Variations in Moisture Deficits over the Maize-growing Region of South Africa II: Temporal Aspects

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Abstract

The behaviour of moisture deficits over the period 1945 to 1974 has been examined. Harmonic analysis of total moisture deficits for 11 sub-regions of the major maize producing area reveals the presence of high frequency oscillations. A space mean series for the study area as a whole has been determined and deviations in monthly deficits of this series provide insight into the nature of wet and dry rainfall periods reported in the literature. Strong evidence has been found that monthly totals should be used rather than annual totals, although the latter may be useful in a general climatic survey.

Introduction

The effect of climatic variability on food production has recently received much attention on an international scale (McQuigg, 1975; National Academy of Science, 1975; Thompson, 1975; Kellogg and Schware, 1981). In a series of papers published during the 1970's it has been shown that since the turn of the century South Africa has experienced a number of regionally and temporally distinctive rainfall variations (Tyson, Dyer and Mametse, 1975; Tyson and Dyer, 1975, 1978; Dyer, 1975, 1976). In addition, temporal order was isolated in temperature (Keen 1971) and rainfall runoff (Abbott and Dyer, 1976) over South Africa.

It has been shown in an earlier paper (Gillooly and Dyer, 1982) that moisture deficits form an aridity index which combines the effects of rainfall and temperature, the latter being strongly related to evaporative demand. It is hypothesized that moisture deficits will exhibit temporal order as a result of above- and below-normal periods of rainfall. For this reason, a description of temporal variations in moisture deficits over the record period, 1945 — 1974, is dealt with in this paper.

Method

Temporal changes in moisture deficits were considered on two scales: firstly on a seasonal basis and then on a monthly time scale. Within each time scale temporal variation was examined on a regional basis and then for the maize-growing area as a whole. In order to achieve the latter, a space mean series was determined from the arithmetic mean of the original regional series (Gillooly and Dyer, 1982). Accumulated moisture deficits for the months of July to March, hereafter referred to as total moisture deficits, were determined for each of the 30 years. These time series (11 regions) were then analysed using Jenkinson's (1976) modified version of harmonic analysis. This method removes the constraint placed on resolution in straightforward harmonic analysis, and having to guess a maximum lag for use in the conventional spectral approach to analyses over the frequency domain (Dyer, 1978).

Results and Discussion

Analysis of Total Moisture Deficits: Regional Scale

Total moisture deficits (expressed as deviations from the long term mean) were plotted for each region for the period 1945 to 1974 (Fig. 1). Deviations greater than plus or minus one standard deviation have been shaded. The larger deficits of the western regions (Figs. 1a — f) compared to the eastern ones (Figs. 1g — k) agree with the spatial patterns of mean total deficits described by Gillooly and Dyer (1981). In this paper fluctuations from one year to the next and between groups of years are of most interest. For example, during the 1950's total deficits were generally lower than in the later 1940's or the 1960's, particularly in Regions C, D, F and I.

A striking feature evident in Fig. 1a — e is the frequency of large deviations at the beginning and end of the record, that is, from 1945 to 1951 and from about 1967 onwards, respectively. Most years during the 1950's have below normal total deficits which are also less variable than the remainder of the record. This pattern of high-low-high variability becomes less distinct as one moves northwards and eastwards, for example, Region F. Further east (Figs. 2g — i) the deviations in the late 1940's are not as striking and, apart from 1951, large values occur after 1965. On the whole it is possible to distinguish groups of years with similar deviations in total moisture deficits. In most regions the 1950's are inversely associated with the 1960's but positively associated with the 1970's. This means that below-normal moisture deficits in the 1950's and 1970's were interrupted by a period of above-normal deficits indicative of a dry spell.

Another feature portrayed in Fig. 1 is the magnitude of the deviations in the west compared to those in the east. In the former areas (Fig. 1a — f) shaded deviations are not only more numerous but also larger than those in the eastern parts of the study area (Fig. 1g — k). A plot of the standard deviation of each regional series (Fig. 2) illustrates that in Regions A and B the standard deviation is more than 150 mm, decreasing to values of about 130 mm in the intermediate corridor, that is, Regions C, D, E and F. Minimum values of 90 to 110 mm are found in Regions H, J and K pointing to the greater year-to-year stability of

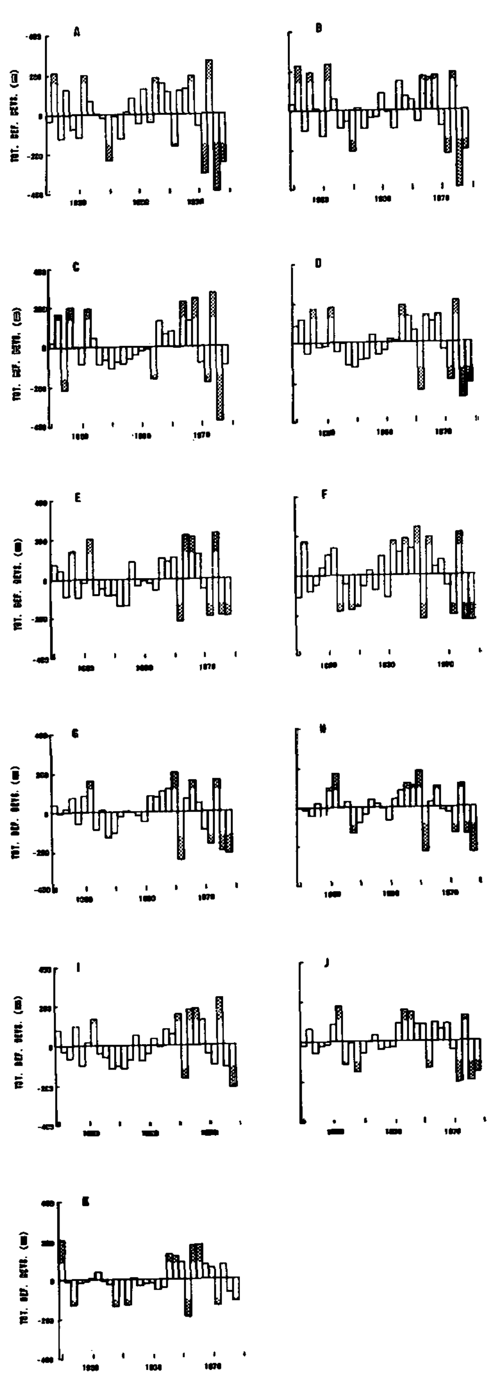

Figure 1
Total moisture deficits (mm) expressed as deviations from the long term regional mean (1945 – 1974) for Regions A to K. Shaded areas indicate deviations greater than plus or minus one standard deviation

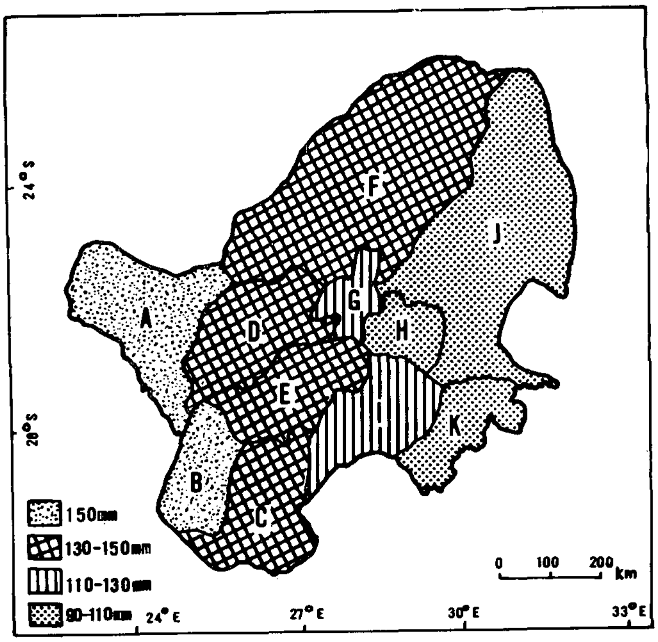

Figure 2
Variation (standard deviation) of regional total moisture deficits, expressed as deviations from the regional mean, showing the increase from east to west

TABLE 1
RESULTS OF HARMONIC ANALYSIS ON TOTAL DEFICITS FOR EACH REGION

First differences were taken to exclude the longer wavelengths and to emphasize shorter ones

REGION	2 – 3 YEARS			3 – 4 YEARS		
A	2,17	2,35	2,65	2,93		4,11
B	2,17	2,35	2,59	2,93		4,03
C	2,17	2,35	2,59	2,93	3,36	3,95
D	2,17	2,35	2,65		3,43	4,03
E	2,17	2,39	2,65		3,43	4,19
F	2,21	2,49	2,75		3,30	3,87
G	2,12	2,39	2,70		3,50	
H	2,12	2,39	2,75		3,57	
I	2,17	2,39	2,70		3,43	4,11
J	2,12	2,36	2,65		3,64	
K	2,12	2,44				3,95

moisture deficits in these areas. These results suggest that in the west conditions are not only more severe but also less reliable than those in the east.

Harmonic analysis was carried out on total deficits for the period 1945 to 1974 for each of the 11 regions, the spectra for which are given in Fig. 3a – k. Only the high frequency end of the spectrum is presented because with a time series of 30 terms it is of little value to consider low frequency oscillations. Moreover, the variances of these higher frequency oscillations have been enhanced by taking first differences of the series to remove the longer waves from the data. To enable comparison between regions the predominant waves and their variances have been tabulated (Table 1).

In the 2 to 3 year wave range there are three main oscillations: the 2,1 year, the 2,35 year (quasi-biennial) and the 2,6 year oscillations. The former two are present in all regions but the 2,6 year oscillation is absent in Region K (northern Natal). The 2,35 year oscillation is strongest in Regions D, E and J whilst the 2,6 year wave is most pronounced in the dry western areas namely Regions A, B and C (Fig. 3; Table 1).

There are two peaks in the 3 to 4 year wave range which warrant mention. The 3,4 year wave is exhibited largely by the eastern regions (Regions E, G, H, I and J) and is fairly strong in comparison to the 3,9 to 4,0 year oscillation which is associated mainly with the western sector (Regions A, B, C, D and F). Northern Natal (Region K) behaves differently to other eastern

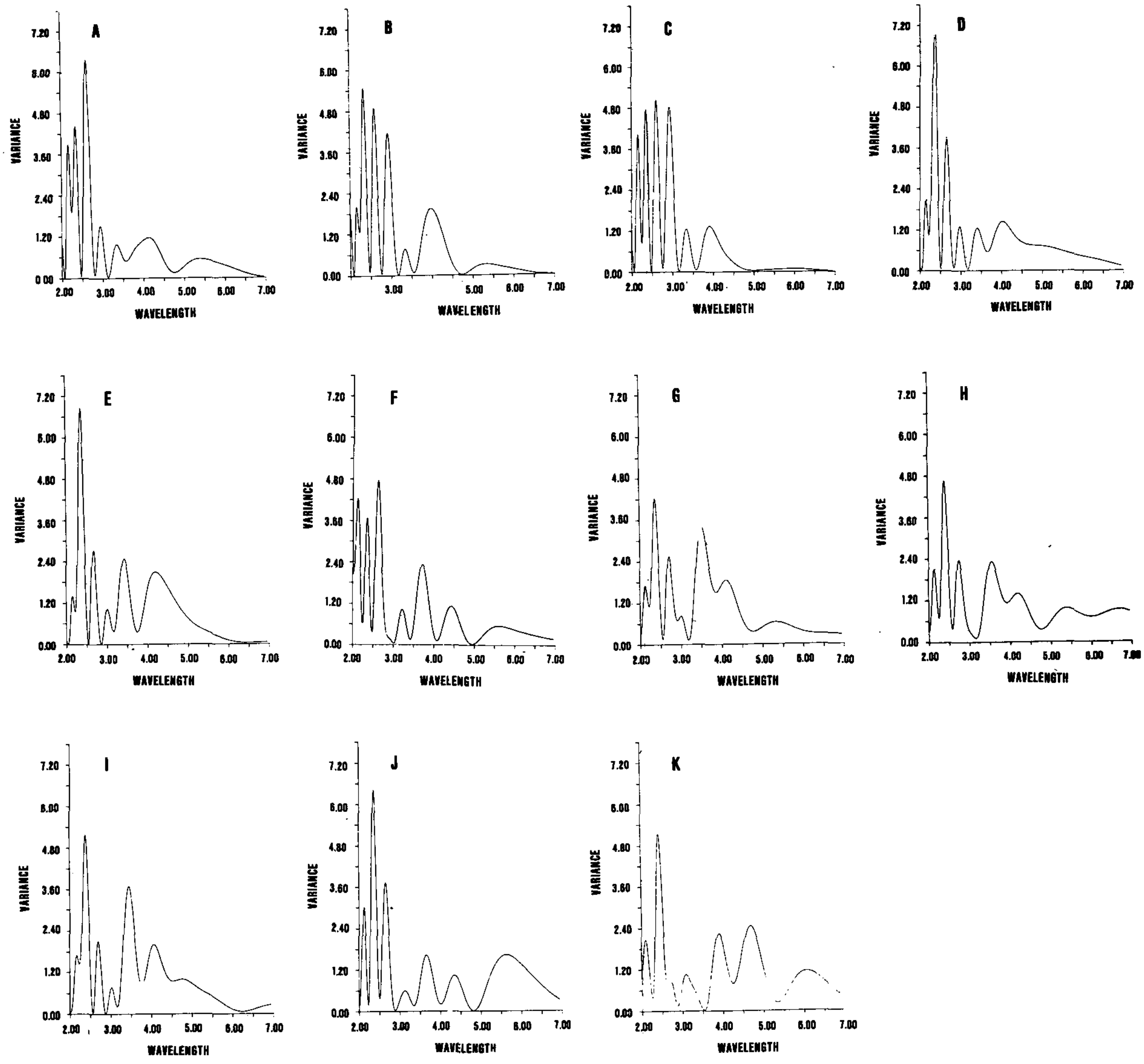

Figure 3
Spectra of total moisture deficits for Regions A to K

regions in that it has a peak at 3,9 years rather than 3,4 years but this could be due to sampling fluctuations (Fig. 3). The fact that both the 2 to 3 and the 3 to 4 year wavebands have been found in rainfall spectra over southern Africa (Dyer, 1976) lends credence to the reliability of total moisture deficits as an agroclimatic index. Furthermore, this index would be of use in studies of the effect of climatic variability on maize production.

Finally, the 5 to 6 year wave range shows some evidence in the furthermost eastern regions only, namely, Regions J and K (Fig. 3j,k). This suggests that the mechanism which generates rainfall in these areas, and hence governs the variability of moisture deficits, behaves differently to the rainfall forcing function in the western areas.

Behaviour of Total Moisture Deficits: Maize Area as a Whole

Total moisture deficits for the space mean series, expressed as deviations from the long term mean, have been plotted (Fig. 4). The blocked nature of below-normal deficits in the 1950's and

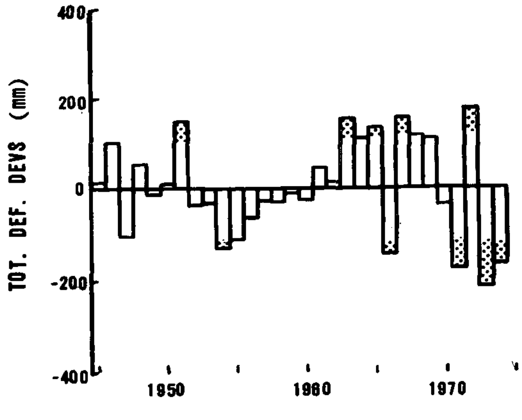

Figure 4
Space mean series of total moisture deficits (mm) expressed as deviations from the long term mean. Deviations greater than one standard deviation have been stippled

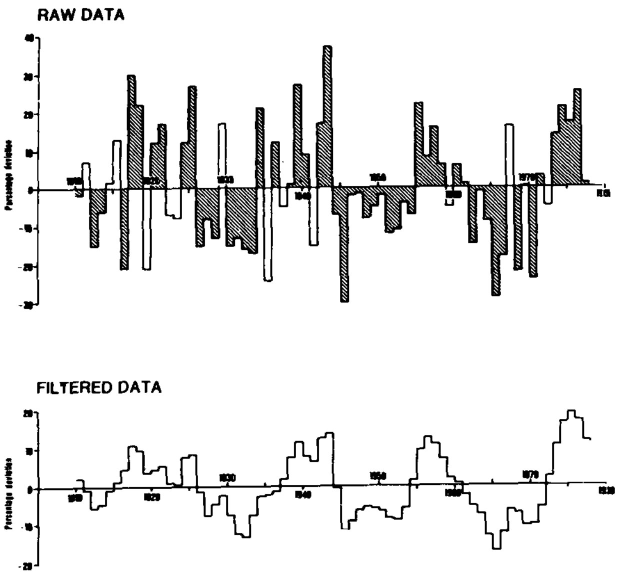

Figure 5
Mean annual rainfall (January – December) expressed as percentage deviations from the 1910 to 1977 mean, for the summer rainfall region as a whole. In the upper diagram (raw rainfall data) individual wet and dry years conforming to the spells in the smoothed series (lower) have been shaded (after Tyson and Dyer, 1978)

the 1970's and the above-normal deficits in the late 1940's and the 1960's emphasizes the undulatory pattern in moisture deficits over the period of record. These periods of above- and below-normal total deficits agree with the temporal distribution of annual rainfall for the summer rainfall region as a whole (Fig. 5) in that wet periods coincide with low moisture deficit years and vice versa. It is ominous that the span of below-normal values tends to last longer than those above-normal.

Analysis of Monthly Moisture Deficits: Regional Scale

Monthly moisture deficits starting in July 1945 and ending in June 1975, that is 360 months later, have been plotted for each region (Figs. 6a – k). In some western regions there appears to be a wavelike trend between groups of years with high and low moisture deficits, indicating some form of oscillatory behaviour. It can also be seen that the buildup to the maximum value in January, for each year, is more regular in the western regions (Figs. 6a – f) than in the eastern wetter ones (Figs. 6g – k).

These temporal changes in monthly moisture deficits may be viewed to better advantage by drawing column charts of months against years (Fig. 7). This method was used by Ledger and Thom (1977) to illustrate the duration of severe moisture deficits during different seasons. Deficits greater than 50 mm have been stippled while those greater than 100 mm are shaded black to emphasize differences between years. In this way it can be seen that certain months, usually at the beginning and end of the season, behave more erratically than others. For example, in Regions C, D, E and F, November tends to have a run of low moisture deficits (less than 50 mm) then one severe deficit (greater than 100 mm) and then a run of deficits between 50 and 100 mm. The month of February behaves in a similar manner in Regions E to K (Fig. 6). These unexpected extremes in available moisture have serious consequences for crop production particularly when they occur during moisture-sensitive growth stages of the crop.

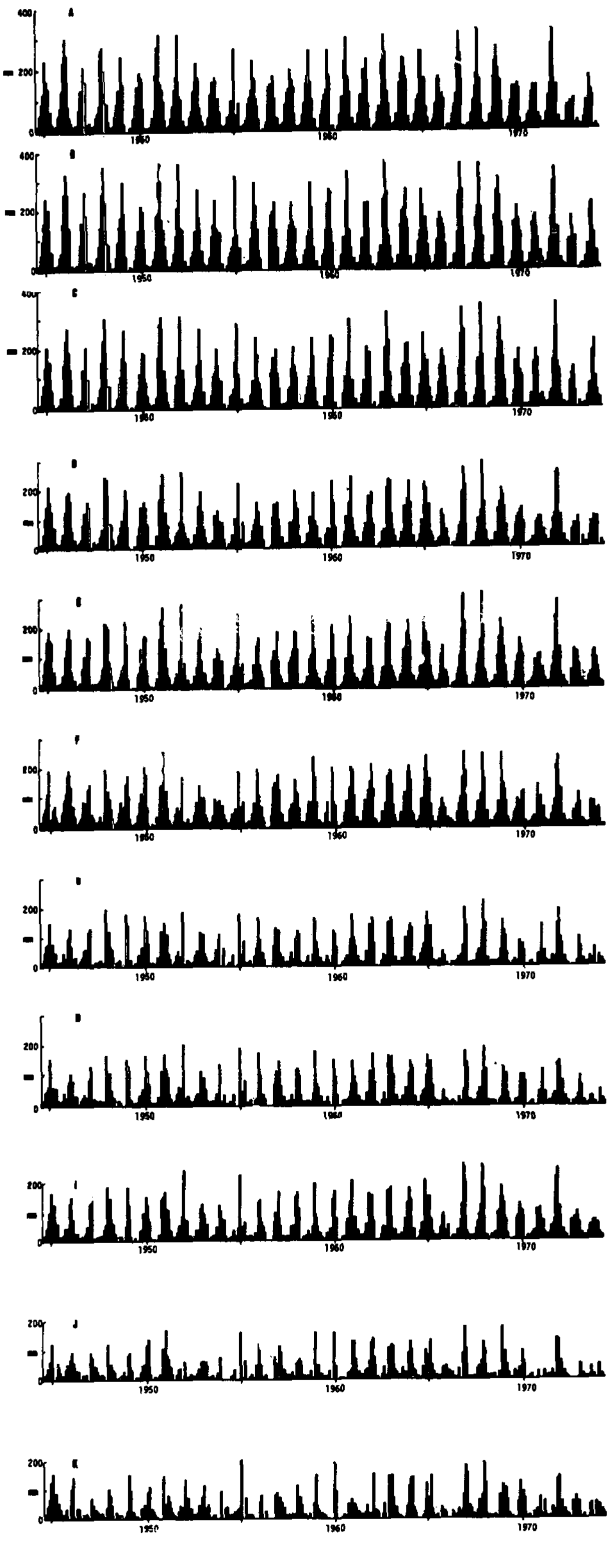

Figure 6
Monthly moisture deficits (July to June) for the 30 years (1945 – 1974) for all regions (A – K)

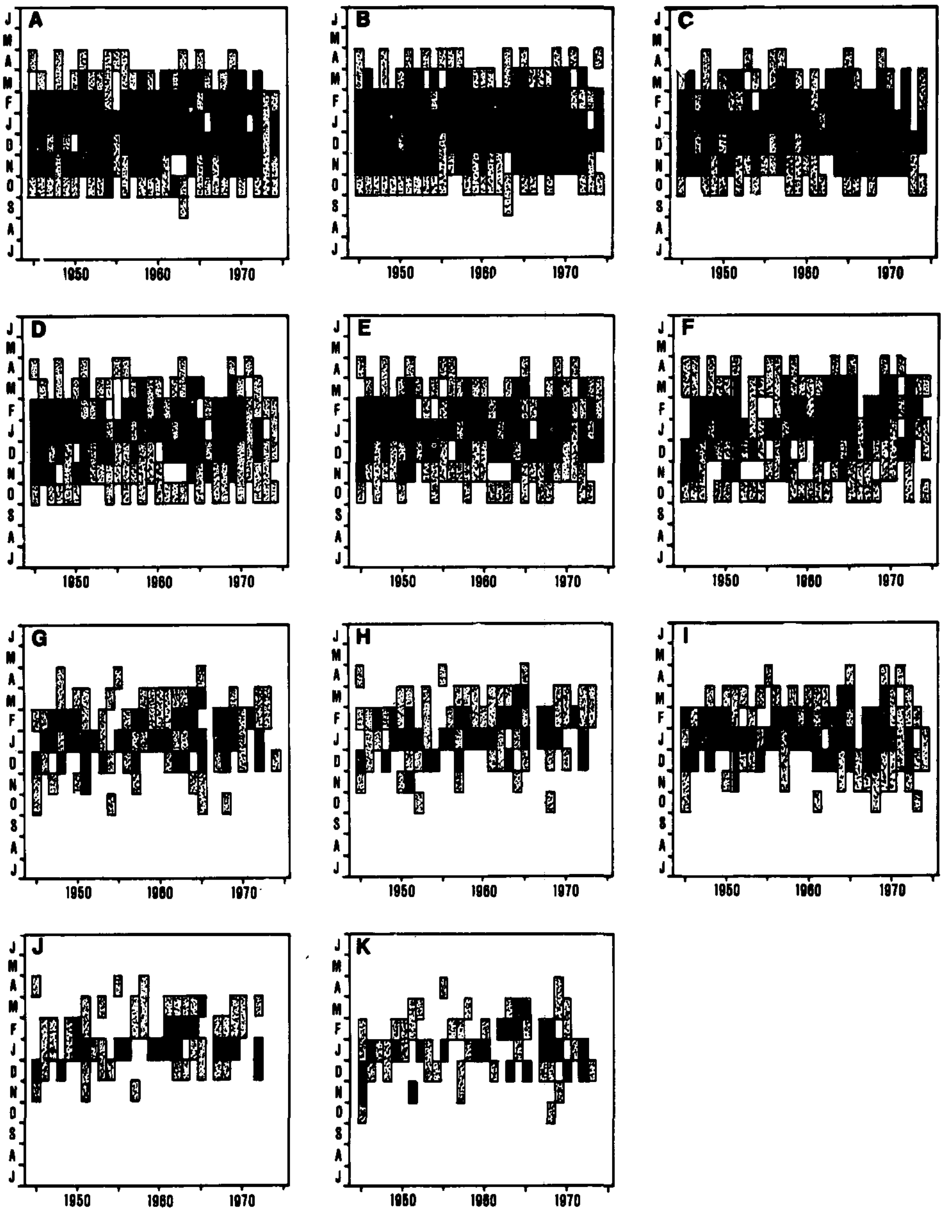

Figure 7
Duration of moisture deficits (mm) from July to June for the period 1945 to 1974 for Regions A to K. Deficits between 50 and 100 mm have been stippled while those greater than 100 mm have been shaded black

In order to examine intra-seasonal changes between groups of years, we consider Region F which was seen earlier to exhibit a marked change in magnitude of total moisture deficits between the 1950's and the 1960's. It can be seen from Fig. 7f that during the 1950's mid-season moisture deficits were low with only occasional months having deficits greater than 100 mm. On the other hand, the 1960's had large mid-season moisture deficits usually lasting from December to March. In other words, during low rainfall periods (1960's) moisture deficits are not only more severe but also their duration within a season is much longer. This point emphasizes the need to investigate rainfall variations in southern Africa in a similar way to moisture deficits in this study, that is, on a time scale shorter than annually, for instance, on a monthly basis.

Behaviour of Monthly Moisture Deficits: Whole Maize Area

Moisture deficits of the space mean series, expressed as percentage deviations from the mean have been plotted for each month (September to April) (Fig. 8). Deviations greater than plus or minus one standard deviation have been stippled. Months with the largest variability are April and March which have standard deviations of 63 and 52%, respectively, and October and November which both have standard deviations of 42%. These results tie in with earlier findings regarding the variability of moisture deficits at the beginning and end of the season (Fig. 7).

Information in Fig. 8 shows quite clearly that, whereas deficits may have been relatively low for a year as a whole, the month-to-month variation within a particular year can be con-

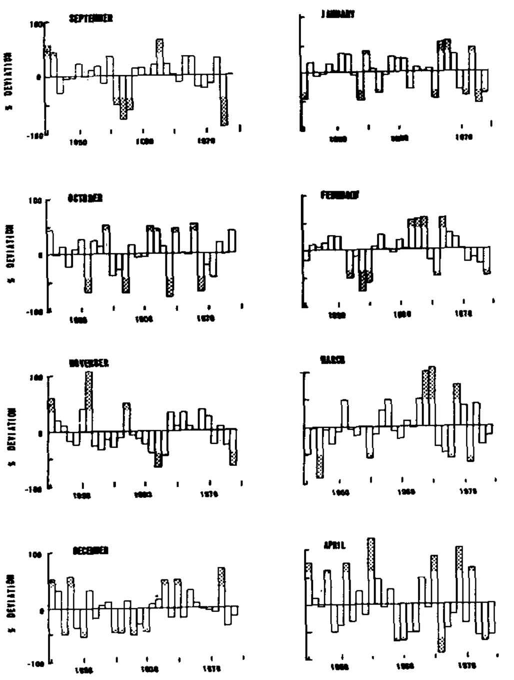

Figure 8
Moisture deficits of space mean series for each month (September to April) expressed as percentage deviations of the mean monthly deficit. Standard deviations of different months are September 40%; October 42%; November 42%; December 39%; January 36%; February 38%; March 53%; and April 63%

siderable. The year 1951 provides a good illustration of this point. In September the deviation was zero; in October there was a deviation of −74% followed in November by one of 118% and deviations of 36% in both December and January; in February the deviation was again zero and in March and April values of 54 and 82%, respectively, were obtained.

Bartlett's test was used to test whether the variability from one month to the next was statistically significant or not. This test is based on a statistic whose sampling distribution is closely approximated by the chi-square distribution when the random samples are drawn from independent normal populations. It was found that the null-hypothesis of equal monthly variations was rejected at the 1% level. These results stress the need to analyse the behavioural patterns of monthly moisture deficits (or rainfall) because the variability from month-to-month is high. Annual values are inadequate because, by smoothing out, they mask the true behaviour of the data.

A frequency count of deviations larger tnan one standard deviation (Fig. 8) was carried out for each month (September to April) for six groups of five years (Table 2). The superscript in Table 2 gives the number of significant positive deviations, the remainder then being the number of negative deviations. From values of Total 1 it can be seen that months with the greatest number of large deviations are October, December, January and April. The maximum number of large positive deviations occur during April and the most frequent negative values are found in January. Positive deviations in April, however, are not only more numerous than in other months but also more severe (Fig. 8). On the other hand, negative deviations in January are less severe than in other months, being only slightly larger than one standard deviation.

TABLE 2
FREQUENCY OF OCCURRENCE OF ANNUAL DEVIATIONS IN MOISTURE DEFICITS GREATER THAN ONE STANDARD DEVIATION FOR THE MONTHS SEPTEMBER TO APRIL
(See Fig. 8). The superscript gives the number of positive deviations in each month

CLASS (Years)		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total 2	TOTAL DEVIATIONS +	TOTAL DEVIATIONS −
1945–49		2^2	1^1	1^1	3^2	1^0	0	1^0	2^2	11	8	3
1950–54		0	2^1	2^2	1^0	1^0	2^0	1^1	1^1	10	5	5
1955–59		3^0	1^0	1^1	3^0	2^1	1^0	1^0	2^1	14	3	11
1960–64		1^1	3^2	2^0	2^1	0	3^3	2^2	1^0	14	9	5
1965–69		0	3^2	0	1^1	3^2	2^1	3^2	3^2	15	10	5
1970–74		1^0	1^0	1^0	1^1	4^1	1^0	1^0	2^1	12	3	9
TOTAL 1		7	11	7	11	11	9	9	11	76		
DEVIATION	+	3	6	4	5	4	4	5	7		38	
	−	4	5	3	6	7	5	4	4			38

The frequency of large deviations over groups of years for the full eight month period is obtained from Total 2 in Table 2. Large values of Total 2, however, do not necessarily indicate great variability during a group of years since extreme values of the deviations are not taken into account. The greatest number of positive deviations occurred during the period 1945 – 1949, 1960 – 1964 and 1965 – 1969, periods which agree with the dry spells isolated by Tyson *et al* (1975). Conversely, the highest frequency of large negative deviations occurred between 1955 and 1959, and from 1970 to 1974. The years 1950 to 1954 seem to span the transition from severe (late 1940's) to less severe (mid-1950's) moisture deficits since the frequency of large positive deviations equals that of large negative ones during the former period. A chi-square test, carried out to determine whether the frequency of positive deviations was significantly different from that of negative ones, showed that the difference between the two frequencies was significant at the 1% level.

It has been possible to isolate high risk months in terms of moisture deficits over the whole maize producing area. In addition, groups of years have been shown to possess significantly different frequencies of large positive and negative deviations. The fact that these deviations link up with the temporal order in rainfall documented earlier, lends credence to the moisture deficits analysed here. It has also been shown that the behaviour of April and October deficits, being most responsible for large moisture deficits (positive deviations) should be examined more closely. This could be done using frequencies of different synoptic situations during these two months, in an attempt to isolate the generating mechanism of temporal order in rainfall and hence moisture deficits.

Conclusions

Moisture deficits have been shown to be more severe and more variable in the dry western parts of the maize growing region of South Africa. The greater variability of moisture deficits in the west is of relevance to agricultural planning since in this area maize is commonly grown under marginal dryland conditions. Moreover, it has been possible to isolate months, or groups of months, during the growing season when deficits exhibit marked variability. Finally, the isolation of periods of above- and below-normal moisture deficits between 1945 and 1975 suggest that the moisture deficit term provides a potentially useful index for assessing the impact of climatic variability on food production in South Africa

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