Variations in Moisture Deficits over the Maize-growing Region of South Africa I. Spatial Aspects

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Abstract

Moisture deficits, equal to the difference between the supply of water (rainfall) and the demand (potential evapotranspiration) for it by the soil-plant system, have been determined for the maize growing region of South Africa. The behaviour of these moisture deficits on a spatial basis has been described on both monthly and seasonal time scales. Differences between large moisture deficits in the drier western areas, indicative of high evaporative demand and moisture stress conditions, and lower deficits in the moist eastern regions have been highlighted.

Introduction

Maize production in South Africa is restricted largely by lack of rainfall and, to a lesser extent, the incidence of excessively high temperatures (Theron, Matthews and Neethling, 1973; Gillooly, (1978). The spatial variation of annual rainfall over the country has been described by Gillooly and Dyer (1979) and temporally by Tyson, Dyer and Mametse (1975), Tyson and Dyer (1978) and Dyer (1975, 1976). Because of likely interaction between rainfall and temperature in their effect on maize yields, an aridity index which combines these two elements has been determined (Gillooly, 1980). This paper deals with the spatial variations of the aridity index, termed the moisture deficits, over the officially defined maize-growing region of South Africa. A companion paper (Gillooly and Dyer, 1982) deals with the temporal behaviour of these moisture deficits during the time period 1945 to 1974.

Data

The area under study is the officially defined maize-growing region of South Africa (S.A. Maize Board, 1980). This area produces about 95% of total maize production and covers about 530 000 km^2. The study area has been delimited into 11 maize-growing regions. This subdivision differs from the official one in that the Northern and Eastern Transvaal has been separated into two regions (F and J, respectively) roughly along the 600 mm isohyet

Rainfall records for officially defined rainfall districts have been used (S.A. Weather Bureau, 1972, 1976). On average, there are about 10 rainfall stations in each official rainfall district. The advantage of using district rainfall rather than individual station records is the increase in reliability when rainfall measurements are averaged over a contiguous region. The 34 rainfall districts covering the study area (Fig. 2) provide monthly rainfall totals for the interval 1945 to 1974.

Weather stations providing continuous records of monthly maximum and minimum temperatures for the 30-year period (1945 – 1974) are shown in Fig. 2 (S.A. Weather Bureau, 1945 – 1974). Because temperature is a conservative element over large areas, particularly when there is little topographical relief, this number of stations was considered adequate for the present study.

Method

Open-water evaporation has been estimated using Linacre's (1977) equation. This is essentially a simplification of Penman's (1948) equation and requires only simple geographical data and temperature records. The equation for the rate of evaporation from an open-water surface is:

$$E_o = \frac{700\,T_m/(100-A) + 15(T-T_d)}{80-T}\ (\text{mm d}^{-1}) \qquad (1)$$

where $T_m = T + 0{,}006h$, h is the elevation (m), T is the monthly mean temperature (°C), A is the latitude (degree) and T_d is the monthly mean dewpoint temperature (°C). Monthly mean values of the term $(T-T_d)$ are obtained using the following empirical relationship, provided precipitation is at least 5 mm per month and $(T-T_d)$ is at least 4°C:

$$T-T_d = (0{,}0023h + 0{,}37T + 0{,}53R + 0{,}35R_{ann} - 10{,}9)\,°\text{C} \qquad (2)$$

where R is the mean daily range of temperature and R_{ann} is the difference between the mean temperature of the hottest and coldest months.

In comparing estimated rates of water evaporation (from eq. 1) with measured rates of pan evaporation, Linacre (1977) found that the average error for monthly mean estimates for locations in various climates was 0,5 mm d^{-1}. Similar errors were found when eq. 1 was compared to pan evaporation data for several South African stations. The difference, however, was considered small compared to the scale of the present analysis, and was discounted. Furthermore, the purpose of the present study was to examine relative spatial and temporal variations of derived moisture deficits rather than their absolute values.

To obtain a monthly total of potential evapotranspiration (ET_o), the daily rate E_o for each month was multiplied by 30,4

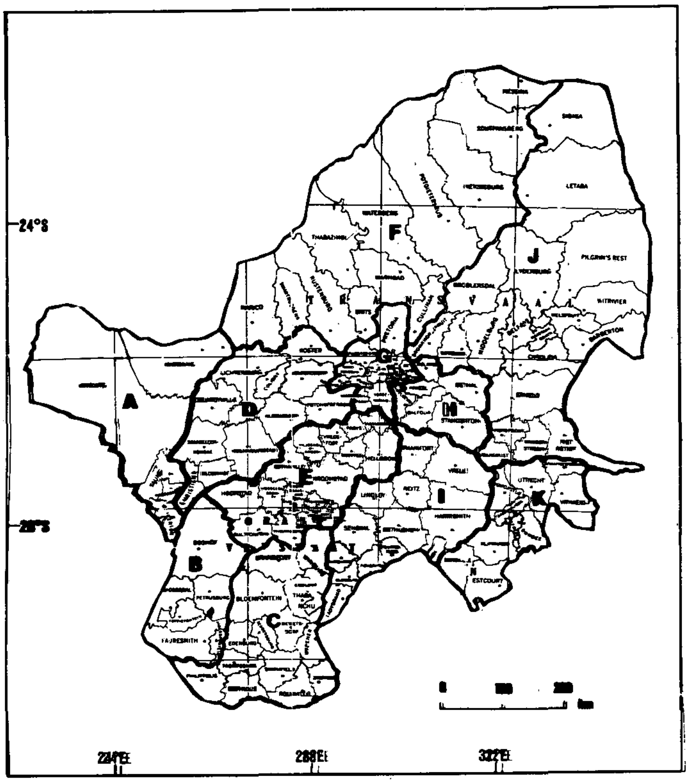

Figure 1
Distribution of magisterial districts within each region of the official maize producing area (S.A. Maize Board, 1980).
A Northern Cape; B — Western Orange Free State; C — Central and Southern Orange Free State; D → Western Transvaal; E — North-western Orange Free State; F — Northern Transvaal; G — Rand; H — Eastern Transvaal Highveld; I North-eastern Transvaal; J — Eastern Transvaal; K Northern Natal.

(average number of days in a month) and by an appropriate monthly crop coefficient (f). This determination was based on the relationship to relate potential evapotranspiration to the evaporation from a free water surface, namely

$$ET_o = f.E_o \qquad (3)$$

when f ranges from 0,2 during the fallow period and 0,4 at planting to 1,0 during full canopy (Gillooly, 1980).

By determining differences between water supply (rainfall) and water loss (evapotranspiration) potential moisture deficits were calculated (Ledger and Thom, 1977). These moisture deficits have been taken to represent an aridity index depicting relative shortages of available water over the maize producing area.

Results and Discussion

Total Moisture Deficits as a Single Measure of Aridity

Assuming an initial soil-water status of 0 mm at the end of a dry winter, a single measure of aridity was determined for each of the 25 weather stations. The total accumulated moisture deficit from July (to include pre-season effects) to the end of March provided the required single measure. These total moisture deficits were averaged for the period 1945 to 1974 and then mapped for each station (Fig. 3). A strong positive gradient from west to east is found, with the largest deficits occurring in the dry western sector and the lowest values in the eastern parts of the study area. Mean maximum temperatures during the flowering period in maize (taken to be January) increase from east to west (Fig. 4) whilst rainfall exhibits the opposite tendency (Fig. 5). Thus, the pattern in Fig. 3 is a combination of the effects of maximum temperature, and its effect on evaporative demand, and rainfall: the largest deficits being found in those areas having high temperatures and low rainfall.

On comparing Fig. 3 with Fig. 6 showing intensities of maize production, it can be seen that areas of high production coincide with areas experiencing large total moisture deficits. Moreover, mean maize yields (production/unit area) shown in Fig. 7 bear little resemblance to the pattern in Fig. 6, which indicates that high production intensities are obtained through large areas being cultivated rather than high yields *per se*.

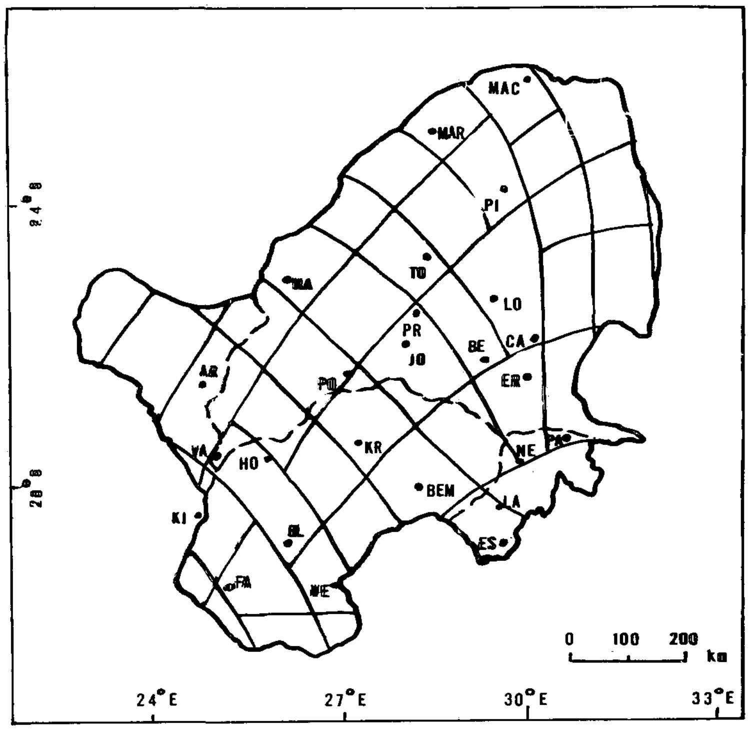

Figure 2
Distribution of temperature stations (●) in relation to officially defined rainfall districts (South Africa, Weather Bureau, 1972).
AR — Armoedsvlakte; BE — Bethal; BEM — Bethlehem; BL — Bloemfontein; CA — Carolina; ER — Ermelo; ES — Estcourt; FA — Fauresmith; HO — Hoopstad; JO — Johannesburg; KI — Kimberley; KR — Kroonstad; LA — Ladysmith; LO — Loskop; MAC — Macuville; MA — Marico; MAR — Marnitz; NE — Newcastle; PA — Paulpietersburg; PI — Pietersburg; PO — Potchefstroom; PR — Pretoria; TO — Towoomba; VA — Vaalharts; WE — Wepener.

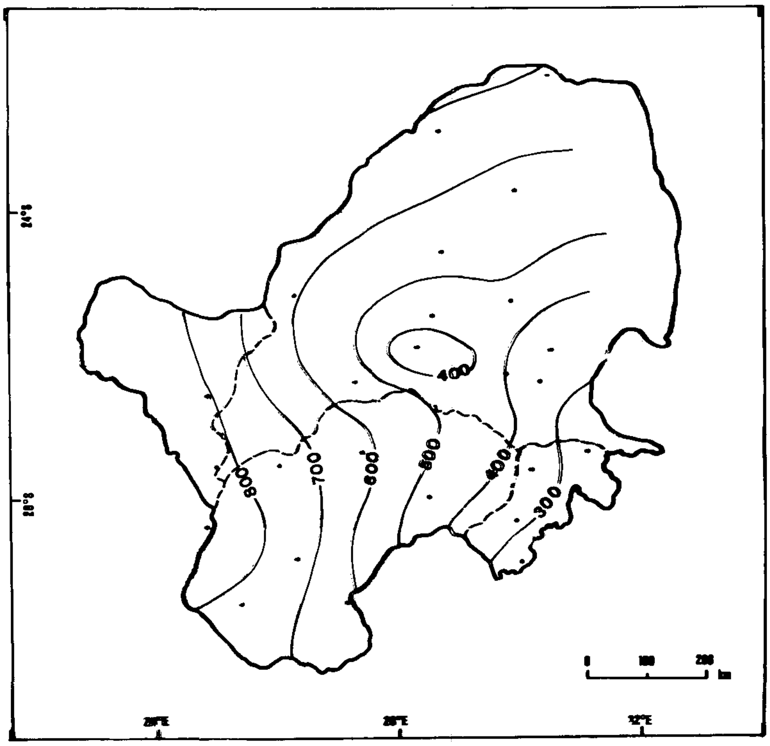

Figure 3
Mean total moisture deficits (mm) for the study area (1945—1974) showing higher deficits in the drier western areas than in the east. Dots denote temperature stations

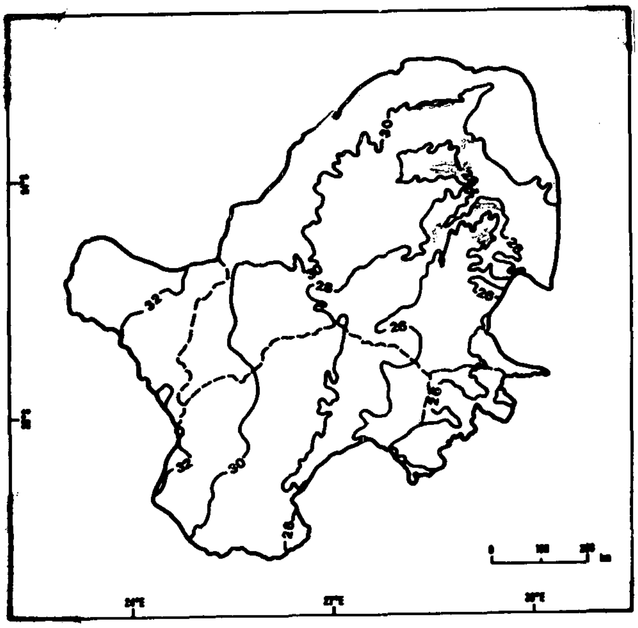

Figure 4
Mean maximum temperature (°C) during flowering of maize (January) showing increasee from east to west

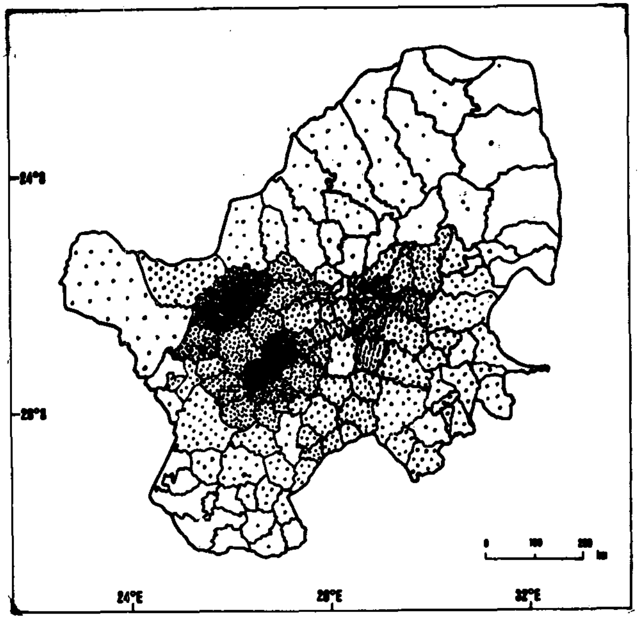

Figure 6
Intensity of maize production; one dot denotes 5 000 t

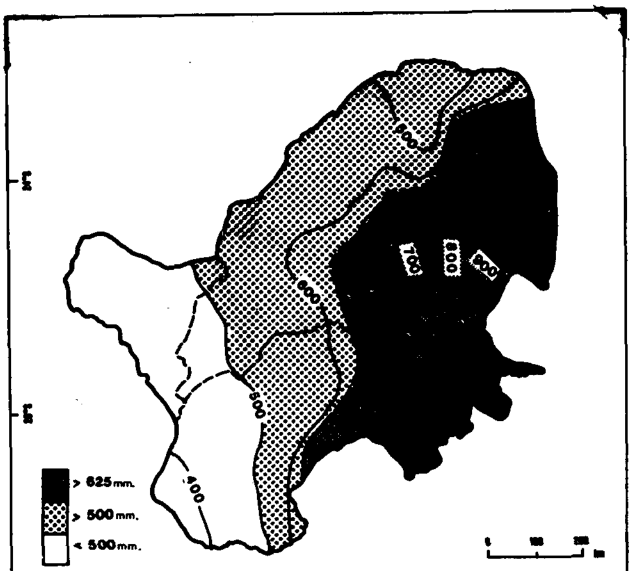

Figure 5
Mean annual rainfall (mm) for the hyetal year (July to June) showing the increase from west to east

Figure 7
Isolines of mean maize yields (t $ha^{-1}.10^2$) for the period 1945—1975

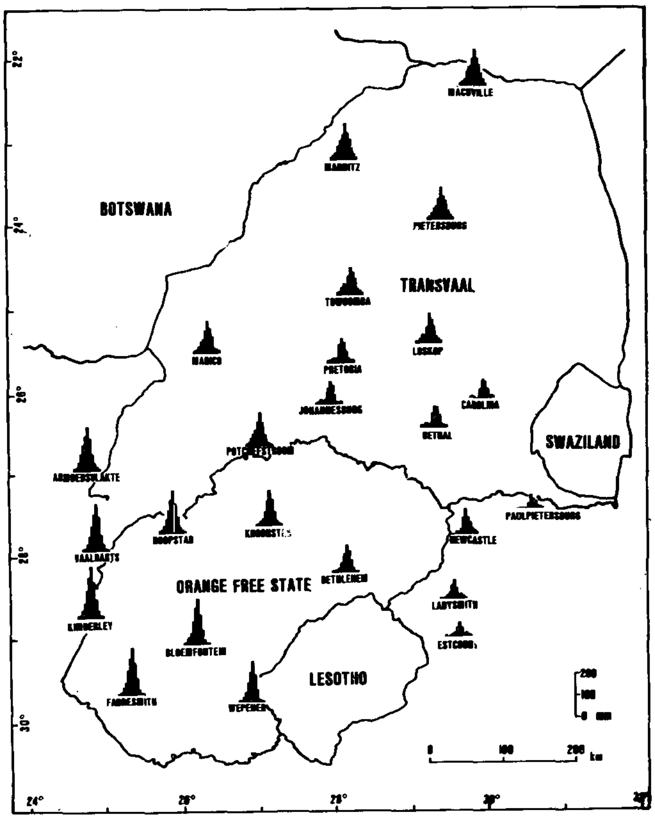

Figure 8
Mean monthly moisture deficits (July to June) for the study area as a whole

Monthly Moisture Deficits Over the Maize-Growing Area

The bar charts in Fig. 8 illustrate the intra-annual variation of mean monthly moisture deficits over the maize growing area. It can be seen that the greatest variation occurs in the west and decreases in an easterly direction. Because of the erratic nature of rainfall over South Africa, monthly moisture deficits are highly variable over time. In order to provide the expectation of particular moisture deficits being obtained during the growing season, probability estimates for monthly moisture deficits were determined for the period 1945—1974 for the 11 sub-regions (see Fig. 1). To assess the reliability of obtaining a particular deficit in a given month, confidence intervals were determined for each region. A 90% confidence interval means that, in the long run, the interval will have trapped the true monthly moisture deficit. With reference to Fig. 9, this means that the monthly moisture deficit will lie within the upper and lower limits in 9 out of 10 years (Hanna, 1976). The largest range between upper and lower confidence limits occurs when the mean monthly deficit is at a maximum, namely, in January. The range of the confidence interval may be looked upon as a measure of reliability, that is, the confidence that can be placed upon a given monthly mean deficit being within a given range.

In regions which tend to experience large monthly moisture deficits (A to F) the increase from about August to January and the decline thereafter is approximately linear (Fig. 9 a—f). However, in regions where the maximum is generally small (Regions G to K) the buildup in deficits from July to January tends to be non-linear (Fig. 9 g—k). In fact, there is a slow increase in moisture deficit from July to November and then a rapid increase to January. Had there been higher values in October and

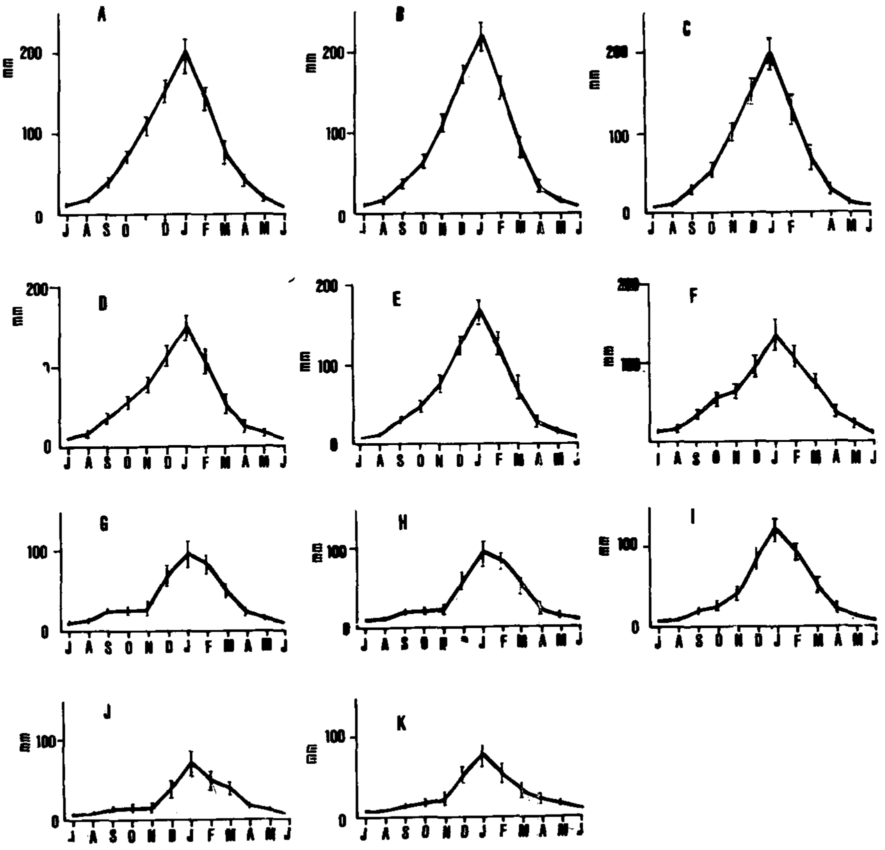

Figure 9
Mean monthly moisture deficits (July to June) with 90% confidence intervals for Regions A to K (see Fig. 1)

November then the pattern would have been approximately linear. This non-conformity in the eastern regions is probably related to the onset and seasonal behaviour of rainfall over the summer rainfall region.

One method for describing the seasonal march of rainfall over the study area is by using cumulative percentage frequencies to give the probability of a percentage frequency of rainfall being exceeded in any given time period (in this case, months). Curves of cumulative percentages of the mean annual rainfall (July to June) were plotted for each of the 34 rainfall districts (see Fig. 2). By using a suitable scale on the X-axis (months) it was possible, by interpolation, to determine by which part of a month a particular cumulative percentage of the rainfall (Y-axis) had been received. In this way cumulative percentage curves were used to determine the approximate number of days taken to reach the lower quartile (25%), the median (50%) and the upper quartile (75%) of annual rainfall. July 1 was taken as the first day and each month was assumed to be 30 days long. Days on which these three percentages were reached have been mapped for each rainfall district (Fig. 10). The 150-day isoline (Fig. 10a) means that, on average, by the end of the fifth 30-day period (that is November) 25% of the total rainfall has fallen. The lower quartile is reached in early November in the eastern areas and during December in the west. The median is reached by the end of December in the eastern Transvaal and by the end of January (210-day isoline) in the northern Cape and western Free State areas (Fig. 10b). The upper quartile is reached before the end of February in Natal whereas the western parts of the study area only attain this level near the end of March (Fig. 10c).

Because of the early onset of summer rains in the east, moisture deficits during November are smaller there than in the western parts. On the other hand, the combination of high temperatures and later rains results in larger moisture deficits during October in the East, and larger moisture deficits during October and November in the west. In this way Fig. 9 can be interpreted in terms of the seasonal march of rainfall given in Fig. 10. After the first flush of summer rains in the eastern areas moisture deficits tend to rise such that gradients from November to January in Regions G to K are fairly similar to those in Regions A to F for the same months (Fig. 9). For the latter regions, therefore, moisture deficits are not only larger but also of longer duration than those experienced in the east (Regions G to K). The gradient of the decline of monthly moisture deficits after January in Regions G to K is less steep than in A to F, meaning that in the former zone moisture deficits tend to persist from one month to the next after mid-season. However, the severity of monthly deficits in the west is probably more detrimental to maize production than the persistence of the milder ones in the east.

Intra-Seasonal Fluctuations of Aridity Over the Maize-Growing Area

The spatial variation in mean moisture deficits from one month to the next is illustrated for the period September to April (Fig. 11). September provides an indication of mean moisture deficits before the start of the rainy season proper, while April generally represents the maturity stage of the maize plant. The 50 mm isoline has been taken as a guide to the intra-seasonal fluctuations of aridity (Fig. 11). This level cannot be considered critical to growth, nor is there much biological justification for its use other than the fact that if maize transpires at an average rate of 4 mm d^{-1} (Gillooly and Mottram, 1979) then 50 mm constitutes

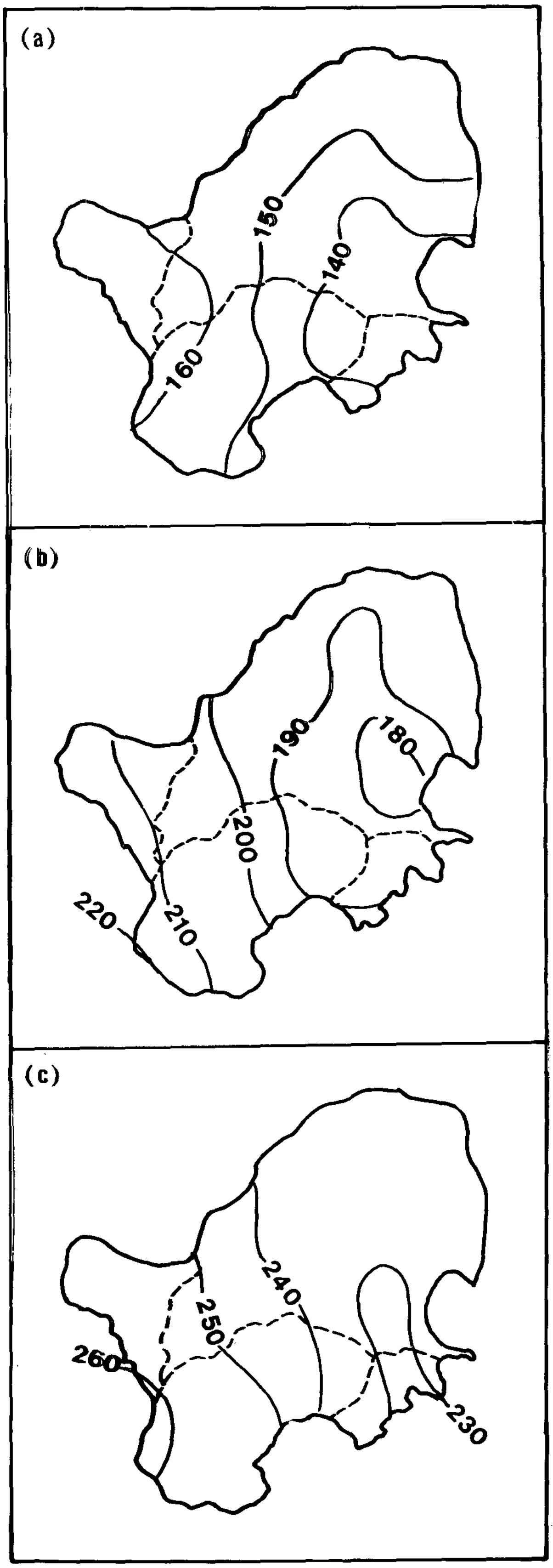

Figure 10
Seasonal march of rainfall from east to west as given by the number of days taken to reach the lower quartile (a), median (b) and upper quartiles (c) of rainfall. July 1 was taken as day one and all months assumed to be 30 days long

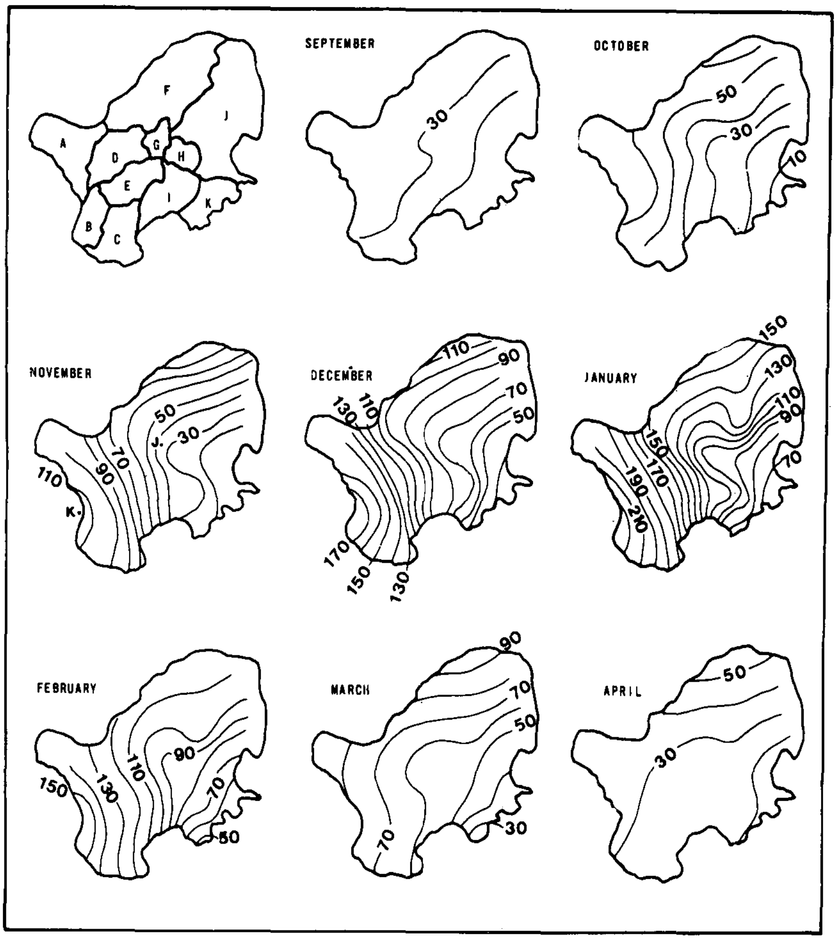

Figure 11
Mean monthly moisture deficits (mm) over the study area from September to April. Regional reference map in top left hand corner adapted from Fig. 1

about 12 days without water. Similarly, the 100 mm isoline would represent about 25 days without water assuming zero soil water storage.

During September (Fig. 11) mean moisture deficits are low, averaging about 30 mm over the maize area. Relief of the contours steepens during the next month, October, and the 50 mm contour appears. In Regions A and F mean deficits of at least 60 mm are experienced, whilst in the east low values between 10 and 20 mm are still present.

By planting time (November), the northwest-soutneast gradient of mean moisture deficit has developed a bend in the southern Transvaal such that isolines then increase from northeast to southwest. The highest deficits occur around Kimberley where deficits greater than 100 mm are experienced. By December about half the study area experiences deficits greater than 100 mm and only a small area in the east (mainly Region K) has deficits less than 50 mm. Gradients of moisture deficits are strong with values near Kimberley being about four times as great as those in northern Natal.

January is the month where available moisture is most scarce, that is, deficits are greatest. Mean deficits of 50 mm are nowhere to be found and about 75% of the study area experiences mean deficits of about 100 mm. During the month of January, maize generally reaches full canopy during which time evapotranspiration may increase to about 7 mm d^{-1} (Gillooly and Mottram, 1979). Hence, a deficit of 100 mm in this month constitutes about 14 days without water and not 25 days. In addition to reaching full canopy during January, maize also flowers about this time, a developmental phase well-known to be particularly sensitive to moisture stress (Garlipp, 1979). The coincidence of maximum moisture deficit and the flowering period of maize emphasizes the need for good agricultural planning in South Africa. For example, early planting (assuming adequate planting rains) of a short season hybrid with a high yield potential should permit the period of maximum moisture stress in January to be avoided.

The month of February is the turning point in the advance of moisture deficits over the study area with gradients that are less pronounced than either December or January. In the drier western zone (Region B) mean deficits are 90 mm larger than those in the east during February in contrast to a 130 mm difference found during December. In some areas, especially in the west, February may still represent the moisture sensitive flowering period.

The contour pattern exhibited during March is very similar to October, except in magnitude, the former being 20—30 mm larger than October values. These results point to a steady advance of mean deficits across the study area but a rapid spatial retreat after mid-season. By April only a small pocket in the northern Transvaal (Region F) have moisture deficits greater than 50 mm. Once again there is little relief and no marked gradients of the isolines are found.

Conclusions

An empirical relationship developed by Linacre (1977) has been used in the determination of moisture deficits for the maize producing area of South Africa. The relationship involves open water evaporation and its dependence on temperature, elevation and latitude. At this point extensive testing of the equation under South African conditions has not been carried out, and so the value of derived moisture deficits lies in their relative variations over time and space rather than their absolute magnitude.

Moisture deficits accumulated from July through March provide a single measure of aridity over the maize area. Intra-annual variability exhibited by monthly deficits was assessed in terms of their buildup and progression over space during the growing season. Confidence limits were useful in determining the reliability of obtaining a particular monthly deficit in any given region. These results were then compared to the spatial patterns exhibited by the lower, median and upper quantities of rainfall, and found to be strongly related to the seasonal progression of rainfall from east to west across the maize growing area.

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