlying assumption here, which is the problem with using  $r$  as a measure of independence, is that the two time series which are used to calculate  $r$  are drawn from normally distributed populations. Now, it is well known that daily or monthly rainfall totals approximately follow a gamma distribution which becomes less positively skewed as the time interval which the totals represent increases (Brooks and Carruthers, 1953). Hence we should expect that the normalized anomalies I have computed will tend to be approximately normally distributed only if they represent sufficiently long time intervals.

It is difficult to assess the robustness of the  $t$ -test to

deviations from normality of the underlying distributions, but, since I have calculated deviations from the mean (as opposed to the median), we would expect that the calculated  $r$ 's would tend to be greater than zero even for independent variables. This is due to the fact that the distributions are positively skewed. The  $t$ -test is not designed to handle this problem and it thus becomes necessary to test the distributions of the anomalies for normality.

There are several such tests available perhaps the simplest of which is merely to construct a normal probability plot of the data. I have plotted several annual series of ANA's from various regions. These regions are each comprised of a group of contiguous grid squares. SAHEL refers to the region at the southern edge of the Sahara Desert, CARIB to the Central American-Caribbean region and NE BRAZIL to the northeastern corner of Brazil (see Table 3 for exact definitions). The results are shown in Figs. 4-6. The fact that the points all fall approximately along a straight line means that the anomalies are approximately normally distributed. This is particularly true for the SAHEL area which includes a large amount of data (1022 station-years).

While the annual ANA's are approximately normal, the seasonal ANA's do not follow a straight line as can be seen in Figs. 7 and 8 which show the plots of seasonal anomalies for the SAHEL and NE BRAZIL regions, respectively. The steep slope of the points in the upper right-hand corner of the graphs is typical and shows the presence of a few large positive values which make the distributions positive skew. The situation is often not quite so serious when only the individual seasons of maximum rainfall in a region, rather than all

seasons, are plotted. For instance, Fig. 9 shows the normal probability plot for June - August of SAHEL. This region experiences its maximum rainfall in late summer and early fall and hence it acts like a wet, rather than semiarid, region when only these months are considered. As Brooks and Carruthers (1953) point out, the positive skewness of rainfall statistics is most pronounced in arid and semiarid regions where a passing shower can boost the rainfall total many times above normal while wetter regions show a more normal rainfall distribution. Thus, although in general seasonal anomalies are not normally distributed, there often occur areas in which the anomalies for the one or more wet seasons can be close to normal.

Another, more quantitative approach to determining normality is to employ a statistical test. O'Brian and Griffiths (1967) suggest using Cornu's ratio since the sample sizes in this case are fairly small. If we have  $N$  samples of a random variable  $\{x_1, x_2, \dots, x_N\}$  then Cornu's ratio is defined as  $e/\sigma$  where

$$e = \left( \sum |x_i - \bar{x}| \right) N^{-1}$$

$$\sigma^2 = \left( \sum (x_i - \bar{x})^2 \right) N^{-1}$$

and  $\bar{x} = \left( \sum x_i \right) N^{-1}$ . The sampling theory of the ratio is known and its value approaches  $(2/\pi)^{\frac{1}{2}} = 0.7979$  for normal samples. The null hypothesis for this test is that the  $x_i$ 's are drawn from a normal population and thus we would like the value of  $e/\sigma$  to be close enough to  $(2/\pi)^{\frac{1}{2}}$  so that we cannot reject the null hypothesis. The 90% and 95% significance levels for  $e/\sigma$  are given by Geary (1935). Obviously, such a result provides a necessary but not sufficient condition which the  $x_i$ 's must satisfy if they are drawn from a normal population. Hence it would be

useful to employ another independent test for normality so as to come up with another necessary condition.

Such a test is the skewness test, also recommended by O'Brian and Griffiths (1967). This test is based on a measure of skewness of the sample, namely the third moment about the mean. This is given by

$$\gamma = (\sum (x_i - \bar{x})^3) N^{-1}$$

O'Brian and Griffiths (1967) give the approximate standard error of  $\gamma$  as  $(6/N)^{\frac{1}{2}}$ . Since  $\gamma$  is normally distributed, the null hypothesis of normality can be rejected at the 90, 95 and 99% levels only if  $\gamma$  exceeds 1.645, 1.960 and 2.576 times the standard error, respectively (this is a two tailed test). This test is of particular interest here since skewness is the major problem with rainfall statistics.

I performed these two tests on the SAHEL, CARIB and NE BRAZIL annual and seasonal ANA's. The results are summarized in Table 2. All three annual series passed the Cornu's ratio and skewness tests although the NE BRAZIL data had a rather large value of  $\gamma$  (equal to one standard error). Of the seasonal series, only the CARIB data passed both tests. The skewness of the NE BRAZIL series is quite large allowing us to conclude that these anomalies are definitely not normally distributed.

From these results it appears that the annual anomalies follow a normal distribution. The seasonal anomalies, on the other hand, are in general not normally distributed. Thus, care must be taken when interpreting correlations between seasonal anomalies.

One way around this problem would be to use the Spearman rank-difference correlation coefficient as suggested by McDonald and Green (1960). The advantage of using this statistic is that it is nonparametric

and hence tests for significance using it do not require the underlying distributions to be normal. Unfortunately, calculation and testing of this coefficient proved to be difficult to implement on the computer and not worth the effort since the majority of calculations involved annual anomalies which I have shown above to be normally distributed.

Still another correlation coefficient, the tetrachoric correlation coefficient, has been used by Kraus (1977a). As described by Brooks and Carruthers (1953), the data is first divided up into a 2 x 2 contingency table and then the number of occurrences in each category are combined so as to give a measure of the relationship between the two variables. In the present case, this amounts to reducing the question of parallel behavior in rainfall anomalies between two areas to the question of whether or not the anomalies of the two regions have the same or opposite sign in a significant number of years. As with the product-moment coefficient, normality of the underlying distributions is assumed when testing for significance.

Kraus (1977a) found that this statistic attained a significant value in a situation where the product-moment coefficient was not found to be significant. I have computed both the product-moment and the tetrachoric correlation coefficients for a large number of cases. I found that, although the tetrachoric method generally gives much higher estimates of the correlation than does the product-moment coefficient, the standard error as given by Brooks and Carruthers (1953) is correspondingly larger and hence it is in general at least as difficult to prove significance as it is with the product-moment coefficient. Another problem with the tetrachoric coefficient is that

it takes into account only the signs and not the magnitudes of the anomalies. This makes it extremely sensitive to any skewness in the underlying distributions. Hence it is not suitable for correlating seasonal anomalies.

In light of the above discussion, we are left with little choice but to use the Pearson product-moment correlation coefficient. For annual anomalies this presents few problems and provides a fairly powerful test of dependence. Again, care must be taken when using seasonal data.



### III. Results

In the following paragraphs, I present the results of the analyses described in the preceding section. First, interannual variations of rainfall in Northern Hemisphere subtropical regions are discussed. The second part concerns itself with the variations which are seen to be attributable to the Southern Oscillation and the corresponding variations in the zonal circulations of Fig. 1 (see Introduction).

A brief note on terminology is in order here. Unless otherwise stated winter will refer to the months December, January and February; spring to March, April and May; summer to June, July and August; and fall to September, October and November, regardless of which hemisphere is being considered. The year of the winter is defined as the year in which the last two months fall. Also, when discussing the zonally oriented cells of Fig. 1, they will be referred to as (reading left to right): the Pacific, South American, Atlantic, African and Indian cells.

I start off by considering the first region I mentioned at the beginning of this thesis: Subsaharan Africa. I will refer to this region as SAHEL and its definition is as indicated in Table 3. This definition includes most of the smaller regions used by Nicholson (1979) and the vast majority of stations used by Kraus (1977a). The result of the F-test for the region (see Table 3) shows that the annual rainfall anomalies are fairly uniform within it and hence it can be represented by a single annual ANA. This uniformity is also borne out by the fact that Nicholson (1979) found good correlations between those of her smaller regions which fall within SAHEL.

The time series of the SAHEL annual ANA is presented in Fig. 10. It agrees well with those given by Tenaka, et. al. (1975), Nicholson

(1979) and others. As noted in the introduction, the major features are the droughts in 1940 and 1970-1973 and the excess rains throughout the 1950's with the exception of 1956. The magnitude of the last drought is astonishing. Below normal precipitation fell every year from 1965 to 1975 with the driest year, 1973, having an anomaly of -1.23.

The SAHEL region receives its maximum rainfall in the late summer when the ITCZ reaches its most northerly position (Riehl, 1954). During the 36 years of data, many stations never received any precipitation during the winter months. Figs. 11 and 12 show the anomalies for the SAHEL winter and summer, respectively. The summer series looks almost exactly the same as the annual series. This is seen more clearly in Table 4 which shows the correlation of each seasonal ANA with the corresponding annual ANA. Note the high correlations of the summer and fall series with the annual SAHEL ANA. The winter anomalies on the other hand, bear little relation to the annual series and in fact, with the surprising exception of 1964, winter rainfall was quite normal throughout the 36 year period (the season for the large positive anomaly in the winter of 1964 is not known). We would expect that the small mean winter rainfall and the resulting small absolute winter anomalies would be swamped by the much larger absolute summer anomalies and hence contribute little to the annual anomaly. However, Figs. 11 and 12 show that, in general, the magnitudes of the normalized winter anomalies are also smaller than those of the normalized summer anomalies. Thus a time series created by the arithmetic mean of the normalized anomalies of the four seasons for each year would also reflect mostly the summer anomalies. Such a result could not be expected

merely because the mean summer rainfall is much higher than the mean winter rainfall, although the low winter precipitation does limit the size of the negative winter anomalies.

Correlations of the annual anomalies of all stations in Africa with the SAHEL annual ANA were computed and the results plotted in Fig. 13. The vast majority of stations between 10 and 30°N correlate well with the ANA with the major exceptions being those lying along the Gulf of Guinea coast and at the northern end of the Nile river valley. Adedokun (1978) also noted that these south coastal stations behave differently from those farther inland. He attributed this to the effects of the descending branch of the Atlantic cell of Fig. 1. This will be discussed further below. South of 10°N, only a few scattered stations show significant correlation with perhaps the most notable being the negative correlations around Madagascar.

Fig. 14 shows the results of correlating each grid square in the tropics with the SAHEL annual ANA. As mentioned above, the SAHEL series correlates well with most of North Africa indicating, as Nicholson (1979) points out, that anomalies seem to occur simultaneously over this entire region. In other areas the results are not very conclusive. No contiguous squares show significant correlation and many that are significant are so only at the 90% level. There seems to be no simple mechanism for these correlations and I will not place any undue emphasis on them.

The lack of clear-cut correlations of SAHEL with other Northern Hemisphere subtropical regions is somewhat surprising in view of Kraus' (1977a) finding of positive linkage between Subsaharan Africa and stations on the edge of the Indian Desert. An examination of corre-

lations of individual stations in India with the SAHEL annual ANA shows no agreement. Kraus had to use a tetrachoric correlation to show a significant linkage because his product-moment coefficients were not significant either. It would seem that if a positive link does exist it is quite weak.

Hastenrath (1976) found a strong positive correlation between Subsaharan Africa and the Central America - Caribbean area. This correlation is not seen in Fig. 14 and infact there is a grid square of negative correlation centered on the north coast of Columbia. In order to explore this problem further, I have performed analyses similar to those mentioned above on a Central American - Caribbean region which is roughly congruent to that used by Hastenrath and which he refers to as CARIB. I will use the same designation here (see Table 3).

The time series of the CARIB annual ANA is shown in Fig. 15. Note the droughts in 1940 and 1972-73 which correspond to the SAHEL droughts. Despite this agreement, however, the correlation coefficient between the two regions is only 0.149 which is not significant. Although the occurrences of two simultaneous droughts does suggest that perhaps some nonlinear process links the two regions during extreme years but not at other times, there is not enough data available at the present time to allow for a definite conclusion.

In Fig. 16, I have plotted the correlation of all stations in Africa with the CARIB annual ANA. Note the high concentration of positively correlated stations in extreme western Africa. Hastenrath (1976) used only 20 rainfall stations in the area he defined as SAHEL (11 - 19°N, 18°W - 9°E) compared to my

definition which extends out to 20°E and includes 40 stations (see Table 3). Hastenrath's region thus includes a proportionately larger share of stations which correlate significantly with CARIB and this contributes to the correlations he finds. As Fig. 16 shows, if my definition of SAHEL had extended out to 20°W so as to include the strongly correlated stations in extreme western Africa, a significant positive correlation may have resulted. Nevertheless, it is surprising that, if the anomalous latitudinal ITCZ positions over Africa and the CARIB region are positively linked as Hastenrath (1976) and Kraus (1977a) claim, we do not see more stations in the Sub-saharan belt which are positively correlated with the CARIB rainfall. This seems to indicate that the proposed linkages are, at best, weak.

In order to be sure that a strong seasonal correlation was not being overlooked due to the fact that I am just considering annual anomalies, a more detailed analysis was performed in which the seasonal anomalies of each station in the CARIB region were correlated with the SAHEL annual ANA. It is important to remember that the SAHEL annual ANA behaves essentially like the SAHEL summer ANA. This analysis did not turn up any significant consistent correlations. Some stations correlate positively in some seasons and negatively in others and the seasons which correlate positively and negatively vary from station to station. Part of this behavior might be due to the skewness of the seasonal rainfall anomalies noted in the preceeding section. In any event, no conclusions of parallel behavior can be drawn from these analyses.

The above discussion indicates that the connections of rainfall anomalies in Northern Hemisphere subtropical regions are weak at best.

A simple model with an ITCZ whose strength and position varies from year to year uniformly at all latitudes does not do an adequate job of explaining the observed interannual variations in these regions.

Having thus failed to find significant connections of interannual rainfall anomalies between various regions which could be ascribed to uniform (in latitude) variations in the strength and position of the ITCZ, I next turn to a consideration of anomalies which seem to be connected with the Southern Oscillation. As mentioned in the Introduction, Kidson (1975) and others have proposed the existence of several zonally oriented circulations at least one of which, the original Walker Circulation over the Pacific (as defined by Troup, 1965 and Bjerknes, 1969), varies in strength in phase with the Southern Oscillation. Kidson's (1975) EOF analysis suggests that the rising motion over northern South America (see Fig. 1) also varies in strength with the Southern Oscillation being greater when the pressure over the eastern South Pacific is higher.

To the best of my knowledge, Walker and Bliss (1932) have been the only investigators to date to plot the correlation of rainfall in the global tropics with the Southern Oscillation. Much work has been done concerning the Southern Oscillation since their paper appeared and many more stations of longer record were available to the present investigation than were at Walker and Bliss' disposal. Thus it is advantageous to repeat their work at this time.

The results of correlating each grid square with the Southern Oscillation Index (SOI) as defined in the preceding section are shown in Fig. 17. Note the extensive areas of strong positive correlations in northern South America, India, Indonesia, eastern Australia and the

South Pacific islands east to 150°W. That so many large areas correlate so strongly with the SOI is astonishing and shows that, as Kidson (1975) points out, the Southern Oscillation is indeed a "preferred mode" of the tropical atmosphere. Henceforth, I will refer to the pattern of correlations shown in Fig. 17 as the Southern Oscillation pattern.

The correlations of Fig. 17 agree well with Walker and Bliss' (1932) map of correlations of June - August SOI with rainfall for the same three months. The major differences are the areas of negative correlation around Madagascar and the east coast of Africa and at the Gilbert Islands just north of the equator at about 173°E. These correlations are not on Walker and Bliss' map. Also of interest and not shown on Walker and Bliss' map are the positive correlations in southern Africa and at Wake Island (19.3°N, 166.7°E).

The importance of the Gilbert Islands and Wake Island stations becomes obvious when Fig. 17 is compared to Kidson's (1975) EOF rainfall analysis. His first rainfall component (see Fig. 18) shows centers in northern South America, the South Atlantic, the North Pacific and the South Pacific - Australia - Maritime Continent region. A major center of opposite sign is located over the Pacific along the equator from about 165°E to 130°W. Tarawa in the Gilbert Islands is the only available rainfall station in this area and the fact that it shows strong negative correlation with the SOI suggests that this feature of Kidson's pattern fits the Southern Oscillation pattern well. Wake Island's positive correlation also verifies the North Pacific center although the Hawaiian Islands do not correlate. The other features of Kidson's map also agree well with Fig. 17 with the exception that the South Pacific center should extend out further northeast on his map to include

the station at about 160°W, 20°S which correlates positively with the SOI. The center over the South Atlantic cannot be verified due to a lack of stations there.

Recalling that the SOI used here is proportional to the sea level pressure at Easter Island minus the pressure at Darwin, Australia, the results of Fig. 17 suggest that higher pressure at Easter Island and lower pressure at Darwin is associated with increased rising motion in the western South Pacific, Australia, the Maritime Continent and India as in the classical picture of the Southern Oscillation (Troup, 1965; Bjerknes, 1969). Increased sinking motion occurs over the eastern South Pacific, but this is not well represented in my results due to the lack of stations there.

Perhaps of most interest here is that the positive correlations in northern South America indicate that the zonal cell with its rising branch over this region varies in phase with the Pacific Walker Circulation. This is in agreement with Boer and Kyle (1974) who found that the change in the vertical motion pattern in the tropics from Dec. '62 - Feb. '63 to Dec. '63 - Feb. '64 showed an increase in intensity of both the Pacific and Atlantic cells. The positive correlations over India indicate that the Indian cell also varies in phase with the SOI.

Other regions of sinking motion seem to be the area around Madagascar and the eastern coast of Africa and in the equatorial Pacific west to at least 170°E. Adedokun (1978) proposed that stations along the Gulf of Guinea coast in Africa are under the influence of the sinking branch of the Atlantic cell but a check of these stations showed only one weak (significant at 90%), negative correlation with



the SOI.

From these results the strength of four of the five cells in Fig. 1 are seen to vary in phase with the Southern Oscillation. There is also a square of positive correlation in Africa just north of Lake Victoria and it is possible that this is the location of the rising branch of the African cell. I will discuss this cell further below.

In order to verify whether or not there are any types of interconnections in the interannual variations of rainfall in the regions mentioned above other than those linked to changes in intensity of the zonal cells, I produced maps similar to Fig. 17 showing correlations with the annual ANA for the various regions. Fig. 19 shows such a map for correlations with the annual ANA of NE INDIA (see Table 3). Note again the negative correlations along the east coast of Africa and at the Gilbert Islands and the positive correlations in northern South America, the South Pacific Islands and eastern Australia. These are all consistent with the Southern Oscillation pattern discussed above.

The only other correlations are a positive one off the west coast of South America and on the eastern end of the Subsaharan zone, along with a negative one near Cuba. There seems to be no simple explanation for these correlations although the positive one in northeastern Africa may be part of the weak linkage between the stations on the edge of the Indian Desert and Subsaharan Africa which was discussed above.

Fig. 20 shows the results of correlating each grid square's annual ANA with that of the region in northern South America which correlates well with the SOI (Fig. 17). This region is referred to as AMAZON in Table 3. Note the positive correlations with the South

Pacific Islands, eastern Australia, parts of Indonesia and northeastern India. Once again, the Gilbert Islands correlate negatively as does one square in the Indian Ocean. Also, two stations in northeastern Brazil (not shown) have significant positive correlation coefficients. These same two stations have significant positive correlation coefficients with the SOI. This indicates that the interannual variations in rainfall in northeastern Brazil are at least partly due to variations in the intensity of the Atlantic zonal cell in agreement with Walker (1928). All of the correlations mentioned above fit the Southern Oscillation pattern. I can think of no simple explanations for the correlations in Africa and the Bay of Bengal, however.

Due to the interest in northeastern Brazil, I computed the correlations of all grid squares with the area defined as NE BRAZIL in Table 3. The results are shown in Fig. 21. Note the significant negative values to the east of Madagascar. Strong positive correlations exist with northern and central Australia. Both of these correlations fit the Southern Oscillation pattern fairly well. Noticably missing, however, are the expected positive correlations with squares over the Amazon Basin and the South Pacific Islands between 180°W and 150°W. This is despite that fact that some stations in northeastern Brazil correlate positively with the SOI as do stations in the Amazon Basin as mentioned above. It is not completely clear, therefore, that the strength of the Atlantic Cell is the primary controlling factor of the interannual variations in northeastern Brazil rainfall.

Table 4 shows the correlation of the seasonal anomalies with the annual anomalies for the SOI and each of the regions defined in Table 3. The number to the right of the slash is the percent of the variance of the

annual ANA the seasonal ANA can explain through a linear model. The table shows that, as with the SOI, the spring months, when the ITCZ has reached its farthest southward position (Kousky, 1979), account for the largest part of the variance of the annual ANA of NE BRAZIL. This is a different seasonal emphasis from that of NE INDIA where the largest percent of the variance is explained by the summer and fall anomalies. This explains why the correlations with NE INDIA fit the SOI patterns of Walker and Bliss (1932) for June - August so well.

In addition to the correlations of Fig. 21 mentioned above, there are some weak negative linkages with a few squares in North Africa and the Caribbean. This latter linkage was discussed by Hastenrath (1976). It is not part of the Southern Oscillation pattern discussed here but it is consistent with Hastenrath's finding that dry years in northeastern Brazil usually occur when the ITCZ stays further north than normal, thus producing more rains in regions to the north and vice versa. This could also account for the negative correlations in northern Africa. When only stations in the northeastern most corner of Brazil were used to generate an annual ANA, a correlation coefficient of  $-0.286$  with SAHEL (significant at 90%) was found. Thus a weak negative linkage does seem to exist between the two regions.

In Fig. 17 the islands in the South Pacific are seen to correlate very well with the SOI. In Fig. 22 I have plotted the correlations of each grid square ANA with the ANA for the area which these islands occupy (see SPI, Table 3). Most of the correlations follow the Southern Oscillation pattern although there are some missing elements such as the negative correlations near Madagascar which don't show up here. Perhaps the most notable features of Fig. 22 are the positive

correlation with Wake Island and the negative correlation with the Gilbert Islands. These correlations are as in the Southern Oscillation pattern and as in Kidson's (1975) EOF analysis.

As shown by Troup (1965) and reinforced by the above results, Australia seems to be an important center of action of the Southern Oscillation. For this reason I decided to produce a map of correlations with the annual ANA of the region labeled AUSTR in Table 3 (see Fig. 23). Most of the features of the Southern Oscillation pattern come out nicely here. The negative correlations which were over Madagascar and the east African coast in Fig. 17 are now east of that position and a more extensive region of positive correlations covers southern Africa. It is possible that southern Africa is also a region of rising motion contributing to the African cell. However, this is not shown in Boer and Kyle's (1974) maps of vertical velocity and an alternative hypothesis of concurrent variations in the maximum southward extent of the rain belts over Australia and Africa should also be considered. The positive correlations in northern South America are also east of their positions in Fig. 17 and a square of positive correlation occupies northeastern Brazil. Only one square in the South Pacific east of 180°W correlates positively and no squares in Central America are seen to correlate.

These differences could be due to the fact that the annual ANA for AUSTR is controlled much less by its summer anomalies than NE INDIA which fits the Southern Oscillation pattern so well (see Table 4). As mentioned above, the pattern of Fig. 17 fits Walker and Bliss' (1932) summer map best which indicates that this is predominantly a summer pattern. Therefore, we would expect annual ANA's with a strong summer

component (e.g. NE INDIA) to show a similar pattern of correlations while other regions such as AUSTR produce slightly different results.

Fig. 23 has another interesting feature. The grid square of positive correlation in eastern Africa bounded by 30-40°E and 5-10°N, or one of its immediate neighbors correlates positively with every region thus far considered except for NE BRAZIL (Figs. 19, 20, 22, 23) including the correlation with the SOI (Fig. 17). Although the correlations are sometimes weak and they do shift from square to square, it would appear that this is the region of rising motion of the African zonal cell of Fig. 1. This would place the rising motion just north of Lake Victoria over the headwaters of the Nile. Thus the African cell is also seen to vary in intensity in phase with the other zonal circulations and the Southern Oscillation. However, the linkage appears to be much weaker than for the other cells.

In order to explore this further, I have correlated all of the grid square ANA's with this region (see C. AFRICA in Table 3). The results are shown in Fig. 24. Positive correlations are seen in northern India, parts of Indonesia and the South Pacific as expected, but the correlations are not nearly as extensive nor as significant as in the other maps presented here. Thus, although I believe this is reasonably good evidence that the African cell varies in phase with the others, the linkage is weak.

Figs. 19 through 24 all paint overlapping parts of the same picture: The intensities of the zonally oriented cells of Fig. 1 all vary in phase with the SOI and their horizontal structure is as shown schematically in Fig. 25 which is meant to represent an annual mean configuration but, as noted above, is probably biased somewhat towards

summer time conditions. Although correlations with different annual ANA's emphasize different aspects of the structure of the cells, none of the evidence is contradictory and much of it is self reinforcing. The fact that all of the correlations show such a consistent pattern indicates that the Southern Oscillation pattern defined above represents an important, robust mode of the tropical atmosphere. Even more significantly, it appears from these results and Kidson's (1975) EOF analysis that this is the most important mode of the tropical atmosphere.

Some evidence of correlations between northeastern Brazil, Sub-Saharan Africa and the Caribbean-Central American region exists but the links are weak. They can be explained by anomalous north-south movement of the ITCZ as has been suggested by Hastenrath and Heller (1977) and Kraus (1977a).

Boer and Kyle's (1974) suggestion that the strength of the Hadley circulations varies inversely with that of the zonally oriented cells is not supported by any of the data presented above. I found no correlations between regions at the centers of the rising motions in Fig. 1 with the most conspicuous Northern Hemisphere subtropical region: SAHEL. This hypothesis also does not explain the simultaneous occurrences of a weak Walker Circulation and the Subsaharan drought in 1972 (Krueger and Winston, 1975) which was presumably due to a weaker than normal Hadley cell over Africa.

#### IV. Conclusions

Using statistical and graphical techniques, I have shown that the normalized annual rainfall anomalies employed in this study are normally distributed. Thus, it is valid to compute and test the significance of the Pearson product-moment correlation coefficient.

Based on this result, I have computed the correlation of time series of normalized anomalies averaged over regional groups of stations. The ability of such ANA's to represent the rainfall anomalies of the region as a whole was determined by testing the significance of the ratio of the temporal variance of the ANA to the average spatial variance of the individual station anomalies within the region.

By calculating the ANA for each  $5^{\circ} \times 10^{\circ}$  grid square in the global tropics and correlating these with ANA's for various key regions and the Southern Oscillation index, I was able to show that most of the interannual variations in tropical rainfall can be explained by considering simultaneous modulations of the zonally oriented circulations shown in Fig. 1. The interannual variations of the strength of each of these cells, as evidenced by interannual rainfall variations, are in phase with the interannual variations of the Southern Oscillation index. The approximate mean annual positions of the centers of rising and sinking motion are shown in Fig. 25 which is meant to be schematic and not exact in every detail.

These results have some interesting consequences, all of which are not clear at this time. The importance of latent heat release in the tropical atmosphere was pointed out by Webster (1972). Using a simple two-layer model with latent heating and orography as the only forcing

functions, he was able to reproduce most of the major features of the observed circulation including the zonally oriented cells. Since the earth's topography does not change significantly from one year to the next, this leaves latent heat release as the primary mechanism of interannual variations in the near equatorial tropics. In subtropical regions, Webster found that lateral forcing by mid-latitude disturbances seems to be important also. From these results it is clear that simultaneous changes in the latent heat release over the tropical continental regions signify important changes in the general circulation of the tropics.

Up until the past decade, descriptions of the tropical circulation concentrated on zonally averaged statistics which showed the thermally direct Hadley cell moving north and south with the seasons (Riehl, 1954). However, as the results of this thesis and those of Kidson (1975) show, the Hadley circulation does not seem to be able to account for most of the observed interannual rainfall variations, and hence general circulation variations, in the tropics. Thus, on interannual time scales at least, east-west circulations must be taken into account. Krishnamurti (1971, 1973) has analyzed 200 mb wind data and found that the east-west circulations are at least as strong as the meridional circulations at this level. Although Boer and Kyle (1974) have suggested that the meridional circulation varies inversely in strength with the zonal cells, there seems to be little evidence to support this hypothesis. At present, the relationship between the two circulations, if there is any, remains unclear.

Much work remains to be done. Work is underway by R. E. Newell and co-workers at MIT to look further into the relationship between the



zonal cells and the Southern Oscillation index using surface pressure data. Since such data is normally distributed, it should be much easier to determine seasonal relationships than was possible in this study. New methods of remote sensing of surface winds by passive microwave sensors aboard satellites are presently being developed which will allow accurate determination of winds over the data sparse oceanic regions. Such data should prove valuable in improved determination of the morphology of the zonal cells and their seasonal variations. Also, remote sensing of precipitation rates over the oceans will be extremely helpful. Finally, analytical and numerical models must be developed which explain the observations presented in this work. Only when this is accomplished will we be able to gain real insight into the mechanisms of these vitally important features of the atmosphere.

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Appendix

The following are the published sources of data which were used to generate the tapes which were received from the National Center for Atmospheric Research:

World Weather Records, "---1920", Smithsonian Miscellaneous Collections, Vol. 79, 1927, Smithsonian Institution, Washington, D.C.

World Weather Records, 1921-1930, Smithsonian Miscellaneous Collections, Vol. 90, 1934, Smithsonian Institution, Washington, D.C.

World Weather Records, 1931-1940, Smithsonian Miscellaneous Collections, Vol. 105, 1947, Smithsonian Institution, Washington, D.C.

World Weather Records, 1941-1950, U.S. Weather Bureau, 1959, U.S. Department of Commerce, Washington, D.C.

World Weather Records, 1951-1960 (6 volumes), Environmental Data Services, 1966, U.S. Department of Commerce, Washington, DC.

Monthly Climatic Data for the World, 1961-1973 (monthly publications), U.S. Department of Commerce. Available from: National Climatic Center, Federal Building, Asheville, N.C. 28801. Attn: Publications.

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Table 1: Number of stations reporting in each year.

<u>Year</u>	<u>No. of stations</u>	<u>Year</u>	<u>No. of stations</u>
1940	185	1958	559
1941	234	1959	548
1942	232	1960	554
1943	225	1961	510
1944	229	1962	513
1945	227	1963	522
1946	236	1964	534
1947	255	1965	531
1948	262	1966	536
1949	263	1967	533
1950	264	1968	535
1951	561	1969	536
1952	563	1970	537
1953	563	1971	504
1954	563	1972	478
1955	565	1973	453
1956	561	1974	468
1957	560	1975	448

Table 2: Results of Cornu's ratio and skewness tests for regions defined in Table 3. Symbols are as defined in the text.  $H_0$  represents the null hypothesis that the anomalies are normally distributed.

<u>Region</u>	<u>Time period</u>	<u>Skewness Test</u>			<u>Cornu's Ratio Test</u>	
		<u><math>\gamma</math></u>	<u>Standard Error of <math>\gamma</math></u>	<u>Reject <math>H_0</math> ?</u>	<u><math>e/\sigma</math></u>	<u>Reject <math>H_0</math> ?</u>
SAHEL	annual	-0.0211	0.4082	no	0.850	no
	seasonal	0.10755	0.2048	no	0.743	no
NE BRAZIL	annual	0.4083	0.4082	no	0.783	no
	seasonal	4.22106	0.2048	yes	1.47	yes
CARIB	annual	0.3902	0.4082	no	0.810	no
	seasonal	0.0123	0.2048	no	0.830	no



Table 3: Definitions of multiple grid square regions discussed in the text. The last column on the right indicates the significance level of the F-test for the region.

<u>Name</u>	<u>Boundaries</u>	<u>No..of stations</u>	<u>No. of station-years</u>	<u>F-test significance level</u>
SAHEL	10-20°N 10°W-20°E	40	1022	>99%
CARIB	5-20°N 50-100°W	35	735	>99%
SEPAC	130-180°W 30-10°S	6	184	>99%
AUSTR	110-160°E 30-20°S and 120-150°E 20-10°S	19	463	>99%
NE BRAZIL	*	18	369	>99%
NE INDIA	15-25°N 70-80°E and 20-25°N 80-90°E	16	512	>99%
C. AFRICA	30-40°E 0-10°N	6	170	>95%
AMAZON	0-10°S 50-70°W	11	246	>99%

\* Includes available South American stations east of 41°W.

Table 4: Correlation coefficients of each seasonal ANA with corresponding annual ANA of each region defined in Table 3. Number to the right of the slash mark is the percent of variance of the annual ANA which each seasonal ANA can explain  $(=(\text{number to left of slash})^2 \times 100)$ .

Region	r/% of variance			
	Winter	Spring	Summer	Fall
SAHEL	.073/0.5	.371/14	.896/80	.701/49
CARIB	.105/1.1	.167/2.8	.790/62	.677/46
SPI	.537/29	.424/18	.685/47	.548/30
AUSTR	.505/26	.681/46	.310/10	.643/41
NE BRAZIL	.520/27	.871/76	.466/22	.499/25
NE INDIA	-0.036/0.1	.342/12	.840/71	.783/61
C. AFRICA	-0.057/0.3	.427/18	.517/27	.479/23
AMAZON	.356/13	.699/49	.420/18	.647/42
SOI	.609/37	.947/90	.791/63	.782/61

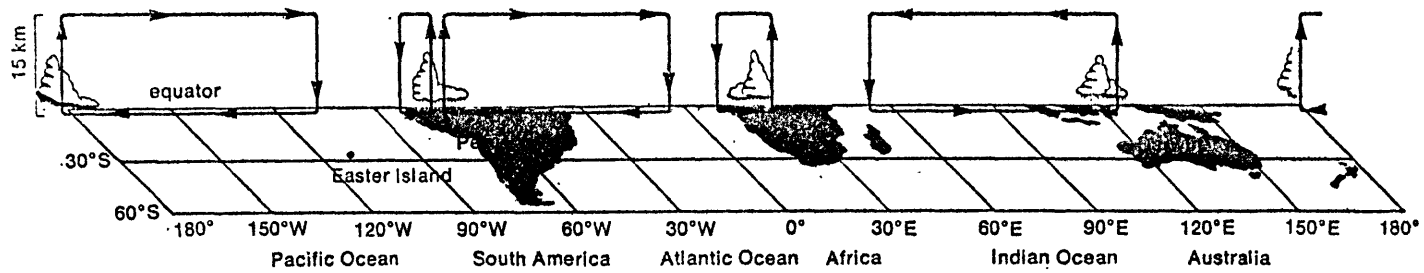


Fig. 1: Zonal circulations (from Newell, 1979).

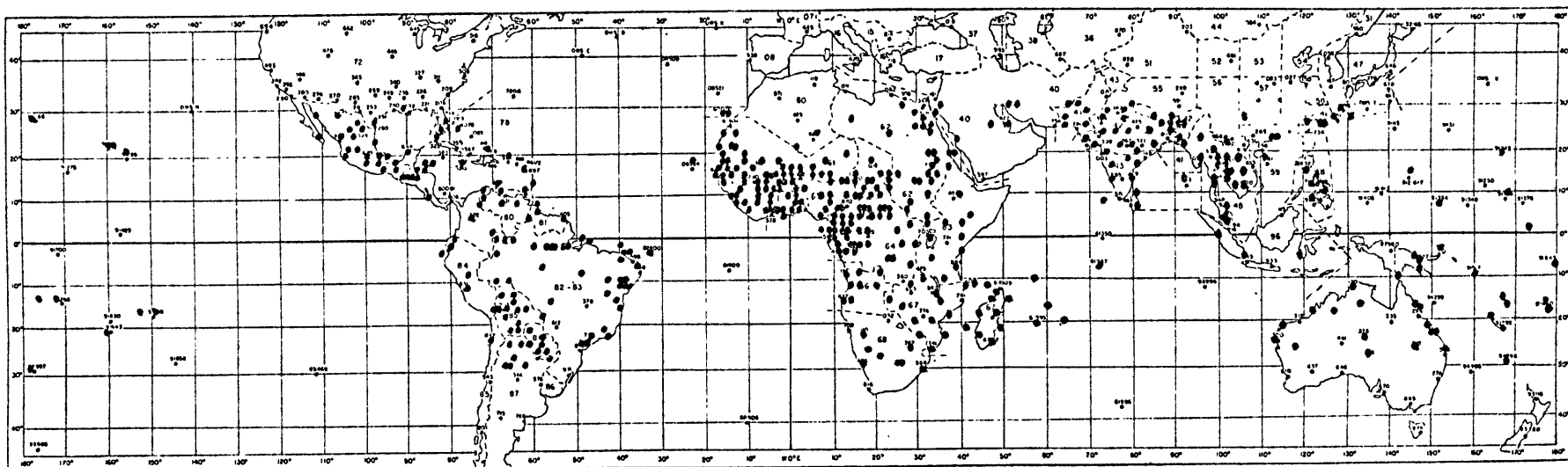


Fig. 2: Station locations.

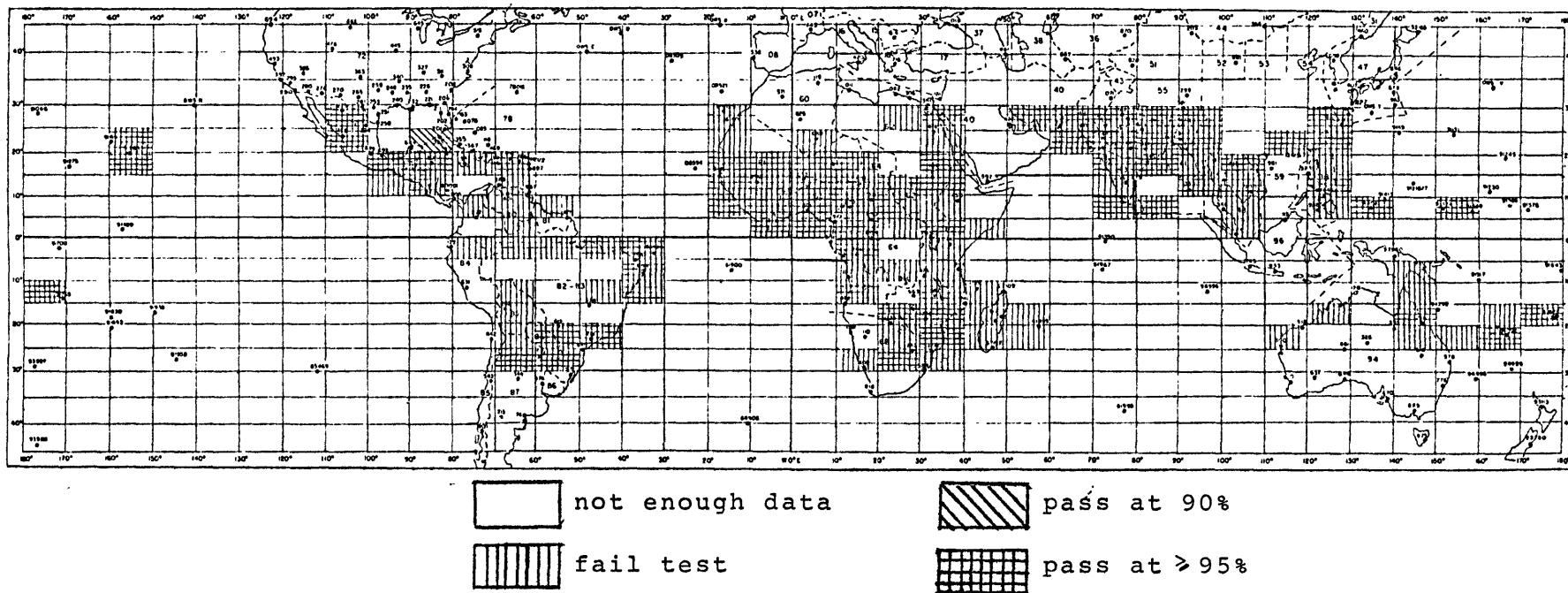


Fig. 3: Significance levels of ratio of temporal to spatial variance for each grid square.

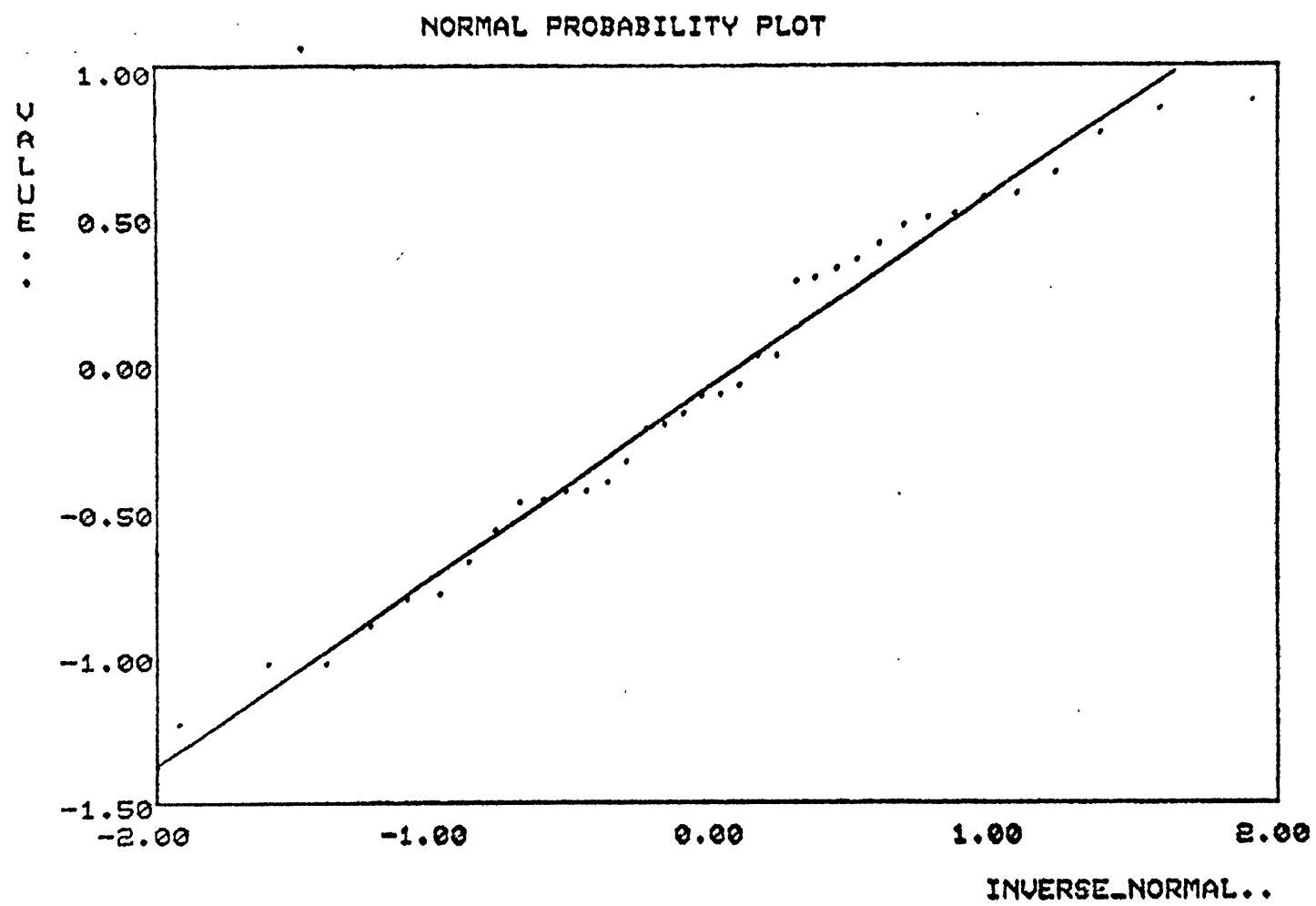


Fig. 4: Normal probability plot of SAHEL annual anomalies.

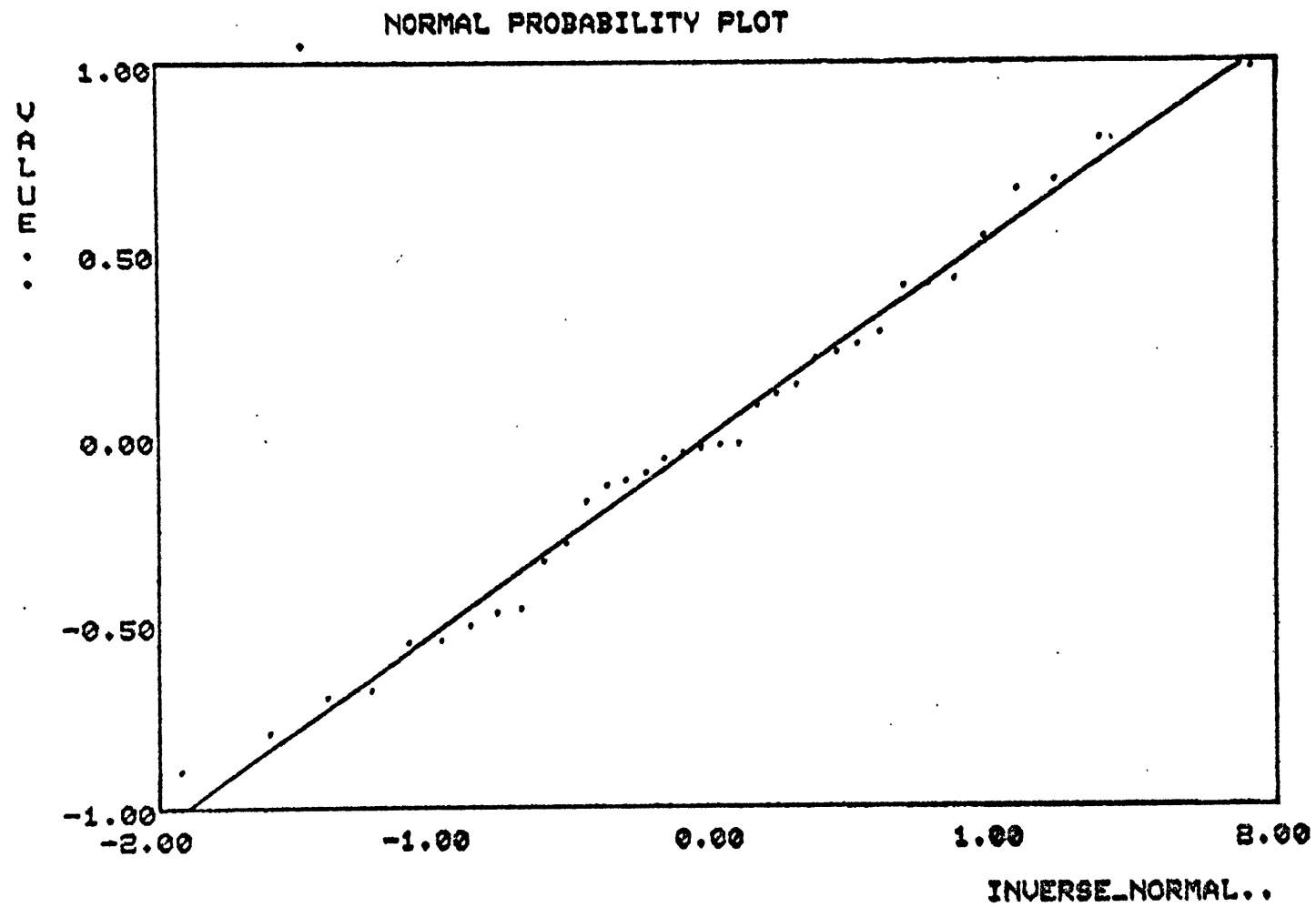


Fig. 5: Normal probability plot of CARIB annual anomalies.

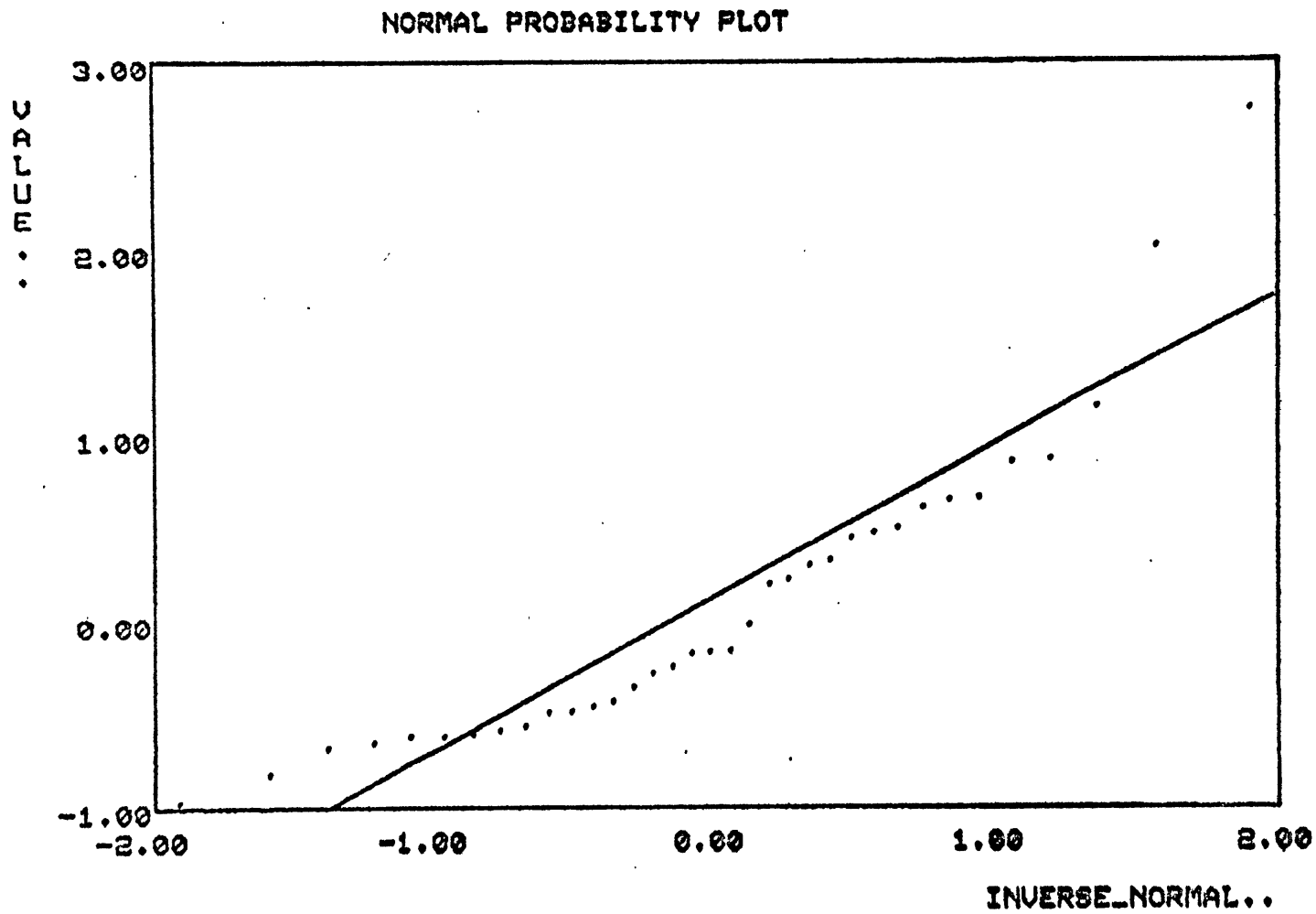


Fig. 6: Normal probability plot of NE BRAZIL annual anomalies.



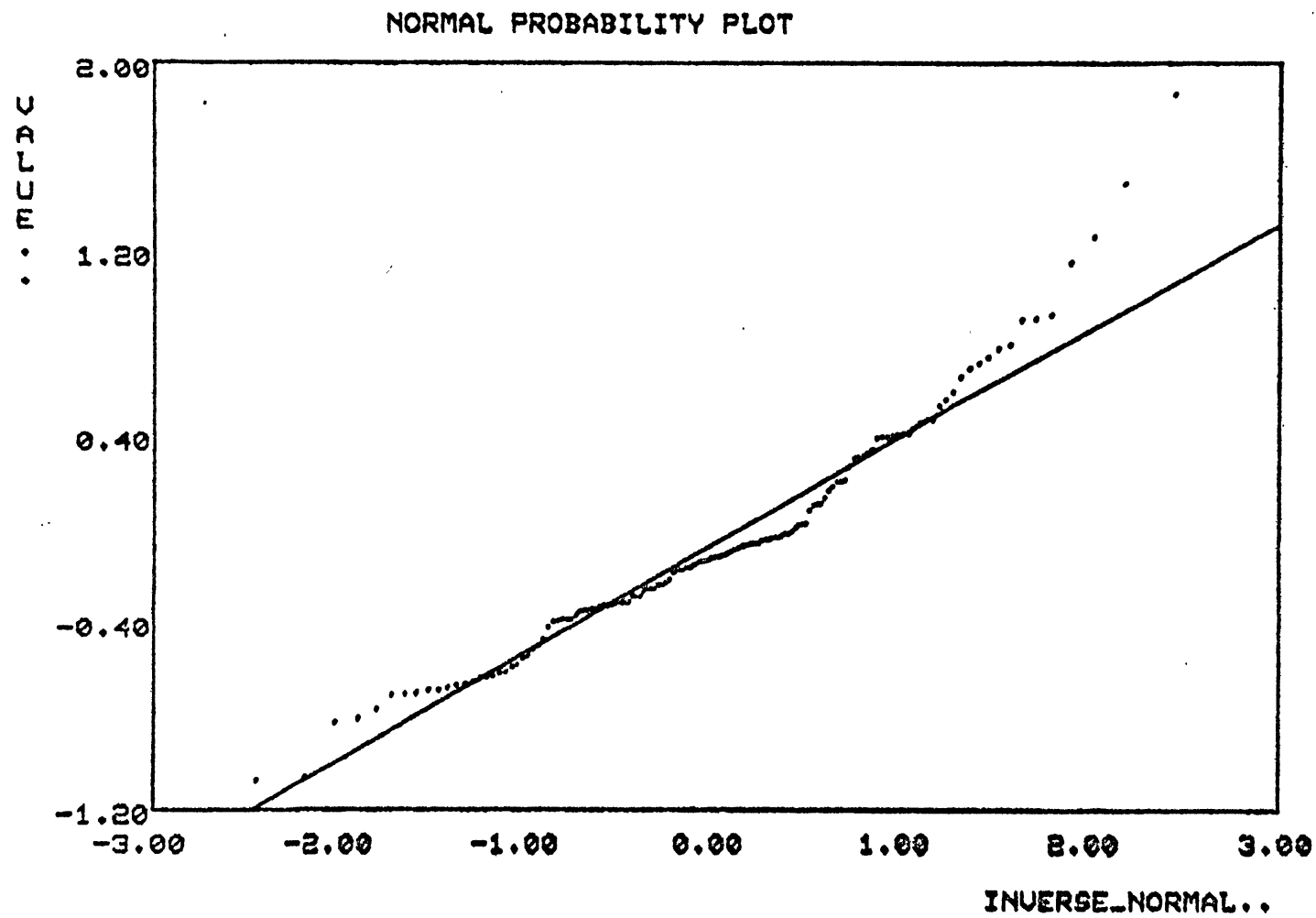


Fig. 7: Normal probability plot of SAHEL seasonal anomalies.

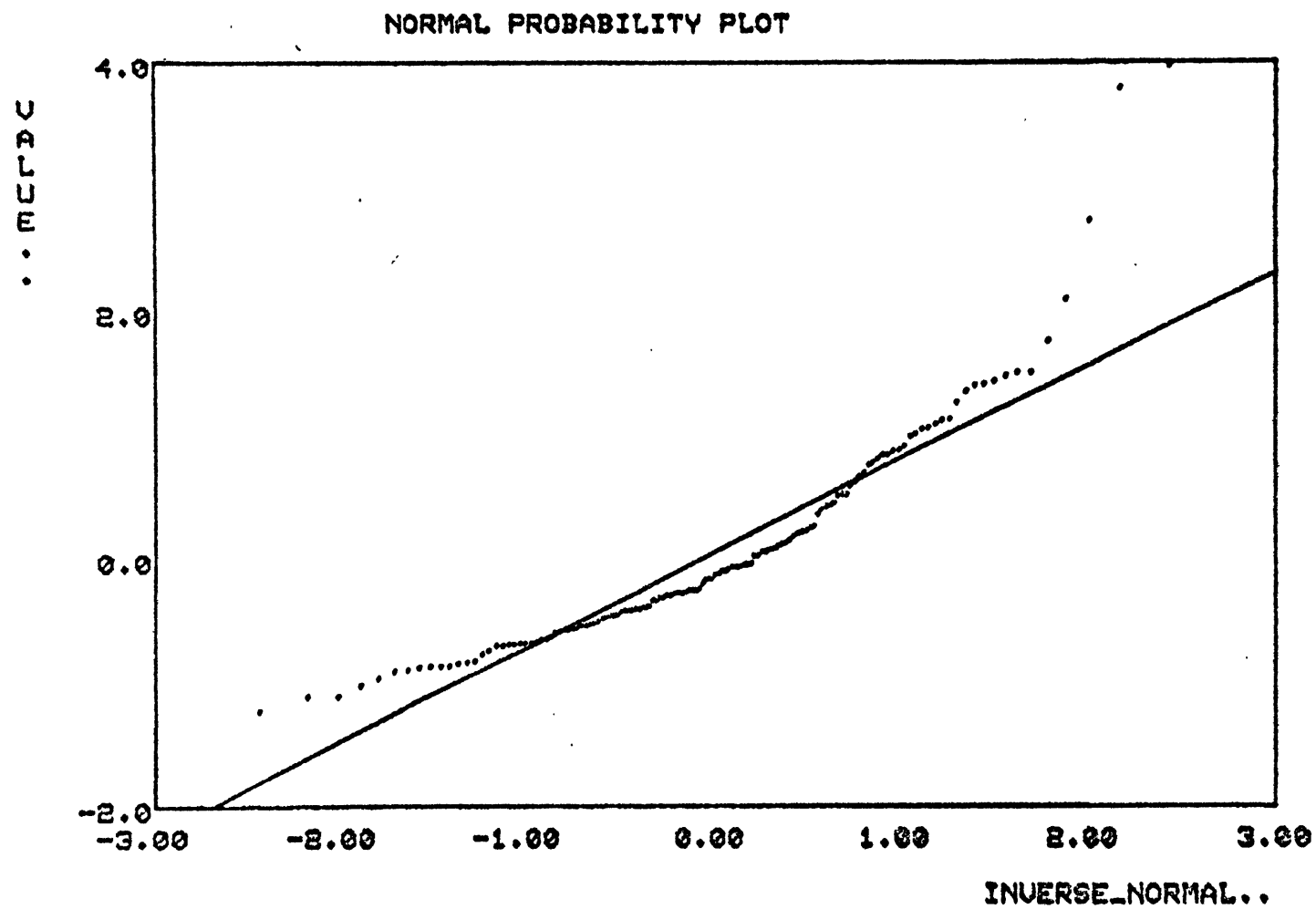


Fig. 8: Normal probability plot of NE BRAZIL seasonal anomalies.

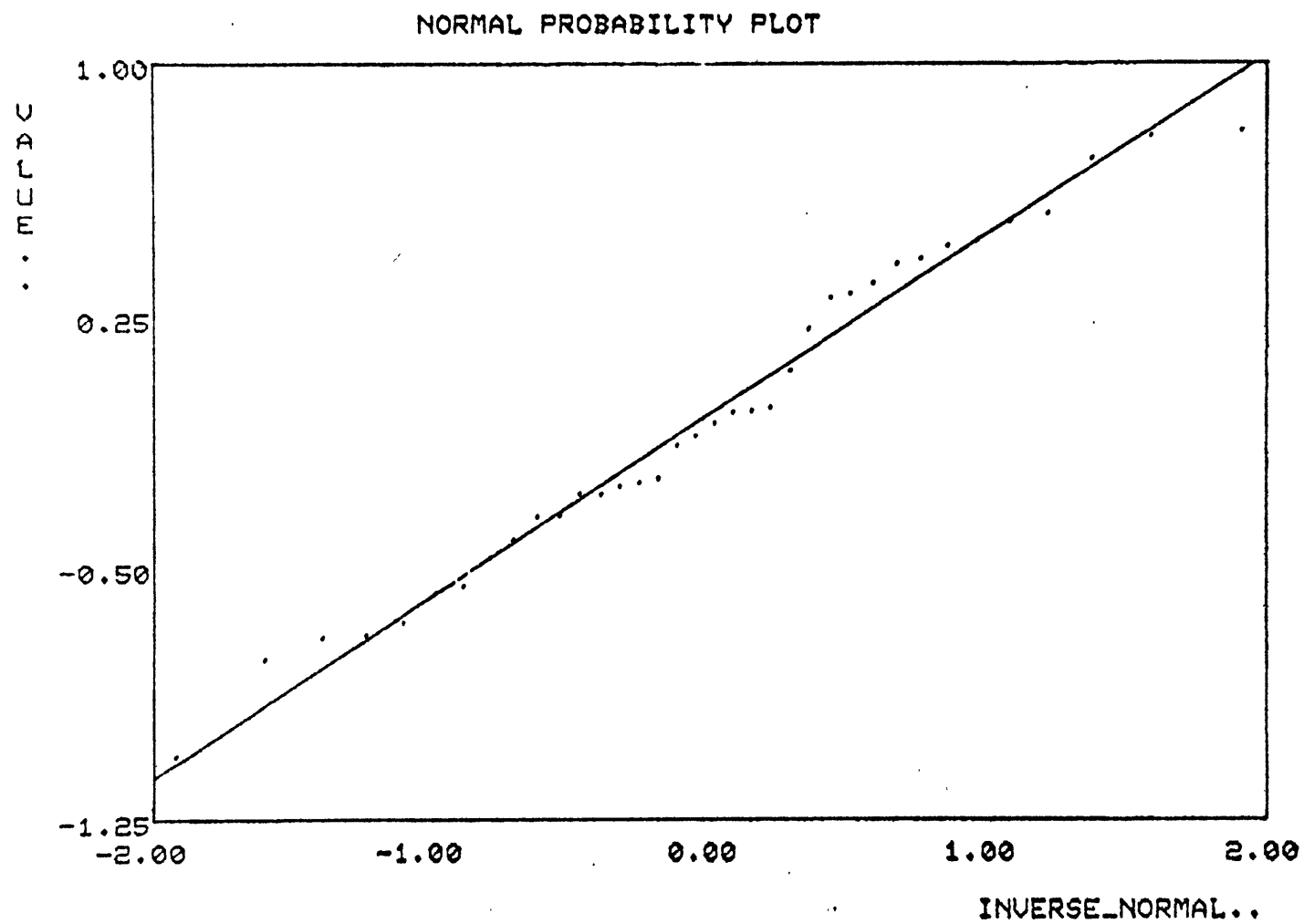


Fig. 9: Normal probability plot of SAHEL summer (June - August) anomalies.

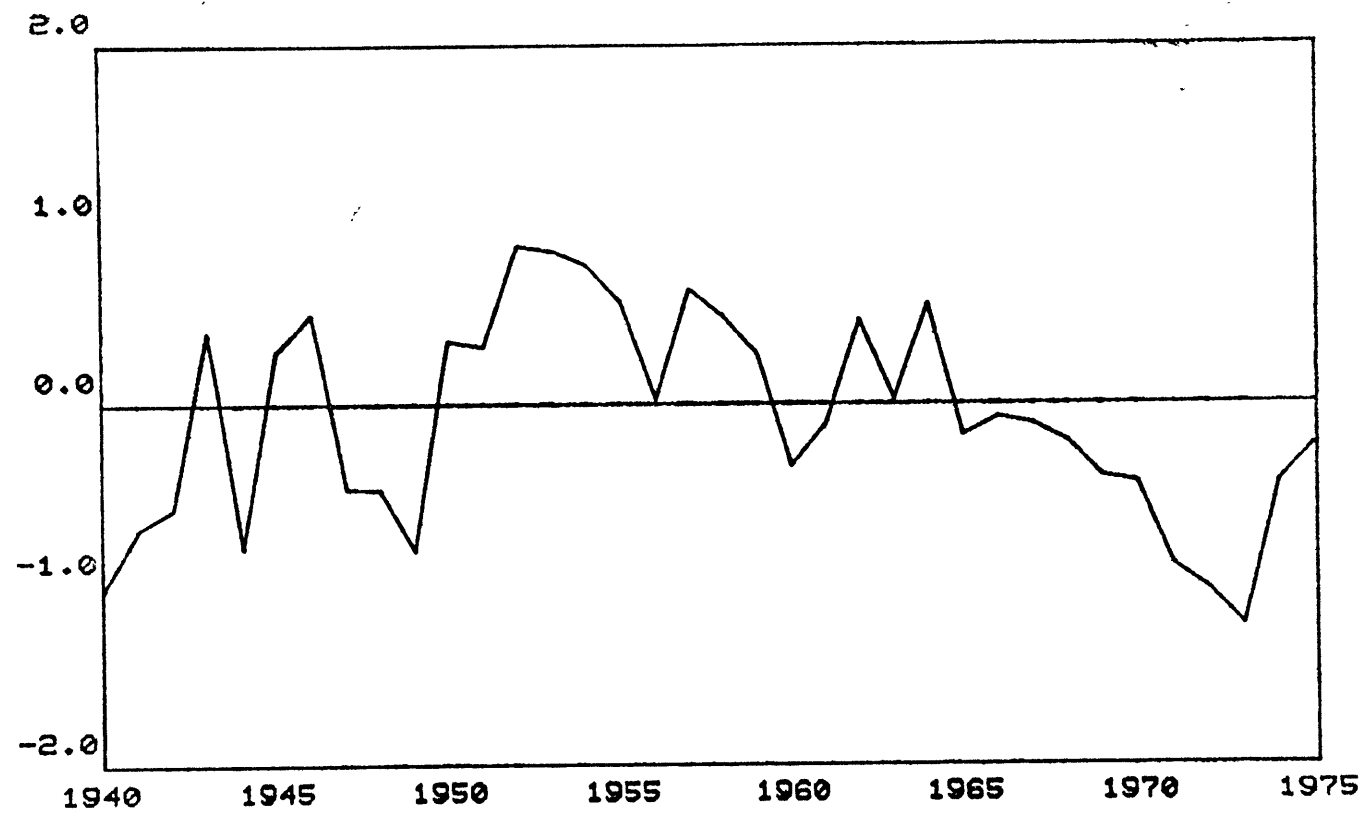


Fig. 10: Time series of annual ANA for SAHEL.

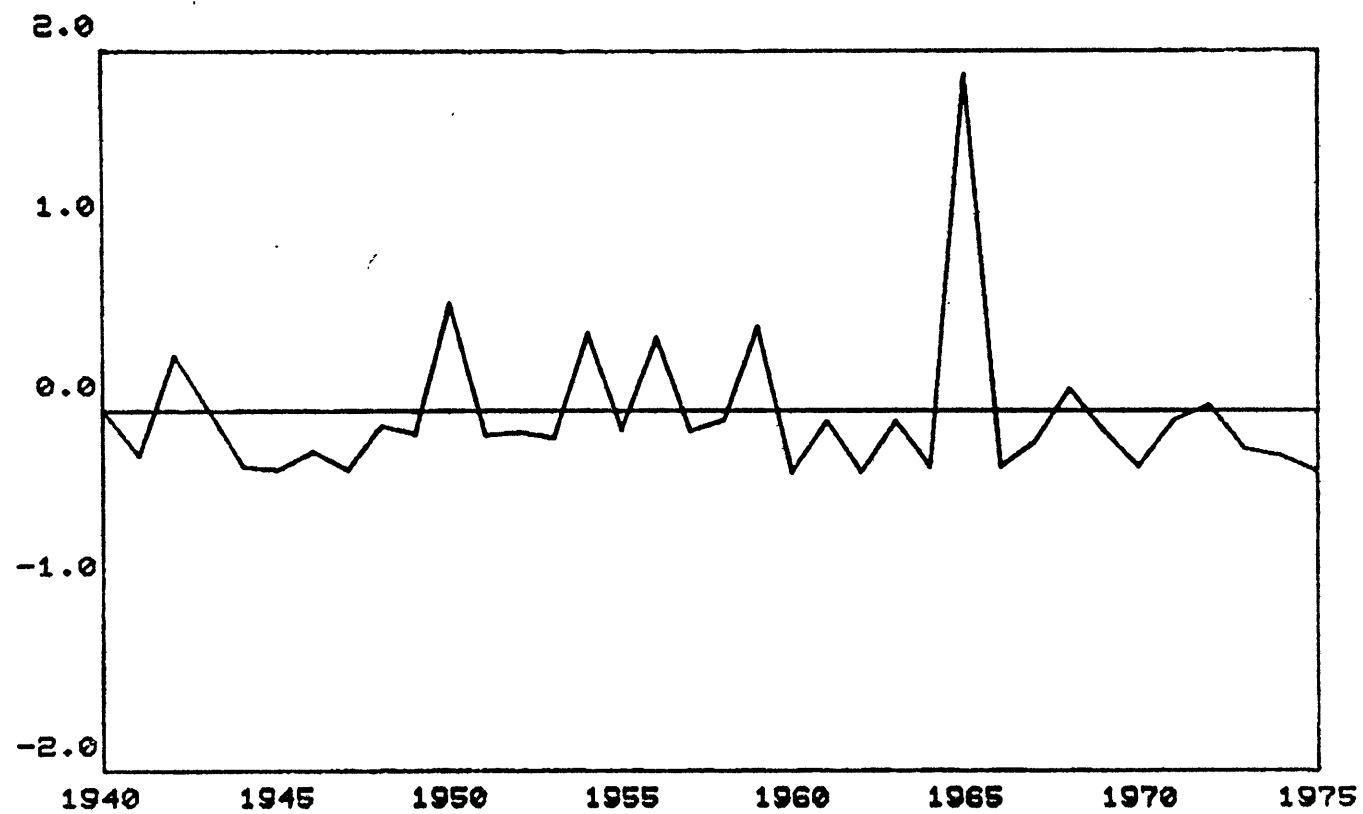


Fig. 11: Time series of Dec. - Feb. ANA for SAHEL.

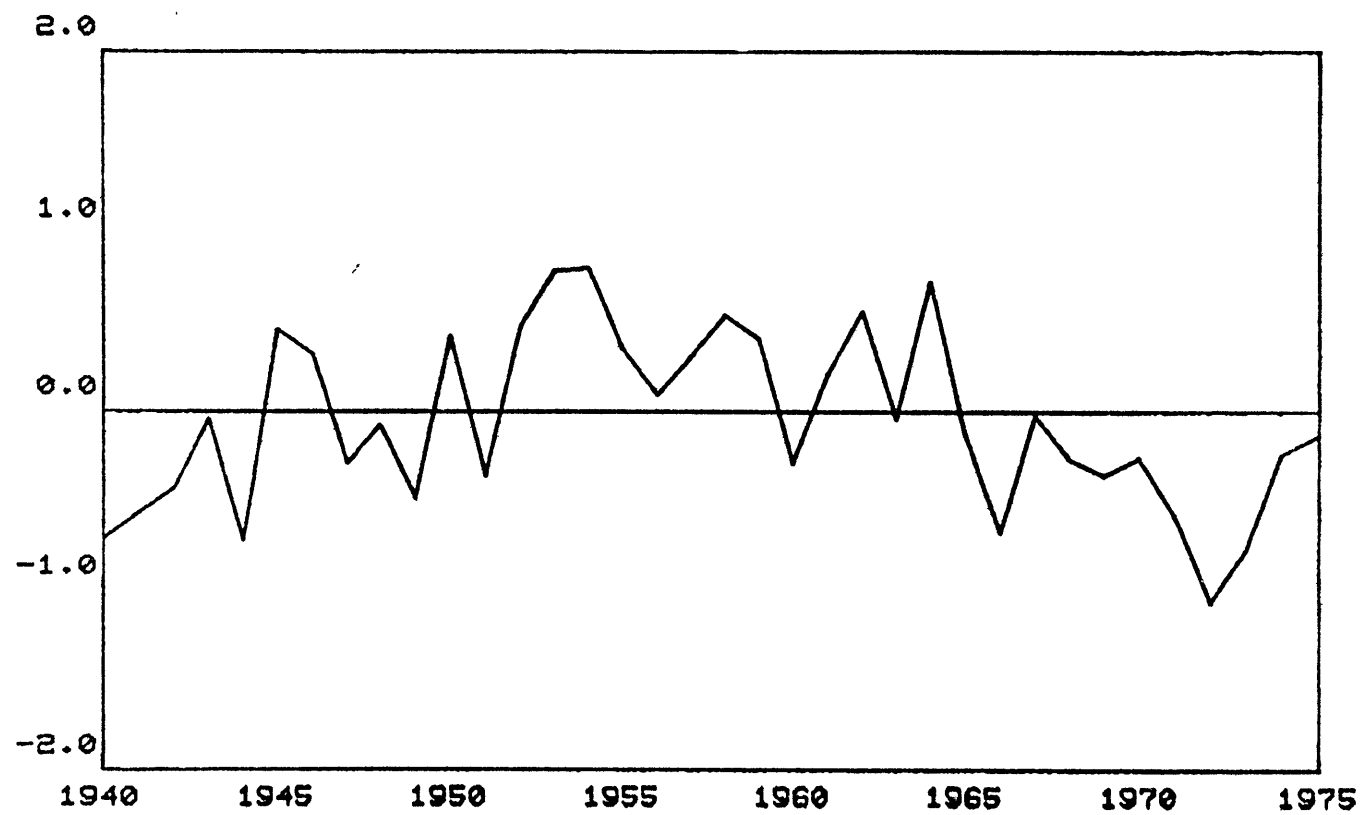


Fig. 12: Time series of June - August ANA for SAHEL.

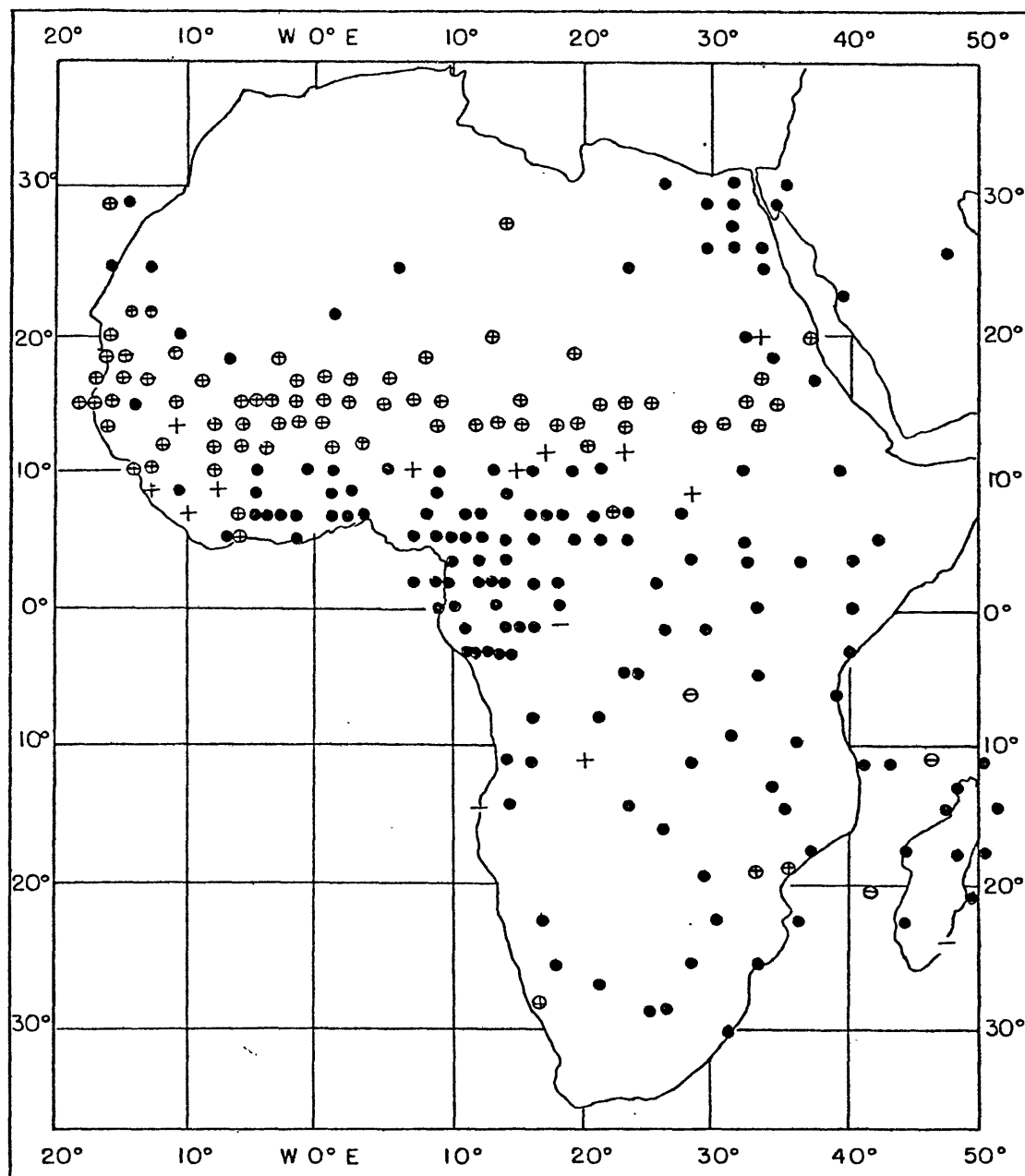


Fig. 13: Significant correlations of African stations with SAHEL annual ANA.

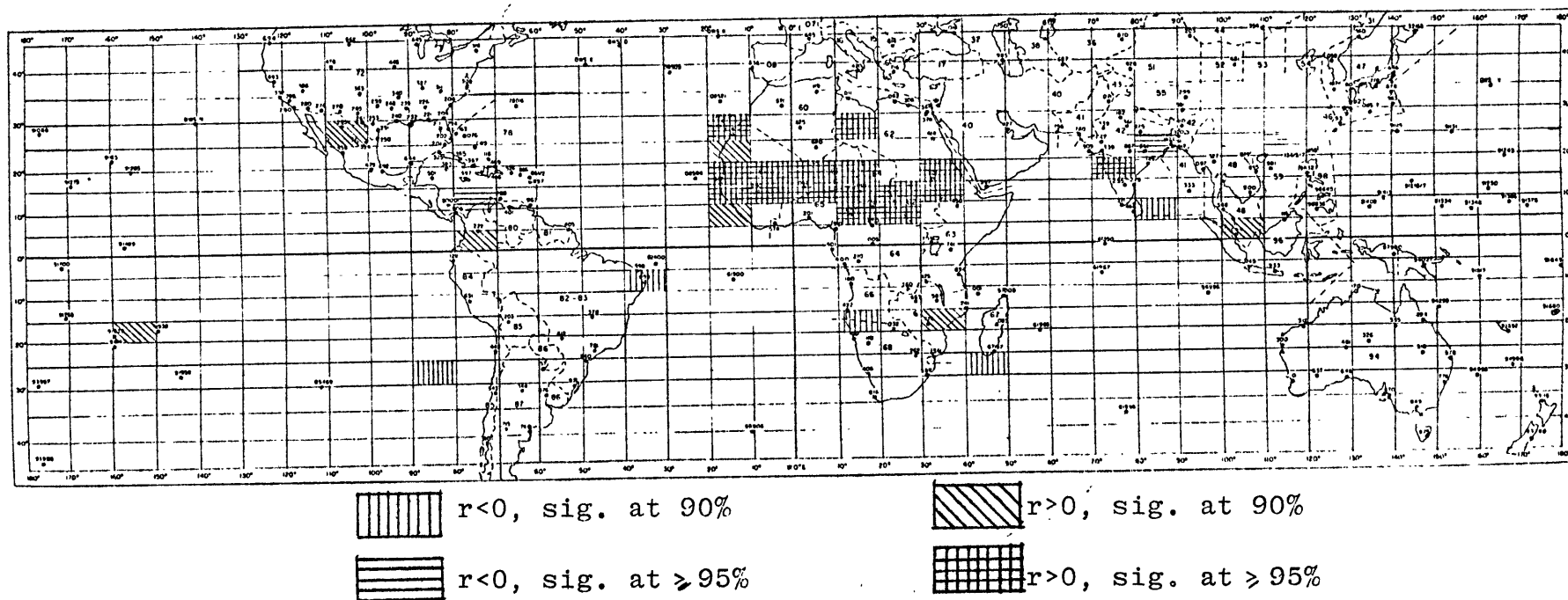


Fig. 14: Significant correlations of grid squares with SAHEL annual ANA.



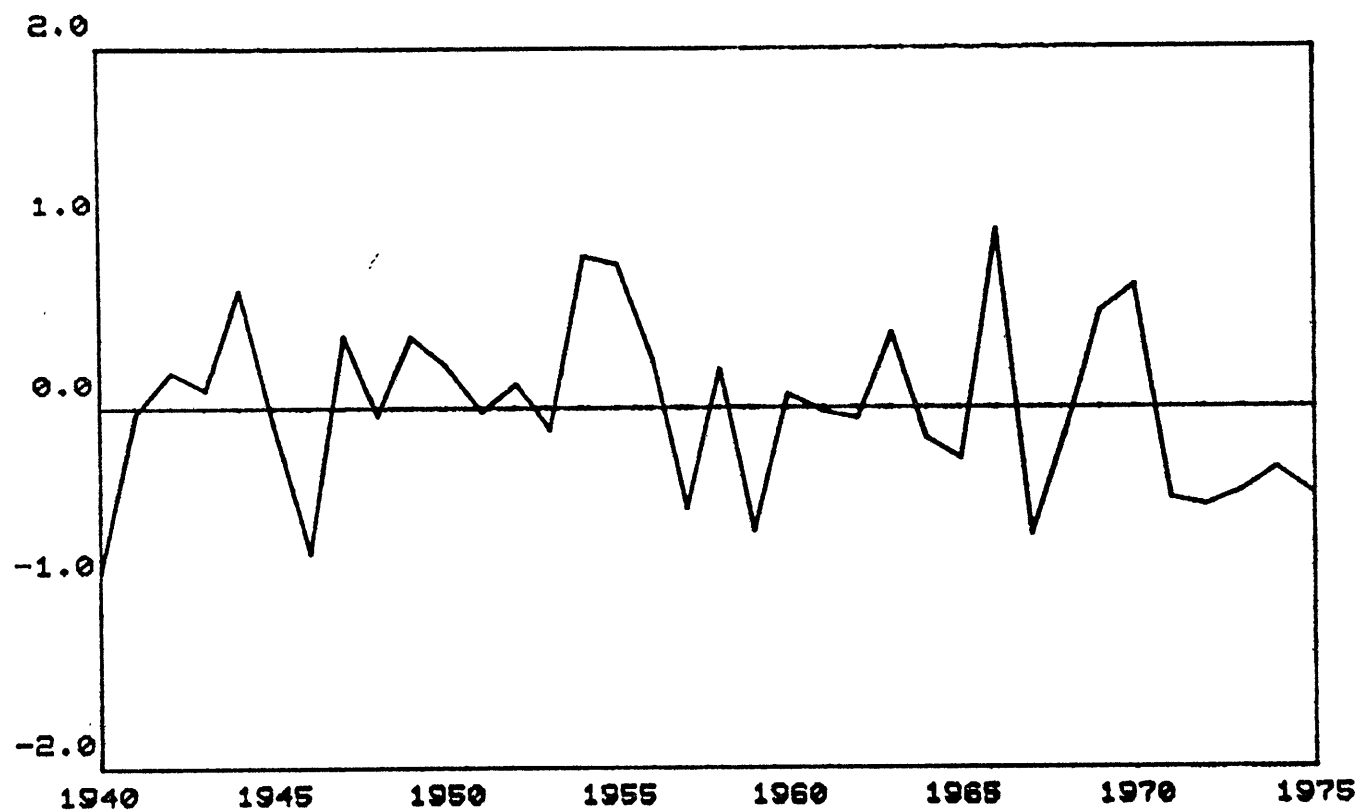


Fig. 15: Time series of annual ANA for CARIB.

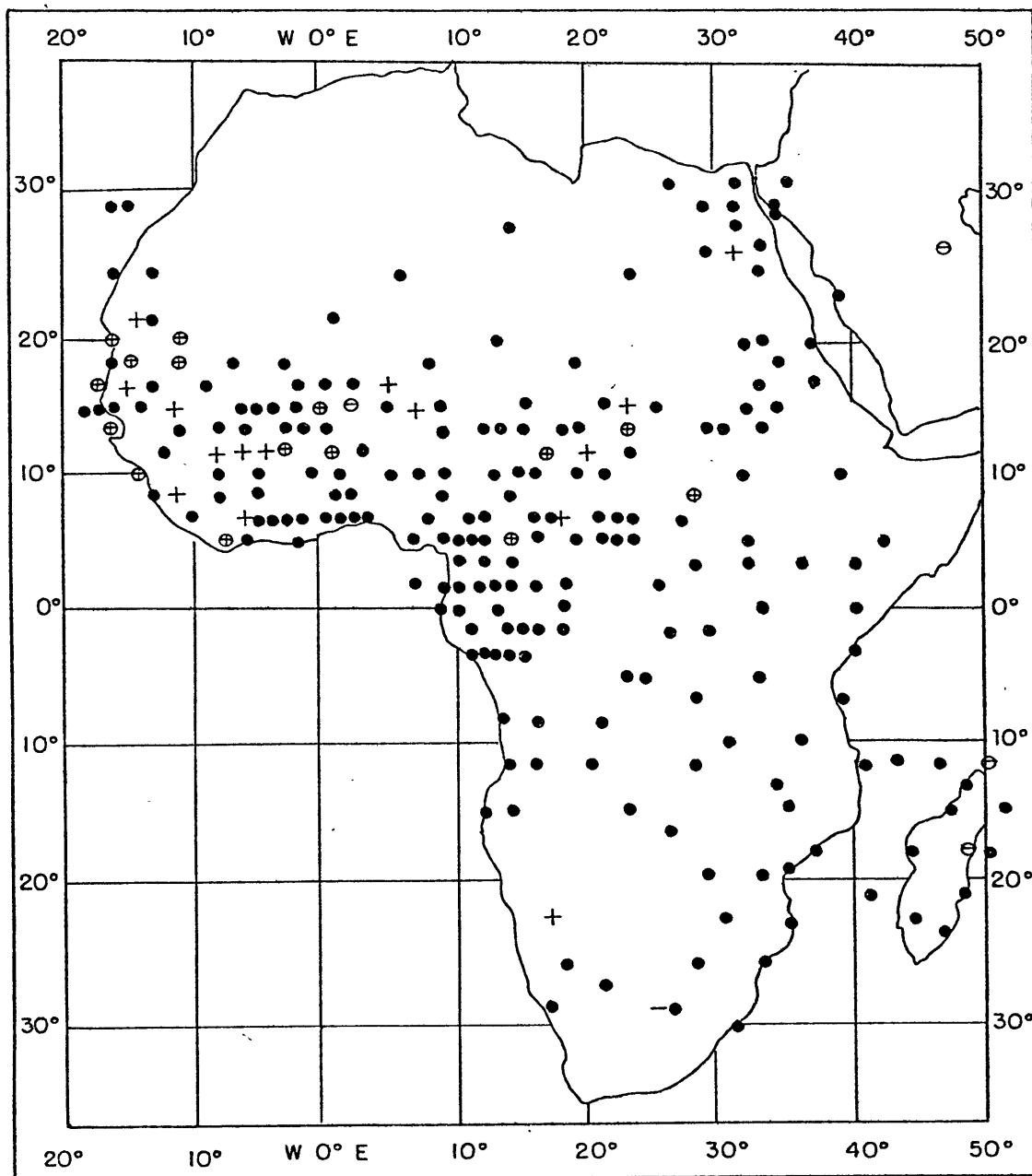


Fig. 16: Significant correlations of African stations with CARIB annual ANA.

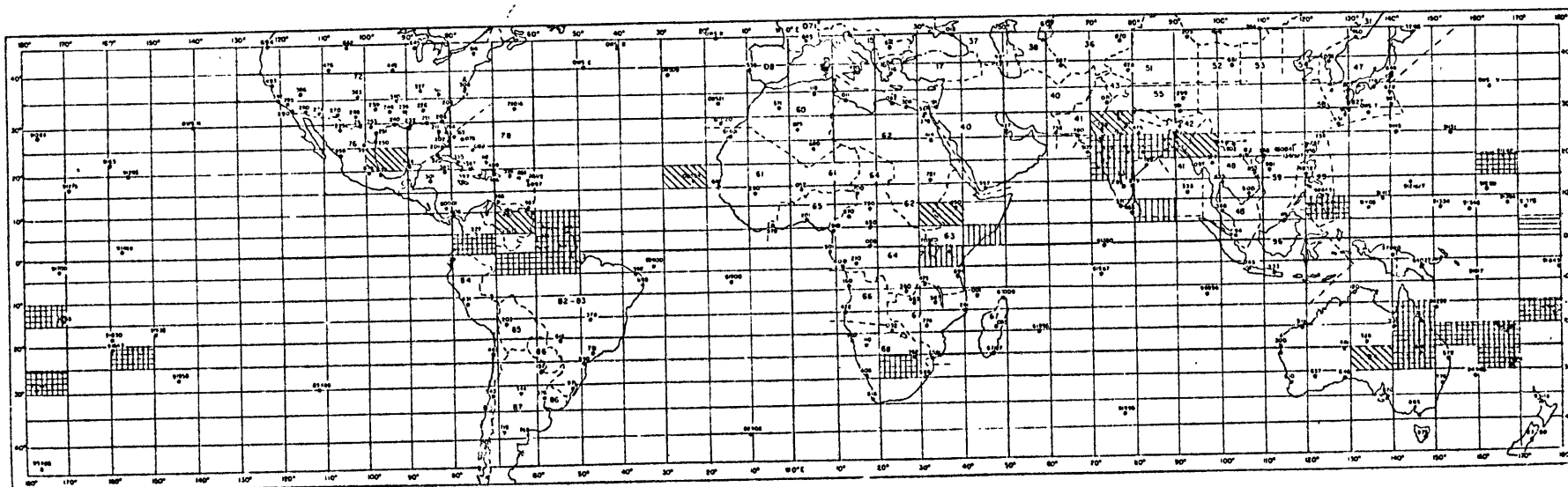


Fig. 17: As in Fig. 14 except for correlations with annual SOI.

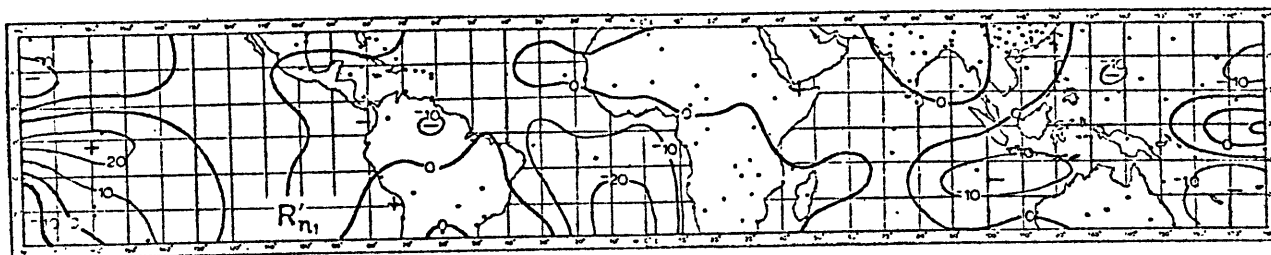


Fig. 18: EOF first component of monthly departures of precipitation from the mean (from Kidson, 1975).

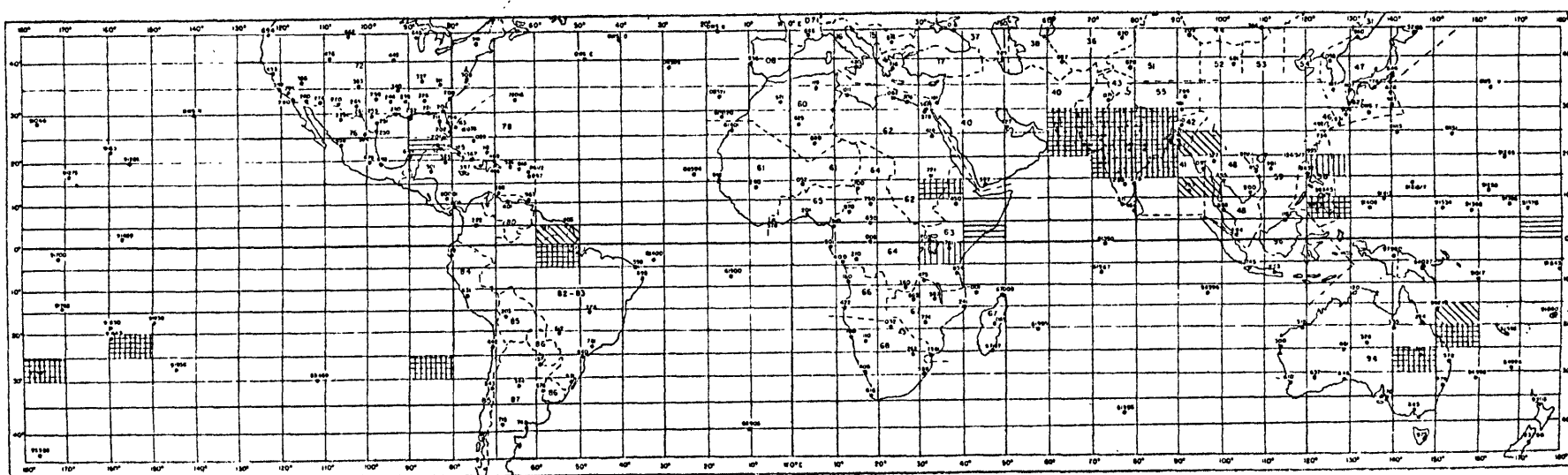


Fig. 19: As in Fig. 14 except for correlations with NE INDIA.

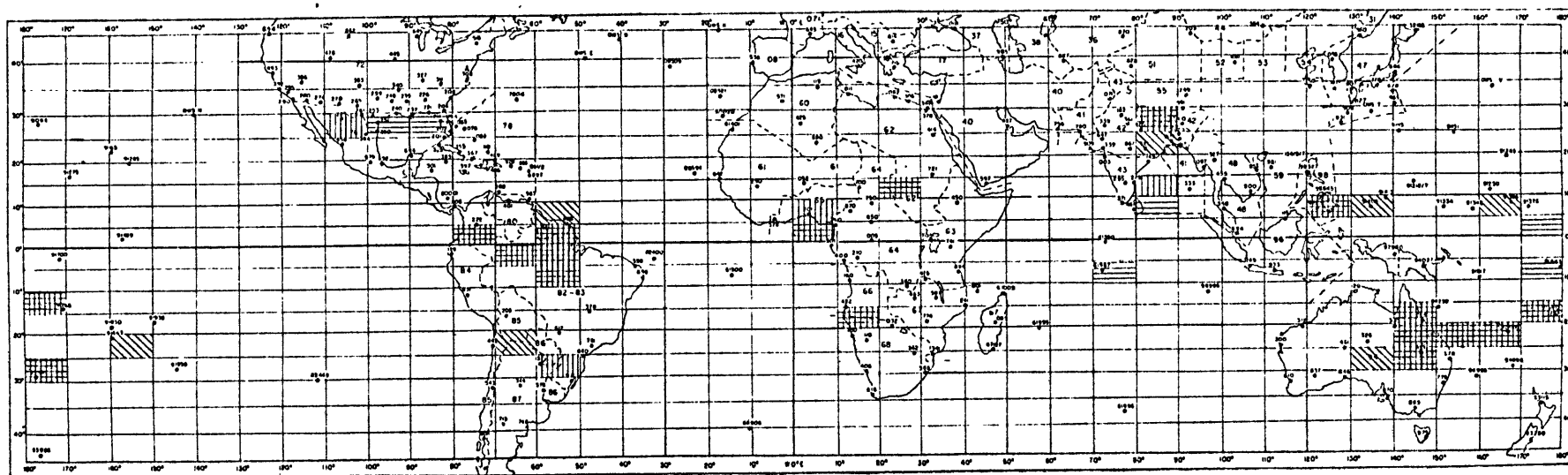


Fig. 20: As in Fig. 14 except for correlations with AMAZON.

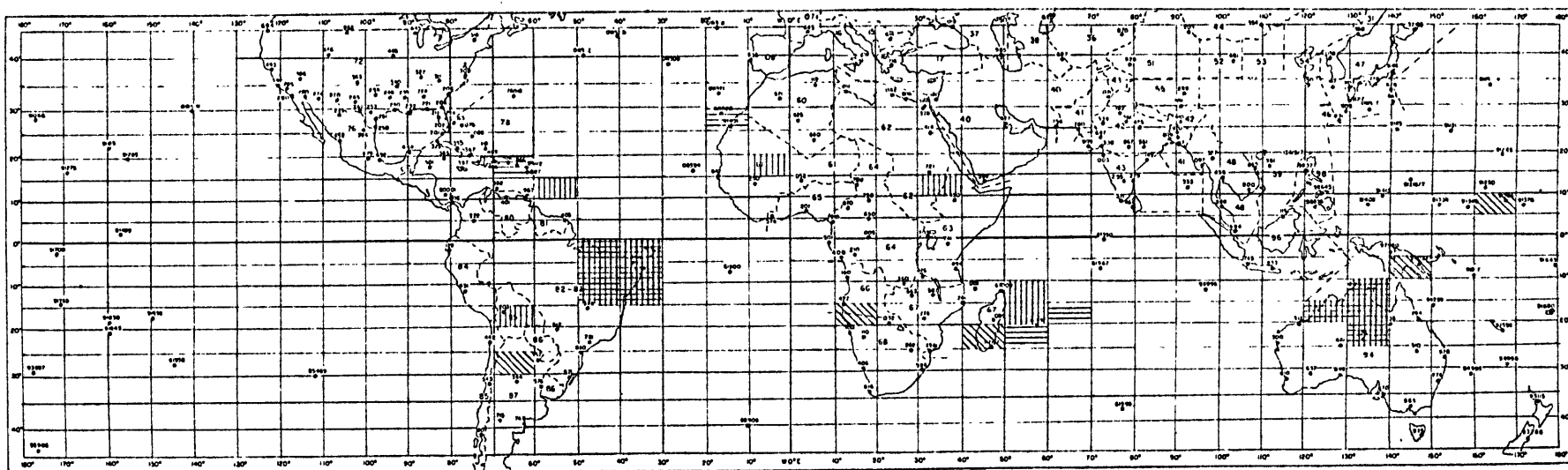


Fig. 21: As in Fig. 14 except for correlations with NE BRAZIL.

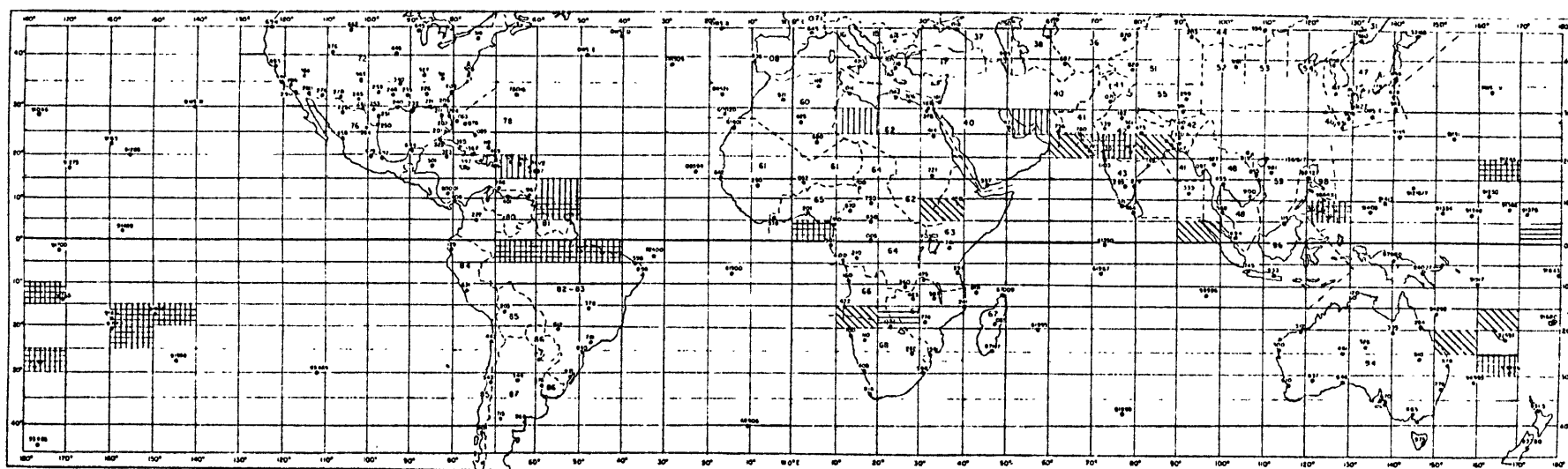


Fig. 22: As in Fig. 14 except for correlations with SPI.



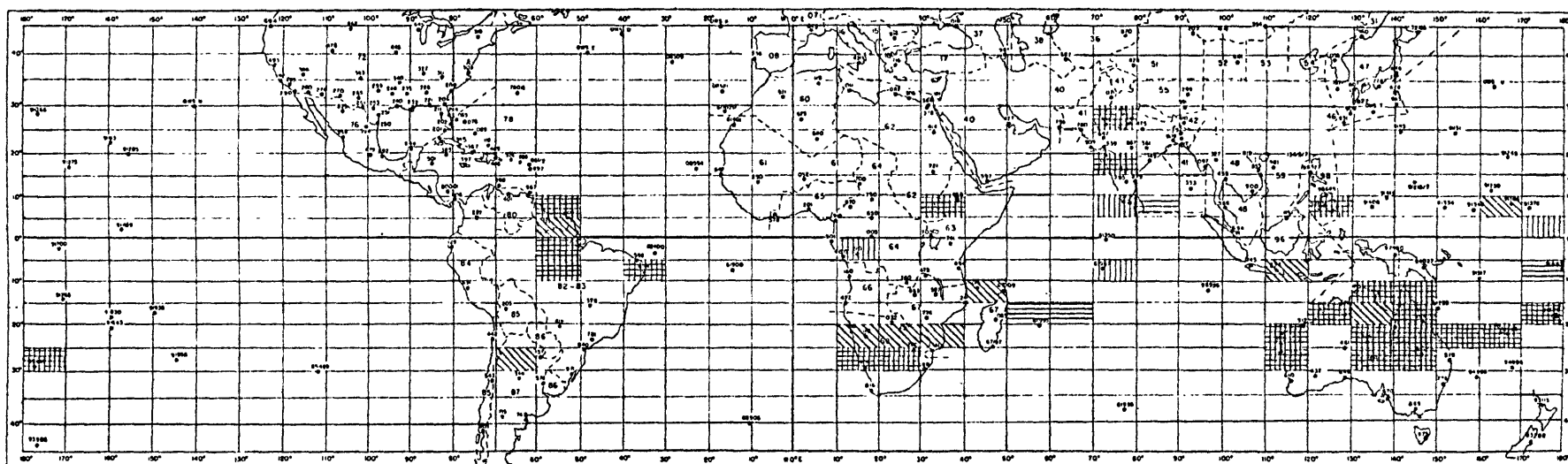


Fig. 23: As in Fig. 14 except for correlations with AUSTR.

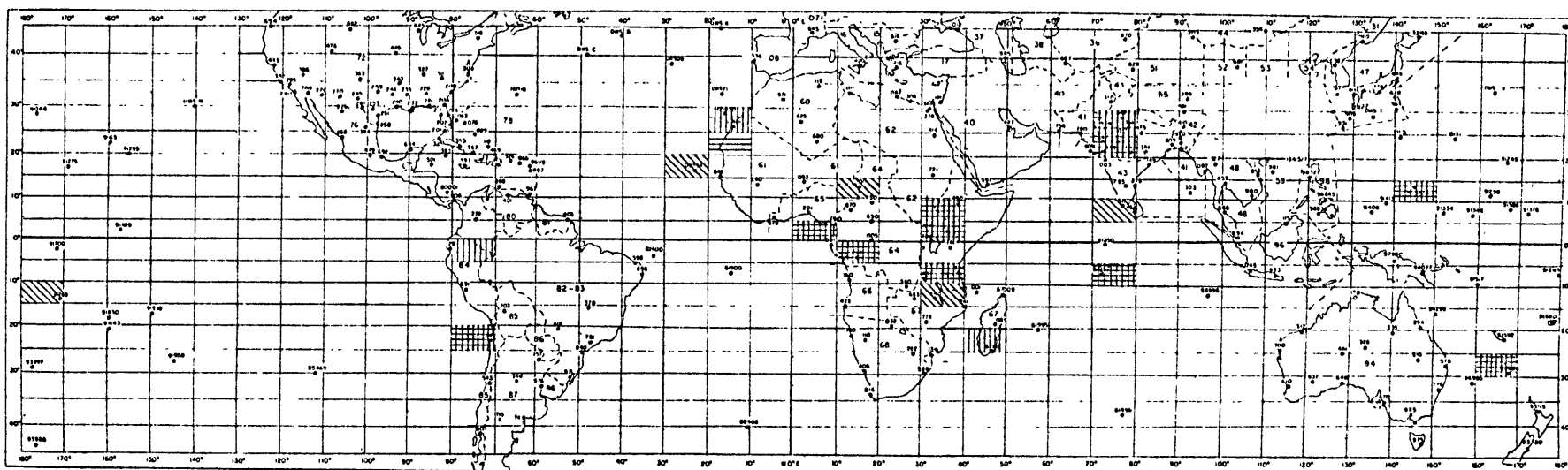


Fig. 24: As in Fig. 14 except for correlations with C. AFRICA.

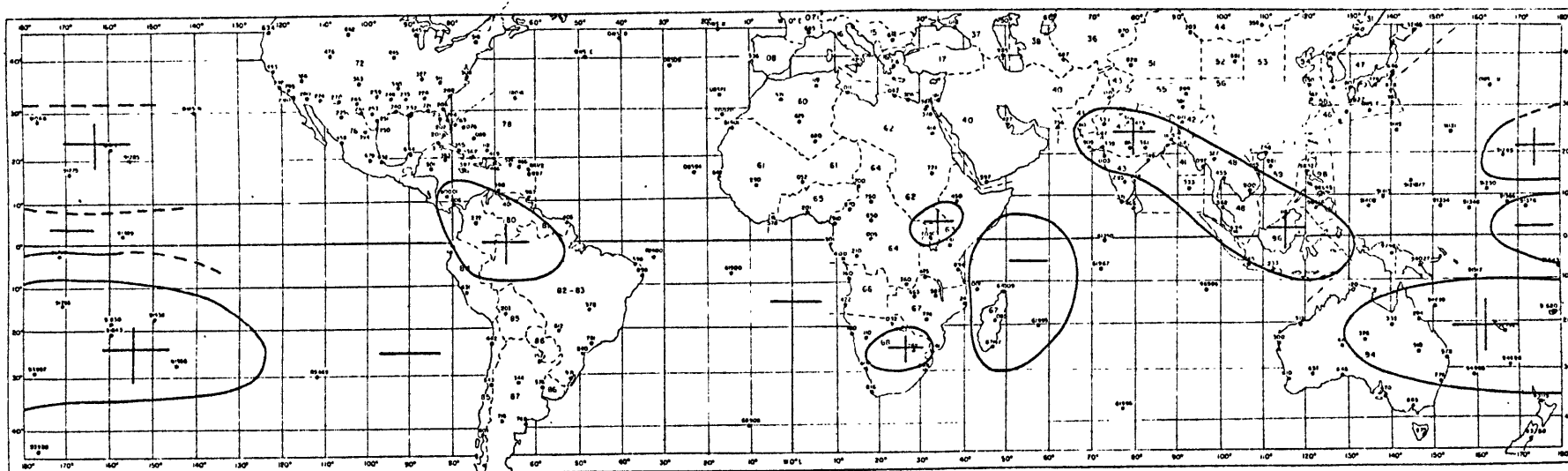


Fig. 25: Approximate locations of centers of rising (+) and sinking (-) branches of zonal circulations as evidenced by rainfall anomalies. Broken lines indicate uncertain boundaries. Lack of data over the oceans precludes locating cell boundaries there but signs are as indicated.