Some aspects of the annual and monthly rainfall over the Sudan

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SOME ASPECTS OF THE ANNUAL AND MONTHLY RAINFALL OVER THE SUDAN

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INTRODUCTION

Scope and Acknowledgments

This work is an attempt to present an analysis of some aspects of the rainfall over the Sudan. In an agricultural country like the Sudan, rainfall is by far the most important single climatic factor, whose distribution, variability and reliability have great effects on the economy of the country, and it is this fact that produced the interest which led to the present study. For the purpose of this work, the rainfall over the Sudan is dealt with on a systematic basis, taking all the country as one region.

The amount and distribution of the rainfall over any particular area is, in fact, the result of a combination of several climatic factors, such as temperature, wind and pressure systems, within and adjacent to the area under consideration. For this reason it is felt necessary to consider briefly the climatic factors that influence the amounts or the distribution of the rainfall over the Sudan.

Special attention is given to the variability of both the annual and monthly rainfall. This again is due to the importance of agricultural production in the Sudan, which is naturally sensitive to such variations. The percentage probability of receiving below or above certain amounts of rainfall is of great significance to the farmer. For this reason it is found necessary to include some account of rainfall probability in this work, following the steps of Glover, Henderson and Robinson on East Africa, (1953 and 1954).

The present investigation is concluded by a statistical analysis of the relationships between the mean rainfall and four climatic factors which appear to be important contributors to the rainfall over the Sudan. This part of the work has been largely influenced by the pioneer studies of Gregory (1964 and 1965) on Mozambique and Sierra Leone respectively, and it is hoped that this account can be usefully compared with these existing surveys and also with similar rainfall analysis which may follow for the African continent.

The data used in this study have been either extracted or calculated from statistics published by the Sudan Meteorological Service. Some of the unpublished data have been extracted from the observations files which are kept in the Headquarters of the Meteorological Service at Khartoum. A standard period of thirty years, 1931-1960, has been chosen for the present work.
This has been followed throughout the course of the investigation, except in some cases when it has been

found necessary to include stations with less than thirty years' records.

Sixty six stations are selected to draw the isohyets and isomeric lines (fig. 1). In the selection of these stations, the intention is to use as many stations as possible especially in the somewhat anomalous areas such as the Red Sea region, the Jebel Marra region and the Nuba mountains. Unfortunately not too many stations are found west of the Red Sea mountains. Also in the extreme north-western parts of the country, between the river Nile and the north-western borders, there are hardly any rainfall stations since this part of the country is practically uninhabited.

Twenty stations are used to calculate the coefficients of variation and to determine the rainfall reliability. This selection is dictated by the availability of the relevant data. Nevertheless, the region covered by the majority of these stations can safely be considered as the economic heart of the country and the most sensitive part to the variations in the annual and monthly amounts of rainfall.

A system of random sampling, by digits and tables, has been applied to select fifteen representative stations for the multiple regression analysis.

These fifteen stations are evenly scattered throughout the country. The Red Sea coast has been excluded from this part of the work because it has different characteristics and rain-producing factors than the rest of the country.

Many thanks are dedicated to the climatological section of the Sudan Meteorological Service for their great help in the collection of the data used in this work.

The multiple regression analysis has been carried out with the cooperation of the Computer Unit of the University of Durham, whose supervisor, Mrs. Templeton, has been of immense and greatly appreciated help.

Lastly, but by no means least, it should be admitted that had it not been for the encouragement, the good advice and the academic skill of Dr. K. Smith, of the Department of Geography, University of Durham, this work would have not come to existence in its present form. It is his great interest and keen supervision that made this attempt a possibility. So a lot of thanks are dedicated to him together with great admiration and respect.

FACTORS INFLUENCING THE RAINFALL OVER THE SUDAN

PHYSIOGRAPHY:-

The Republic of the Sudan is the largest political unit in Africa. It has an area of just under one million square miles and its area is equal to 8.3% of the area of Africa and 1.7% of the land area of the world (Lebon, 1965). Except for a few hundred miles along the Red Sea the country is completely land-locked. The whole of the country lies in the Northern hemisphere roughly between latitudes 3° and 23° North, whilst longitudinally it extends between 22° East and 38½° East.

In terms of general relief, the Sudan consists mainly of plain lands interrupted only by a few relatively high areas along the Red Sea coast, in the Jebel Marra area and the Nuba mountains (fig. 1 & 2). According to Bhalotra (1963) the general level of the Red Sea mountains is 3000ft. above sea level; the peak height in Jebel Marra is 10000ft. above sea level; and the top of the Nuba mountains rise to nearly 5000ft. above sea level.

As indicated by Barbour (1961), less than 2% of the country lies lower than 1000ft., some 45% lies between 1000ft. and 1500ft. and a further 50% lies

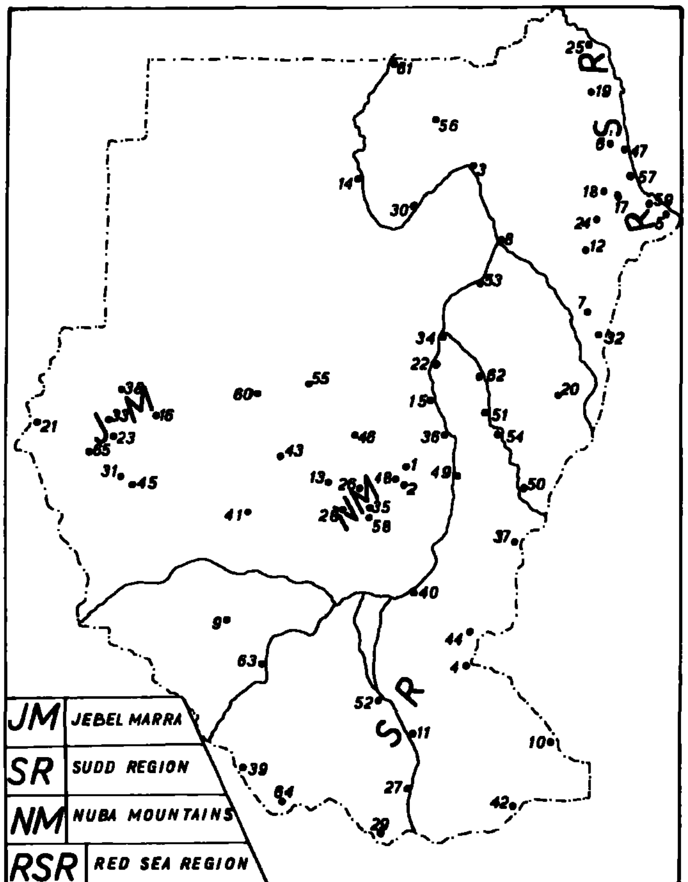


Fig. 1 Stations used in the investigation

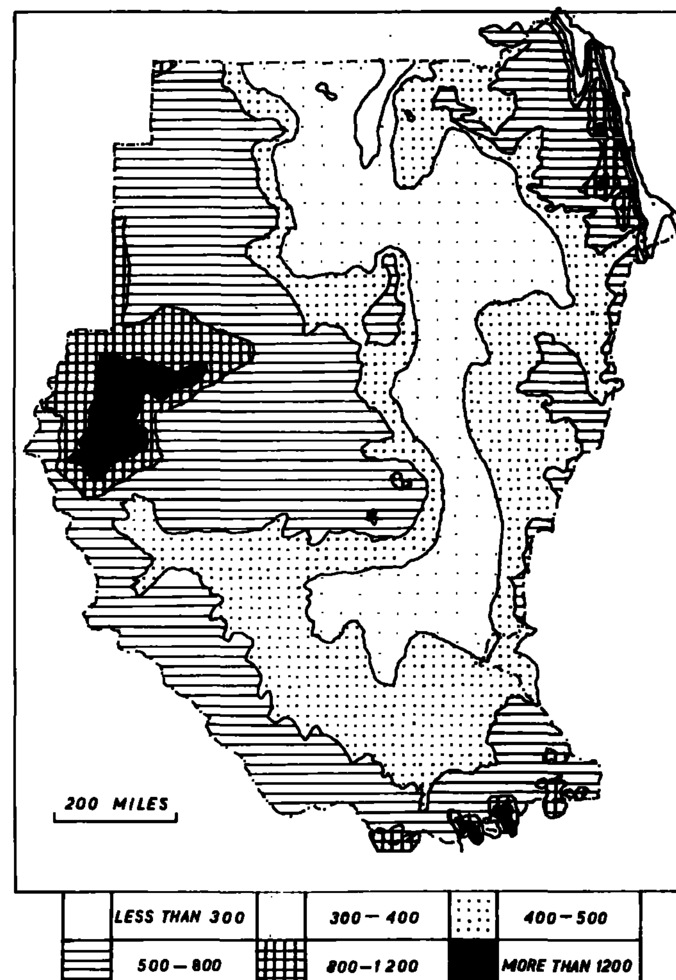


Fig. 2 Selected contours in metres

below 4000ft., which suggests that there are only small areas that are sufficiently high to have a markedly different climate from the other parts of the country at the same latitude.

Except for the Nile and its tributaries, there are hardly any water bodies or inland lakes that may give rise to even local climatic conditions. The only possible exception to this is a large swampy area known as the Sudd Region which is found in the southern part of the country (fig. 1). This is caused mainly by the over flowing of the White Nile river beyond its banks. This Sudd region is responsible for the loss of large amounts of water from the White Nile and its tributaries through evaporation and evapotranspiration.

It would also seem that the effect of the Red Sea on the climate of the Sudan is very limited. This is mainly due to the narrowness of the sea itself, which does not give the rain producing winds ample distance to pick up enough moisture from the sea. Its effect is confined to the narrow coastal plain and the eastern slopes of the Red Sea mountains. Its effect is hardly felt west of these mountains. It will be shown later that the prevailing north easterly trade winds flowing over the Red Sea may cause some rains on the Sudan coast throughout the year; but the largest proportion of the rains associated with these north eastern trades fall during the winter season.

The topography of the lands around the Sudan has no major effects on the climate of the country. The only exception to this seems to be the high Abbyssinian plateau which rises sharply from the eastern boundaries of the Sudan. According to Bhalotra (1963) the effect of the Abbyssinian plateau on the Sudan climate is in the form of line squalls or line storms that build up along the western foot hills of the plateau and then travel westwards into the Sudan leading to thundery activity and showers. The remaining boundaries of the country are not characterised by any features that may hinder the free passage of winds, or affect the general distribution of rainfall.

Thus, the general relief framework of the Sudan is fairly simple and characterised by the absence of extensive mountain ranges lying across the face of rain producing winds. The effects of the relatively high regions are very localised and confined to a short distance beyond the crests of the mountains. Maritime effects from the Red Sea are also very limited.

According to the modified Köppen classification of climates, more than two thirds of the Sudan lie within the Arid or semi-arid zones (Finch & Trewarth, 1957). The rainfall over the country is largely influenced by the pressure systems within and adjacent to the African continent. The Sudan lying north of the Equator, is greatly affected by the seasonal changes of pressure in the northern hemisphere. The pressure and wind systems seem to be the main climatic factors influencing the distribution of rainfall over the Sudan. These two factors will now be considered separately in some detail.

PRESSURE:-

During the Northern Hemisphere winter, represented by January (fig. 3), a high pressure belt exists over the Saharan desert. This is normally considered as an extension of the Azores anticyclone, and the associated winds flow in a clockwise direction. The Sudan, lying east of the centre of this high pressure belt, is affected by north eastern winds known as the north eastern Trades. These winds originate in the Sahara desert and are associated with subsidence of air from the upper atmosphere. They are generally dry, except in small areas along the Red Sea coast, where they may acquire some moisture during their passage over the Red Sea waters.

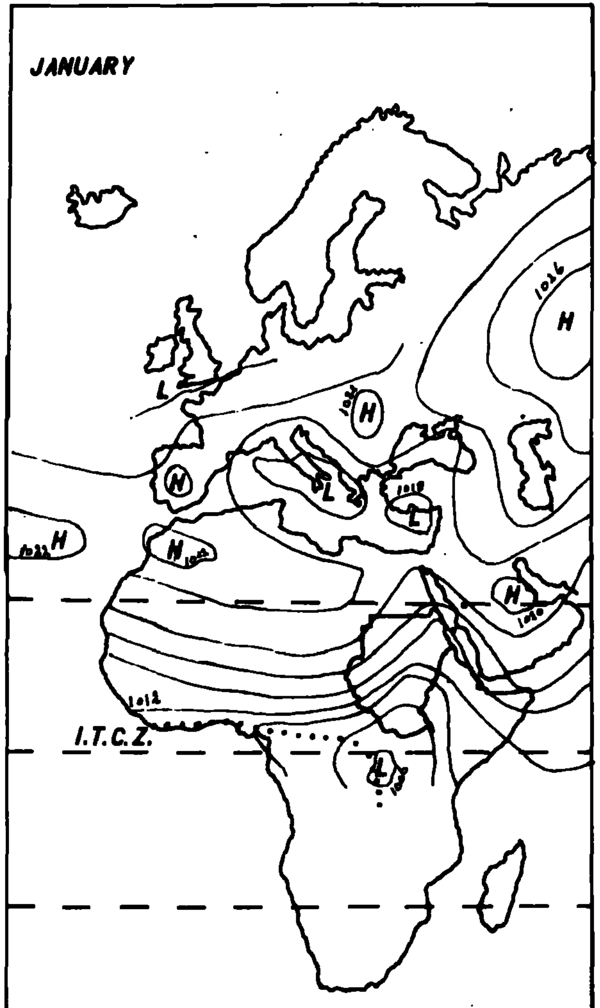


Fig. 3 January Pressure: after Bhalotra

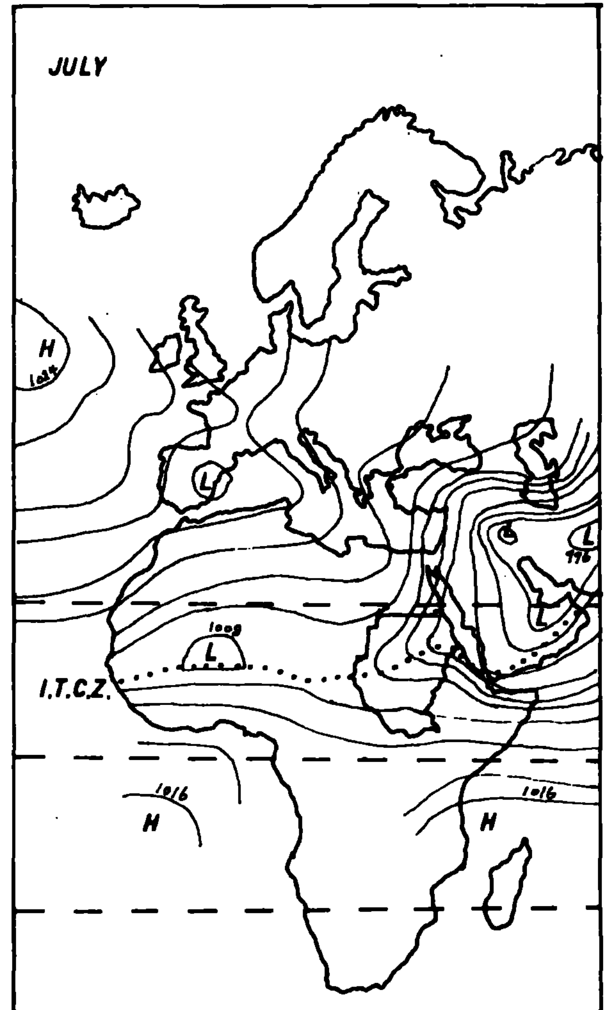


Fig. 4 July Pressure: after Bhalotra

East of the Red Sea lies another belt of high pressure centred over the Arabian peninsula. This is also associated with a clockwise circulation of winds. The Sudan lying west of the centre of this anticyclone, is affected by southerly winds. Due to the presence of high mountains along the Red Sea coast, these southerly winds may lead to orographic rains in the southern part of the Red Sea coast.

Over the Red Sea and between the Saharan and the Arabian anticyclones lies a trough of relatively low pressure known as the Red Sea trough. The origin of this trough is rather controversial. Bhalotra (1963) argues that it is due to the convergence of the Saharan and the Arabian anticyclones. On the other hand, Solot (1950) thinks that this trough must, for the most part, be a surface reflection of an upper trough since surface gradients of air mass properties are usually slight.

Further north lie the Balkan and the Asiatic anticyclones. The effect of these anticyclones over the Sudan is in the form of occasional cold dry air that sweeps over the country leading to a sharp drop in temperature.

Besides these high pressure belts, there are two low pressure zones affecting the Sudan. One of these is centred over the Mediterranean Sea, and this may attract some of the cyclones affecting western Europe. These cyclones move eastwards into the east Mediterranean countries but they never reach the Sudan. Their passage over the Mediterranean is associated with the northward and southward oscillations of the wind belts within the Sudan. The other low pressure belt is found over central Africa. This is the permanent Equatorial low pressure zone, which is thermal in character and generally very shallow.

During the summer period, represented by July (fig. 4), the picture is quite different. The overhead sun is now centred on the tropic of cancer and the Sahara desert becomes one of the hottest places on the Earth. A low pressure area replaces both the Saharan and the Arabian anticyclones. The Saharan low pressure attracts the south eastern trade winds from the Indian ocean and the Gulf of Guinea in the southern hemisphere. As these winds cross the Equator they change direction and become south westerly winds which flow over the northern half of Africa as far as latitude 20^{o} north. These winds are very humid, and are generally known as the south western monsoons. Trewartha (1962) thinks that this seasonal wind reversal i.e. from north east to south west is not a consequence of the differential heating of land and water; it simply follows upon the orderly advance and retreat of the wind systems consequent upon the course of the sun. Nevertheless he does not object to calling these winds "the Monsoons" and it is these winds that give the Sudan all its summer rains.

A high pressure belt replaces the central Africa low pressure zone. This high pressure zone is formed by the westward extension of the subtropical Indian Anticyclone and the eastward extension of the subtropical south Atlantic anticyclone.

A feature associated with this change in the pressure systems is the advance of the Inter-Tropical convergence zone over the Sudan. This is the zone that separates the northern hot-dry winds and the southern cool-moist winds. They meet along a mildly sloping surface which is not always continuous, slopes upward to the south and decreases in intensity with height (Bhalotra 1963).
In the Sudan, the I.T.C.Z. reaches 20° north which, according to Solot (1950), is a large deviation from the mean annual position of the I.T.C.Z. as is observed anywhere else on Earth excepting India.
The lag between the overhead sun and the position of the I.T.C.Z. is about six weeks. It moves slowly across the Sudan. It does not advance steadily but in a series

of forward and backward movements. This oscillation is associated with the passage of cyclones and anti-cyclones over the Mediterranean Sea together with the intensification of the subtropical anticyclones in the Indian and southern Atlantic oceans. However it does not reach the Red Sea, and according to Solot (1950) this is due to the presence of the high coastal range.

A feature associated with the I.T.C.Z. in the Sudan is the presence of a low pressure cell over the north eastern part of the country. It always lies north of the I.T.C.Z. and is known as "the Sudan low". This cell may be considered as part of the thermal Equator, (Bhalotra, 1963). It oscillates north and south according to the movement of the overhead sun. El Fandy (1949) believes that the air currents which invade the lower atmosphere of the Sudan and the Ethiopian plateau are influenced partly by the Sudan low and partly by the Ethiopian plateau and the low pressure over the south west of the Arabian peninsula. Actually this low pressure cell has no major effect on the general circulation of winds. Soliman (1950) seems to be the only authority advocating a greater significance for the Sudan low. He thinks that the south-western hot winds over northern Sudan and southern Egypt are due to the turning of the prevailing north eastern trade winds round the Sudan low. So they are quite different from the cool and moist south western monsoons that flow over the rest of the Sudan, and they are separated from each other by a frontal zone or a zone of separation. Soliman's ideas seem to have no solid grounds since they are based on a mis-interpretation of some maps provided by El Fandy in 1949. During the summer period the "Sudan low" merges into the extensive Sahara and Arabian low pressure belts.

The spring and autumn are transitional periods during which one pressure system gives way gradually to the other according to the season. During the spring, represented by April (fig. 5), the Saharan anticyclone moves north westwards while the Arabian anticyclone and the Mediterranean low, though still persisting in their effects, are greatly reduced. During the autumn, represented by October (fig. 6), the Saharan anticyclone becomes dominant as does the Arabian anticyclone. Associated with the Arabian anticyclone is a large influx of air from Arabia which affects the north eastern part of the Sudan (Bhalotra, 1963). It is during this period that the Sudan coast gets the largest percentage of its annual rains in contrast to the rest of the country, which is everywhere else dry. The I.T.C.Z. retreats to the south during this period and leaves the Sudan completely by the end of November.

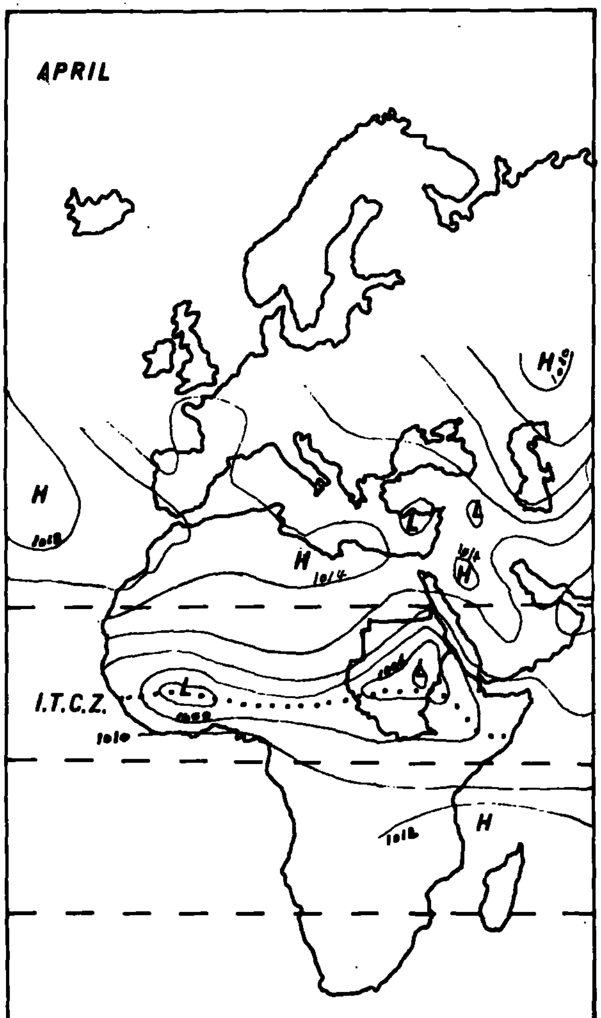


Fig. 5 April Pressure: after Bhalotra

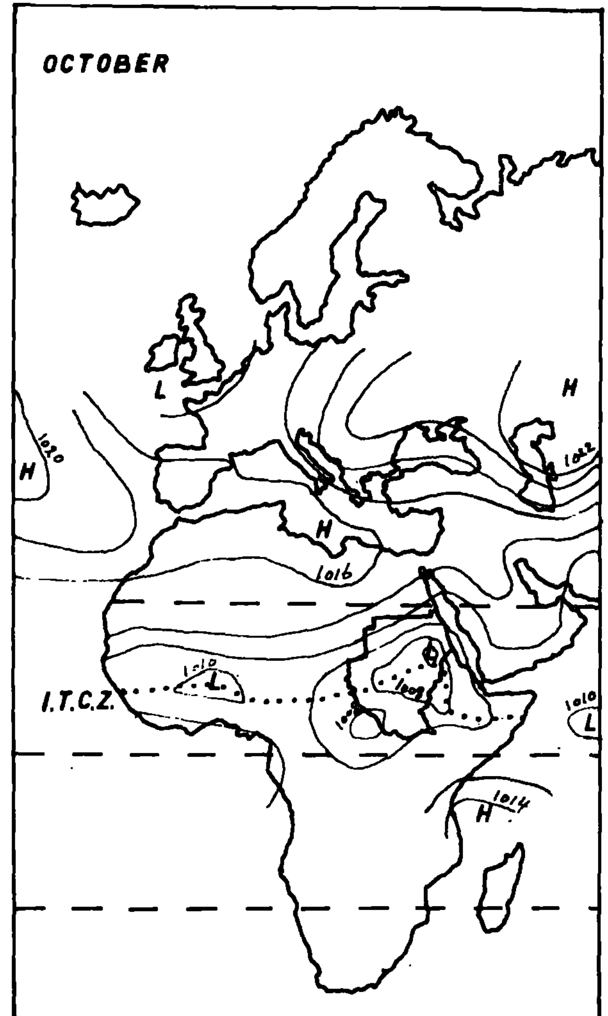


Fig. 6 October Pressure: after Bhalotra

WINDS:-

The prevailing winds over the Sudan are the north eastern Trades. They flow on the Red Sea coast throughout the year, and they may cause some rains at any time of the year in this coastal region. Further inland they are very dry winds.

During the rainy season the flow of the prevailing north eastern Trades, except in the Red Sea coast, is checked by the advance of the south western monsoons. This wind reversal can be illustrated clearly by (fig. 7) and (fig. 8) showing the percentage frequency of direction of surface winds for January and August. Since the prevailing winds are very hot and dry and hence light, they are forced to rise over the cool and moist monsoons, but they continue to maintain their north eastern direction in the upper atmosphere. Most of the rain-storms over the Sudan are seen approaching from the north east, despite the fact that the surface winds are south westerlies. Actually these rain storms start by convectional currents rising from within the monsoonal winds. They continue to cool by rising further until they reach the level of the prevailing north easterlies which then carry the storm south westwards and the storms appear to be moving in the opposite direction to the surface winds. It was noted by Sutton (1930), that when

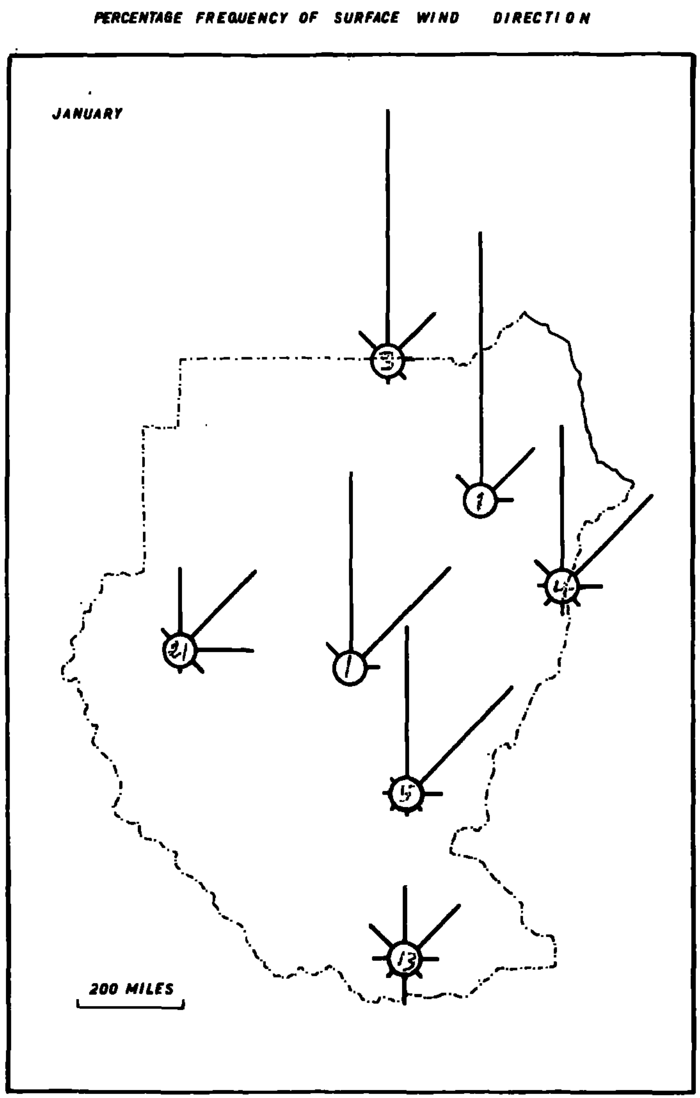


Fig. 7 Wind direction: January

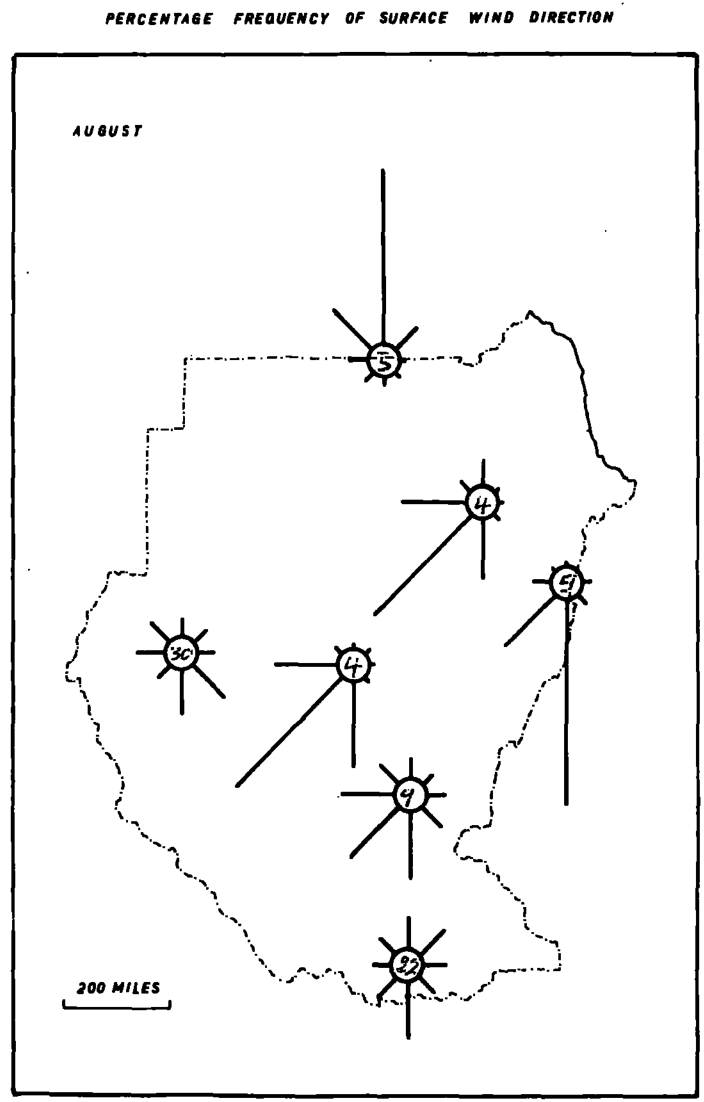


Fig. 8 Wind direction: August

the north eastern Trades blow further south, on the surface, than usual, as a result of the oscillations of the I.T.C.Z., a spell of dry weather occurs in the Sudan in the summer. When the monsoonal winds retreat, the prevailing north eastern Trades dominate the country again.

A direct south easterly air stream may occasionally reach the southern Sudan from the Indian ocean. Also, as a result of the persistence of the Arabian Anticyclone during winter, a south easterly air stream may affect the southern part of the Sudan coast and this may be associated with some rains on the windward side of the Red Sea mountains.

According to El Fandy (1949), the upper air circulation over the Sudan is generally from east to south east. Several factors control this upper air movement. Variations in the depth of the south western monsoons accompanying the oscillations of the main pressure systems seems to influence this upper air movement. Another factor influencing these movements is the location over the Great Sahara desert and the Arabian peninsula of a belt of maximum temperature round the Equator and a belt of temperature minimum over an area covered by the tongues of the South Atlantic and the Indian subtropical anticyclones.

Some cyclones that are not traceable on the usual pressure maps may occur in the upper air in the northern part of the Sudan and Egypt. These lead to deviations in normal wind directions. They may also lead to the developments of some clouds and the occurence of hot spells over the Middle East and the Northern Sudan. They are frequently associated with thunder storms. As suggested by Ashbel (1938) and presented by El Fandy (1950) these thunderstorms are due to the influence of barometric lows from the Red Sea. These cyclones travel northeastwards and it is observed that they are not active except near the Red Sea and the south eastern Mediterranean sea, where they give rise to thundery precipitation in autumn. In summer these cyclones are associated with the out-spreading of heat waves over the Middle East.

So by far the most important factors influencing the rainfall over the Sudan are the pressure systems, within and adjacent to the African continent, and the winds systems associated with them. Temperature has little influence on the distribution of rains over the Sudan. As will be shown later, the influence of topography is very localised.

THE DISTRIBUTION OF THE ANNUAL RAINFALL

Before considering the distribution of the rainfall over the Sudan, it seems suitable to give a brief idea about the mechanism of the rainfall itself in the country. Except for the Red Sea coastal area the rainfall over the Sudan is mainly associated with the movement of the I.T.C.Z. The rains are mainly convectional in character. Due to convectional activity, thunderstorms develop south of the I.T.C.Z. within the cool and moist south western monsoons. These thunderstorms give rise to heavy showers of rather short duration which are typical of the Sudan rains. In addition to these short showers, Harry (1947) noticed the occasional outbreaks of rains covering a wide area and lasting up to twenty four or thirty six hours. Thundery activity is not unexpected throughout the rainy season, but storms are particularly severe during the transitional periods. Thunderstorms rarely occur north of 18° north, (Harry 1947).

According to Bhalotra (1959 and 1963), the rainfall over the Sudan comes from either a single thunderstorm, a group of thunderstorms, or a line of thunderstorms. The largest proportion of these thunderstorms develop over the Ethiopian plateau and move west-southwestwards, with the upper winds, into the Sudan. The most violent type is the line storms or line squalls. These are violent cumulu-nimbus cells which develop about 100 miles south of the I.T.C.Z. Bhalotra, (1959) suggests that these line squalls start as single thunderstorms, which are then roughly formed into a line by the effect of topography. Sometimes these thunderstorms may be formed along the meeting zone of the south eastern monsoons from the Indian ocean and the south western monsoons from the South Atlantic. Bhalotra (1959) also suggests that a few line squalls may develop over the western slopes of the Red Sea mountains; but these are not expected to be severe due to the shallow depth of the moist air in the northern latitudes. Also it seems that the line squalls affecting west Africa might be a continuation of those developing over the Ethiopian plateau and affecting the Sudan. However, Bhalotra (1959) reports that an unpublished study by J. Sissons, (1955), does not support this assumption, since the line squalls affecting the Sudan seem to disintegrate not too far beyond the western boundaries of the Sudan.

Bearing this mechanism in mind, we may now proceed to discuss the annual distribution of rainfall over the Sudan. The distribution of the annual rainfall over the country appears to be fairly simple. Generally the mean annual rainfall decreases steadily from south to north, (fig.9)

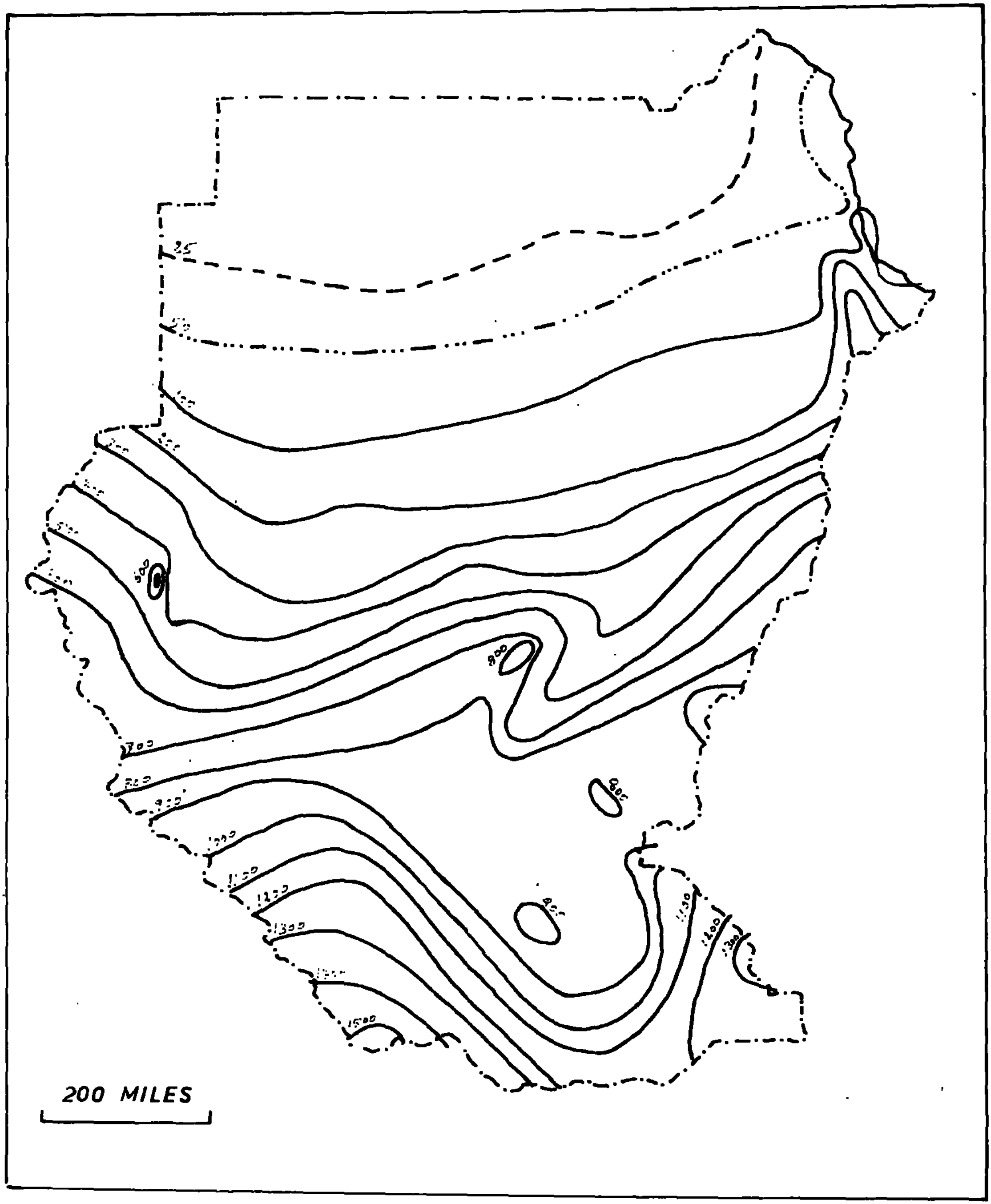


Fig. 9 Mean annual rainfall in m.m.

It ranges between 1512 m.m. received at Yambio (64) in the extreme south, and 3 m.m. received at Halfa (61) in the extreme north, (fig. 10). The annual isohyets run smoothly from south-west to north-east, but they show a tendency to run further north in the eastern part of the country. This is due to the influence of the Abbyssinian plateau which helps to extend the rains further north. Another factor may be the nature of the I.T.C.Z., which tends to extend further north in the east of the continents rather than the west. In the north-east of the Sudan the I.T.C.Z. is in the form of a tongue which is prevented from reaching the Red Sea coast by the existence of the high coastal mountains.

In the Sudan a rain-day has generally been defined on two criteria: as a day upon which the rainfall was equal to, or greater than, 1 m.m., in one case; and equal to, or greater than, 10 m.m. in the other, (S.M.S. 1963). Wahab in (S.M.S. 1963) gave a correlation coefficient between the mean annual rainfall and the number of rain days as defined above. For the 1 m.m. criterion the correlation coefficient was + 0.954; and in the case of the 10 m.m. criterion it was + 0.963. A correlation coefficient of this magnitude shows that the mean annual rainfall and the number of rain-days in the Sudan are very highly positively correlated throughout the country.

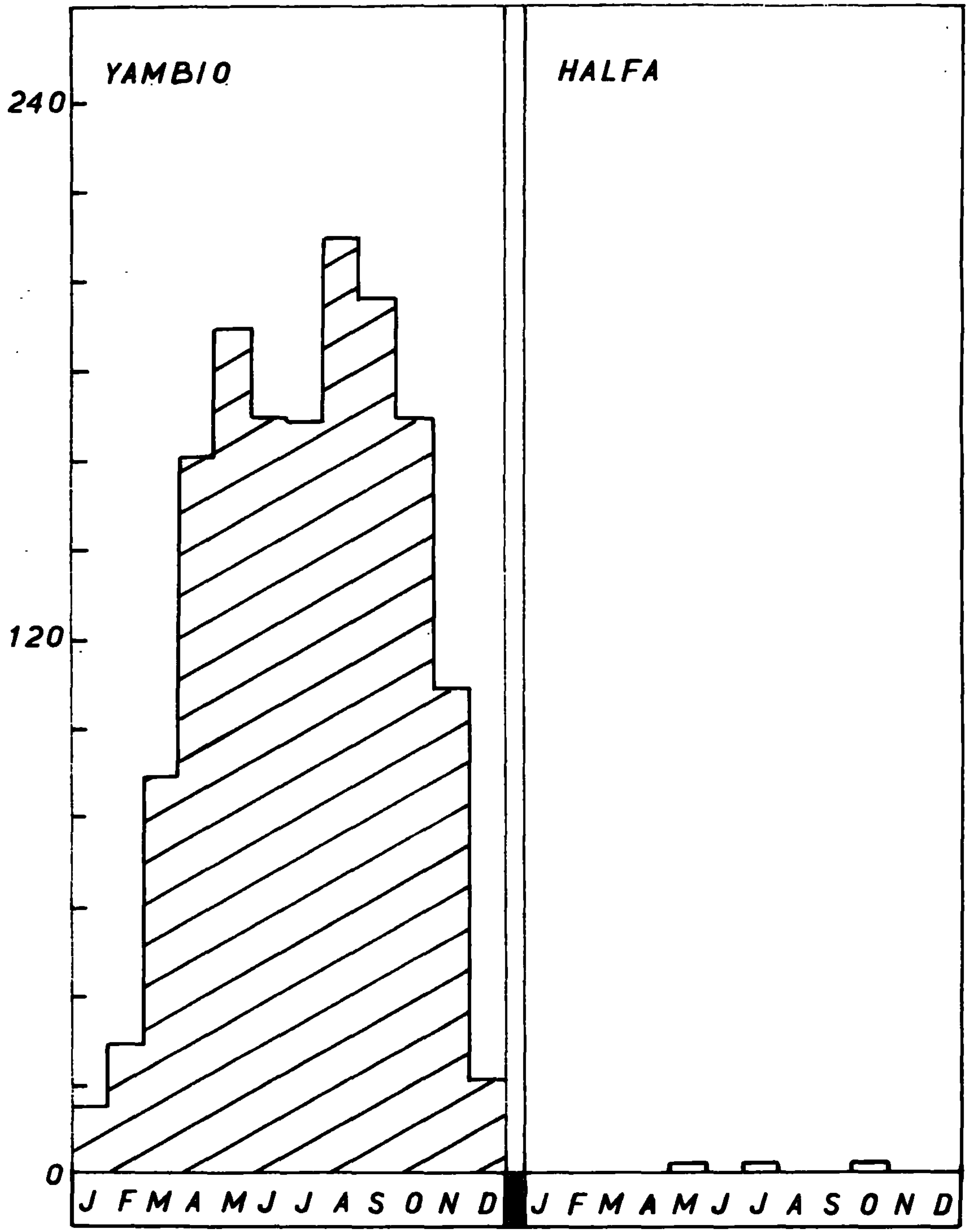


Fig. 10 Annual rainfall for Yambio and Halfa in m.m.

Using the above definitions of a rain-day, a rough measure of rainfall intensities in the Sudan, can be calculated by dividing the average rainfall by the average number of the rain days. This shows that the rainfall intensity is also positively correlated with the mean annual rainfall; it increases southwards as can be illustrated by the following table which is extracted from the data published by the Sudan Meteorological Service, (1963).

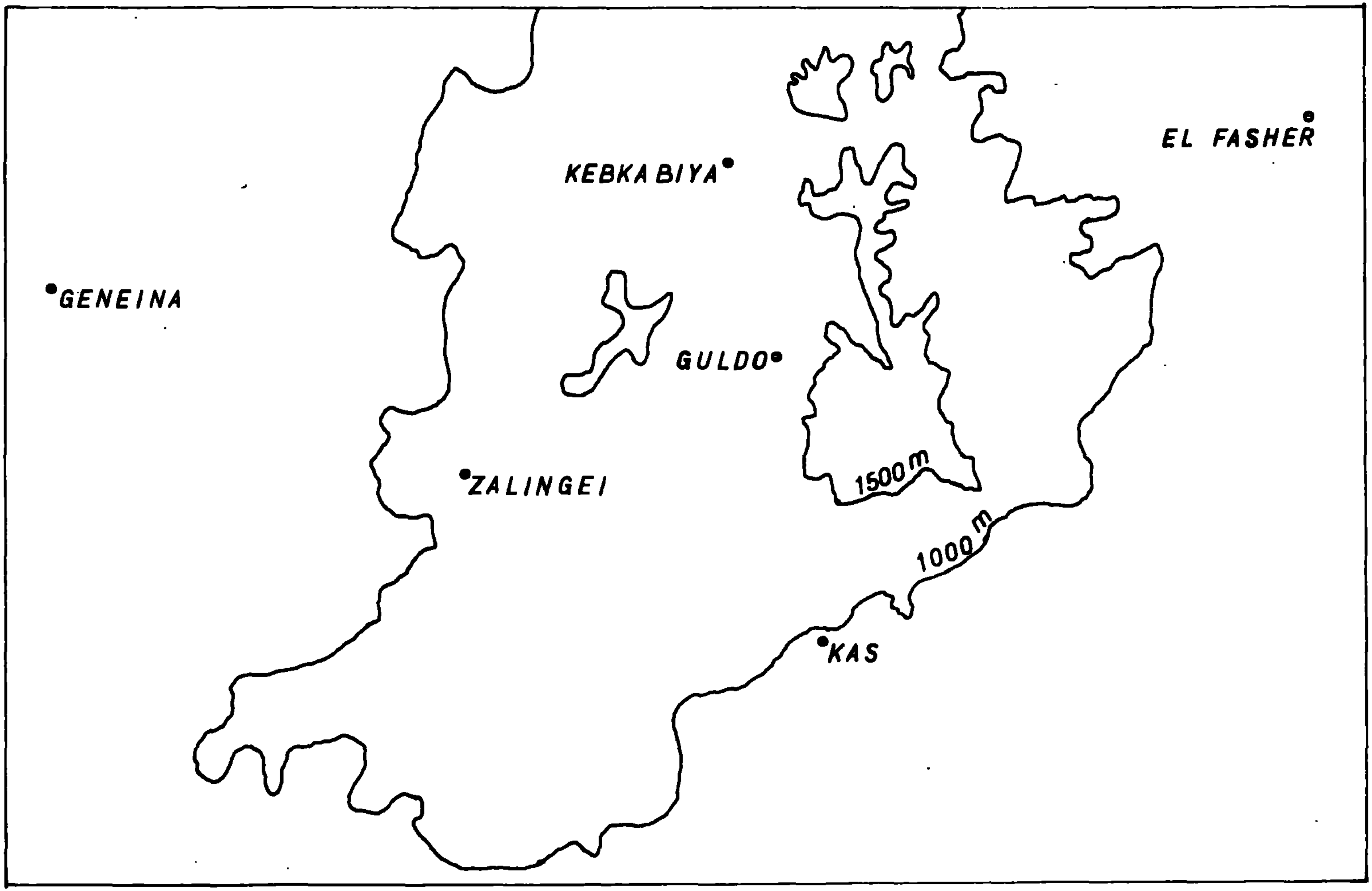
Table No. 1

STATION	Mean Annual Rainfall in m.m.	Rainfall intensity	
		1 m.m. criterion	10 m.m. criterion
Juba (27)	982	110	410
Malakal (40)	783	88	231
Gedaref (20)	614	75	164
Kosti (36)	406	60	159
Fasher (16)	287	44	92
Shendi (53)	136	43	95
Port Sudan (47)	110	43	77
Abuhamad (3)	17	10	0

The fairly simple pattern of the annual rainfall distribution over the Sudan as outlined above and represented by (fig. 9), is often interrupted due to local conditions. Such interruptions can be observed in the Jebel Marra region, the Nuba mountains, the Red Sea region, the Sudd region and the Central Sudan plains, (fig. 1). These local interruptions will be dealt with in order.

The relatively smooth west-east alignment of the annual isohyets is interrupted east of the Jebel Marra region. Here the isohyets show a tendency to run southwards along the eastern slopes of the mountain, which indicates the presence of a rain shadow east of these relatively high areas. Unfortunately, the altitude of most of the stations within the Jebel Marra region are not available. Nevertheless the location of the stations according to the mountain crest may illustrate the role of these mountains on the distribution of the annual rainfall, (fig. 11). The areas to the west and south-west of the core of the Jebel Marra region can be represented by Geneina (21), Zalingie (65), Kebkabiya (33), Kas (31) and Guldo (23). Except for Kebkabiya, which has a mean annual rainfall of 405 m.m., all the other stations receive more than 500 m.m. annually. Guldo (23), which lies just west of the highest part of the mountains, has a mean annual rainfall of just less than 700 m.m. In contrast to this, the areas east of Jebel Marra generally receive

Fig. 11 *THE LOCATION OF REPRESENTATIVE STATATIONS IN JEBEL MARRA*



less than 300 m.m. annually. These eastern areas can be represented by El Fasher (16) which, although it is not too far from the latitude of Geneina (21), it receives a mean annual rainfall of 287 m.m. which is almost half the amount received at Geneina (21) west of the high region.

Similar topographical influences are found in the region of the Nuba mountains (fig. 1). Here the isohyets also indicate the presence of a rain shadow east of the mountains. This region differs from the Jebel Marra area in that it consists of several isolated hills, while the latter is almost a compact high region. This characteristic of the Nuba mountains has led to sharp differences in the amount of mean annual rainfall within very short distances. Such differences can be illustrated by comparing the amounts received annually at three representative stations namely: Rashad (48), Abbassiya (1) and Abu Gubeiha (2). They lie within very short distances from each other, (fig. 1). Despite this, Rashad (48) which lies slightly to the west receives a mean annual rainfall of 806 m.m. while Abbassiya (1) receives 660 m.m. and Abu Gubeiha (2) 666 m.m., (fig. 12).

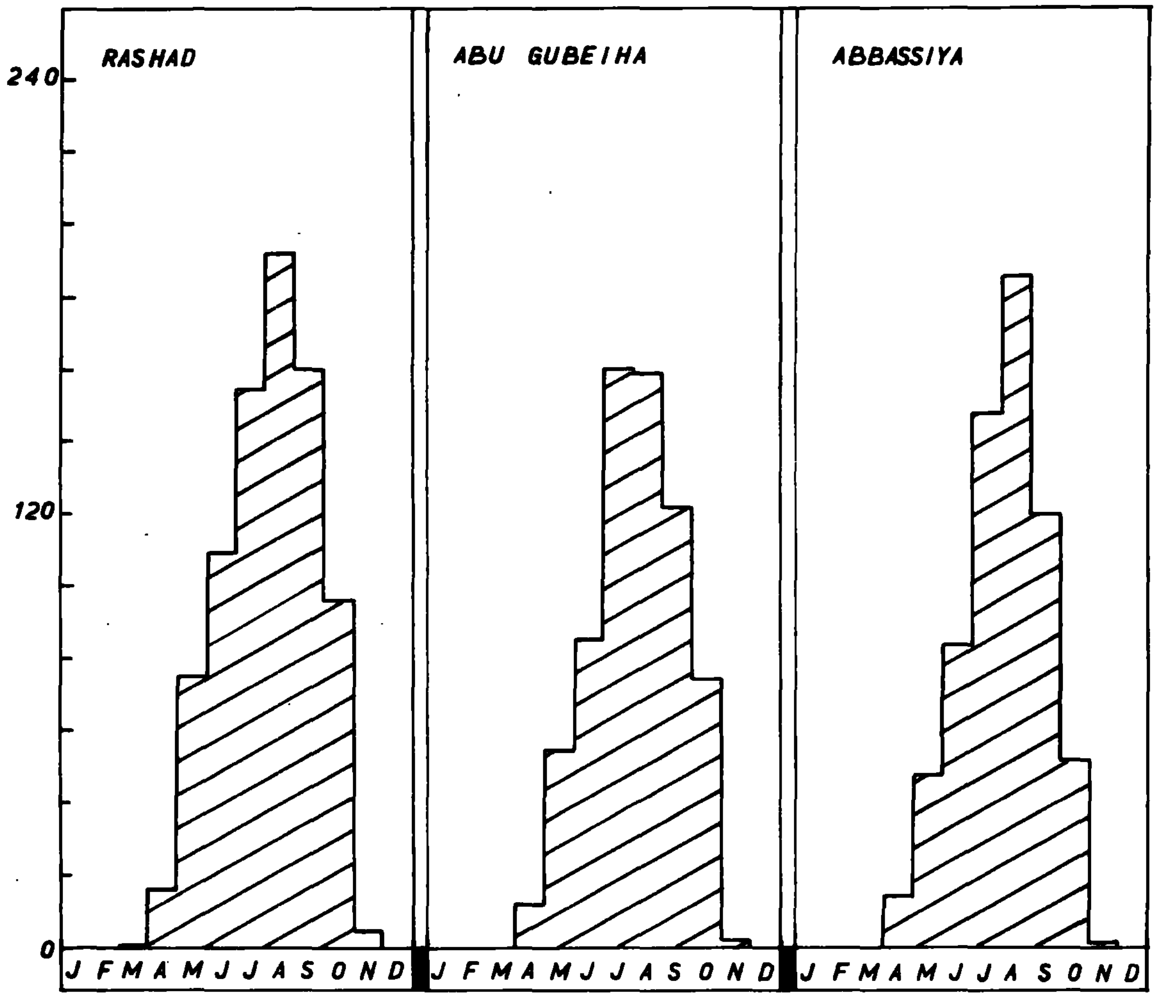


Fig. 12 Annual rainfall for Rashad, Abu Gubeiha and Abbassiya in m.m.

Another feature to be observed on the western side of the Nuba mountains is that the rains are heavier near the mountains than on the plains on the same latitudes. On the plains, Muglad (41) has a mean annual rainfall of 496 m.m. while Kadugli (28), which is nearly on the same latitude of Muglad (41) but lies within the hilly region, has a mean annual rainfall of 767 m.m., making a difference of 271 m.m. between these two stations. Otherwise the rainfall distribution within the Nuba mountains is similar to that over the country as a whole and is generally heavier in the south than the north.

The Red Sea coast also has some indication of a rain shadow beyond the mountains, although here the rain shadow lies west of the mountains. The reason for this is that the rain producing winds flow from the north east in the case of the Red Sea coast, which contrasts with the previous cases of Jebel Marra region and the Nuba mountains. The lack of climatic observations west of the Red Sea mountains makes it rather difficult to investigate in detail the effects of topography on the distribution of the annual rainfall in this part of the country. However, from the information available there seems to be a positive relationship between the altitude and the mean annual rainfall east of the mountains crests. This relationship can be illustrated by comparing the amounts of rainfall received annually at Port Sudan (47), Erkowit (17) and Haiya (24). These are shown by the following table:-

Table No. 2

STATION	PORT SUDAN	ERKOWIT	HAIYA
ALTITUDE IN METRES	5	1095	640
MEAN ANNUAL RAINFALL	110 m.m.	271 m.m.	89 m.m.

The above table indicates that Haiya (24) lies within a definite rain shadow. Moreover Haiya does not receive any winter rains although it lies at the foot of the western slopes of the Red Sea mountains. Such relationship may better be illustrated by the case of Suakin (57), Erkowit (17) and Sinkat (*) the latter of which lies in a gap just west of Erkowit. This relationship can readily be recognised from the following table:-

Table No. 3

STATION	SUAKIN	ERKOWIT	SINKAT
ALTITUDE IN METRES	5	1095	870
MEAN ANNUAL RAINFALL IN M.M.	136	271	138

Of these three stations, Erkowit (17) has the highest mean annual rainfall. The western-most station, i.e. Sinkat (*), although very much higher than Suakin (57) yet they nearly receive the same amount of mean annual rainfall. This illustrates clearly how the mean annual rainfall increases gradually from the coast towards the mountains and then drops suddenly to the west of the mountains crests; and thus show the role of topography on the inland distribution of the annual rainfall.

Another feature to be observed in the Red Sea region is the increase of the amount of the mean annual rainfall southwards along the coast. Moving southwards along the coast, Halaib (25) near the north eastern end of the Sudan receives a mean annual rainfall of just 45 m.m., while Port Sudan (47) receives 110 m.m., Suakin (57) 136 m.m. and in the extreme south Aqiq (5) receives 147 m.m. This may be because towards the south, the rain producing winds have greater chances to pick up moisture from the Red Sea since they have a longer fetch over the water. Another explanation may be found in the nature of the coast itself. Actually the Sudan coast tends to run from north-north-west to south-south-east with a sharp bend to the east between Suakin (57) and Aqiq (5). Thus, the coast to the south stands more prominantly in the face of the rain producing winds and so the on-shore effects of these winds are much greater on the south than the north. An additional reason for this feature may be found in the fact that occasional rains from the south western monsoons, which are not experienced in the north, may reach the southern part of the Sudan coast through a gap in the mountains.

A further anomaly in the smooth pattern of the annual isohyets is found in the Sudd Region, which is an extensive swampy area lying approximately between 30^{o}-40^{o} east and 5^{o}-9^{o} north, (fig. 1). This region seems to be relatively drier than the adjoining lands to the east and west on the same latitudes. This can be illustrated by figure (13) in which Wau (63), in the west, has a mean annual rainfall of 1145 m.m., while Shambe (52), in the centre has 736 m.m. and Akobo (4) in the east, has a mean annual rainfall of 984 m.m. Although these three stations lie on nearly the same latitude, there is a marked difference between them in terms of the annual amounts of rainfall. This feature can also be illustrated by the case of Boma (10) on the western slopes of the Abbyssinian plateau and Bor (11) which lie within the Sudd region (fig. 14). Boma and Bor lie on nearly the same latitude, but insspite of this, Boma has a mean annual rainfall of 1339 m.m. while Bor has a mean of 860 m.m., making a difference of 479 m.m. between these two stations, which are only 200 miles apart.

This phenomenon has not yet been investigated thoroughly. The effect of topography on this peculiar distribution of the annual rainfall, may be true in the case of Boma (10) and Bor (11), since the former at an altitude of more than 800 metres above the mean sea level, receives much higher annual rainfall (1339 m.m.), than the latter, which is at an altitude of 400 metres above the mean sea level, (479 m.m.). But this simple relationship between the altitude and the mean annual rainfall does not seem to be true throughout the Sudd

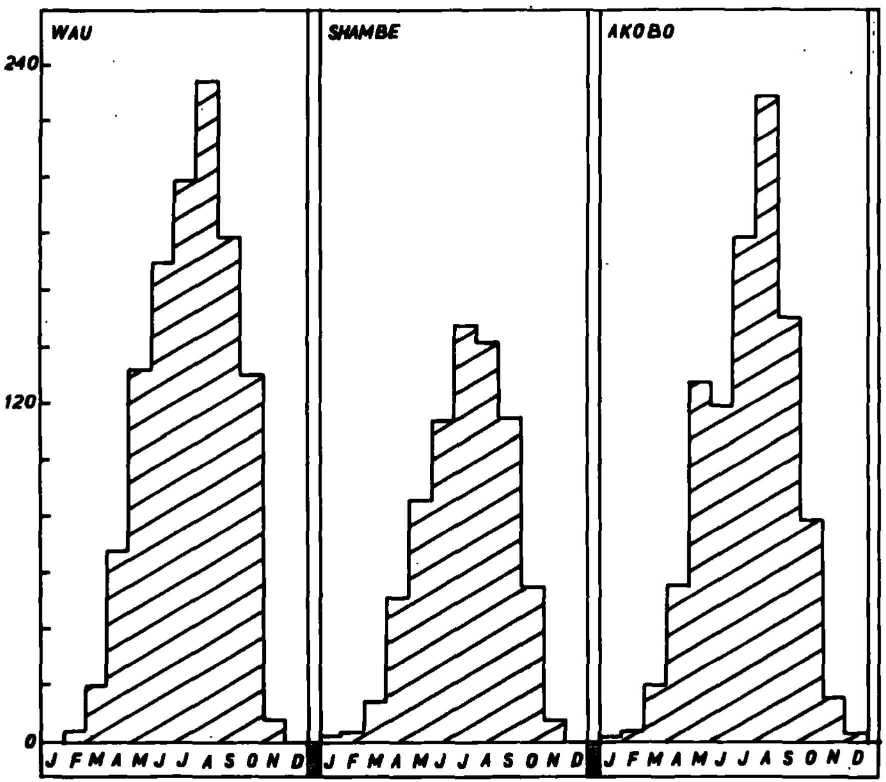


Fig. 13 Annual rainfall for Wau, Shambe and Akobo in m.m.

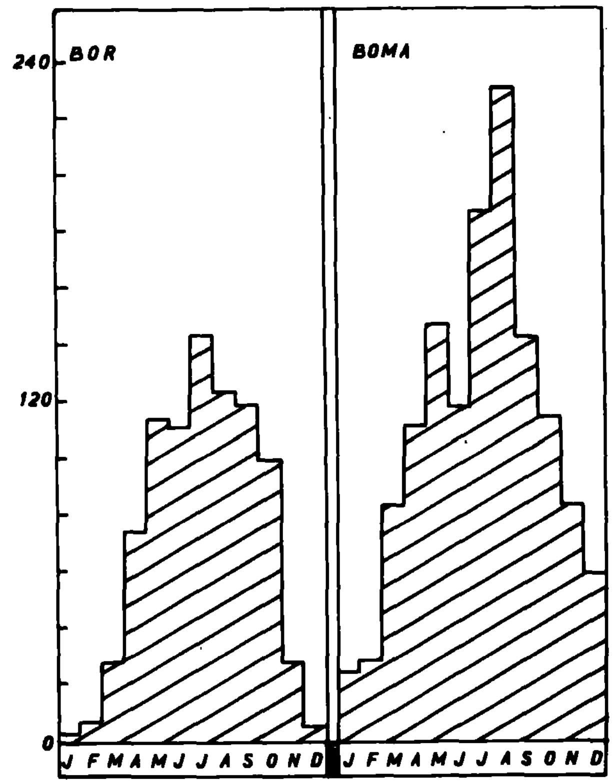


Fig. 14 Annual rainfall for Bor and Boma in m.m.

region. Stations on the same latitude and at nearly the same altitude, receive quite different amounts of annual rainfall, according to whether they lie within or outside the swampy area. This latter condition can be illustrated by the case of Wau (63), Shambe (52) and Akobo (4), (fig. 13). The altitudes of these three stations are 435 metres, 405 metres and 400 metres respectively, but still Wau and Akobo receive much higher annual values than Shambe. However, the scarcity of climatic observations within the Sudd region, as well as the unavailability of the altitudes of most of the existing stations, make any further analysis difficult. Several factors seem to be involved in this problem, and it could be that the map is unreliable, since the isohyets are based on only a few observations.

Another feature imposed on the general distribution of the annual rainfall over the Sudan is found in the central parts of the country. Here the mean annual rainfall tends to decrease from east to west on the same latitudes. This can be illustrated by comparing the average amounts of annual rainfall received at Gedaref (20), Eddueim (15) and El Fasher (16), (fig. 15). These three stations lie on almost the same latitude. In the extreme east, Gedaref (20) has

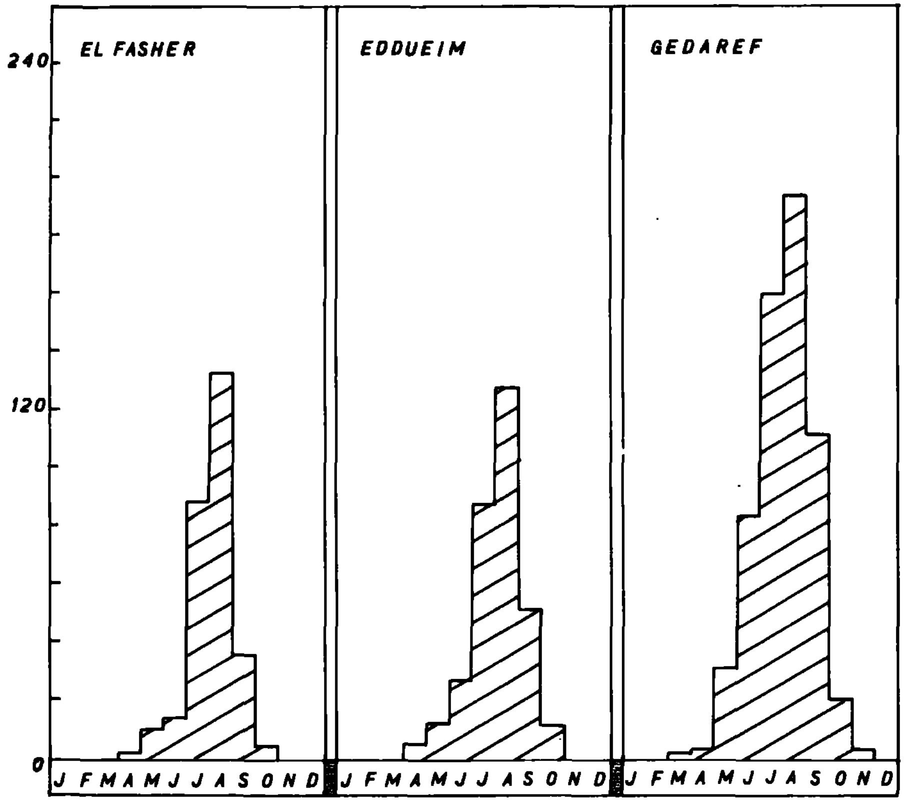


Fig. 15 Annual rainfall for Fasher, Dueim and Gedaref in m.m.

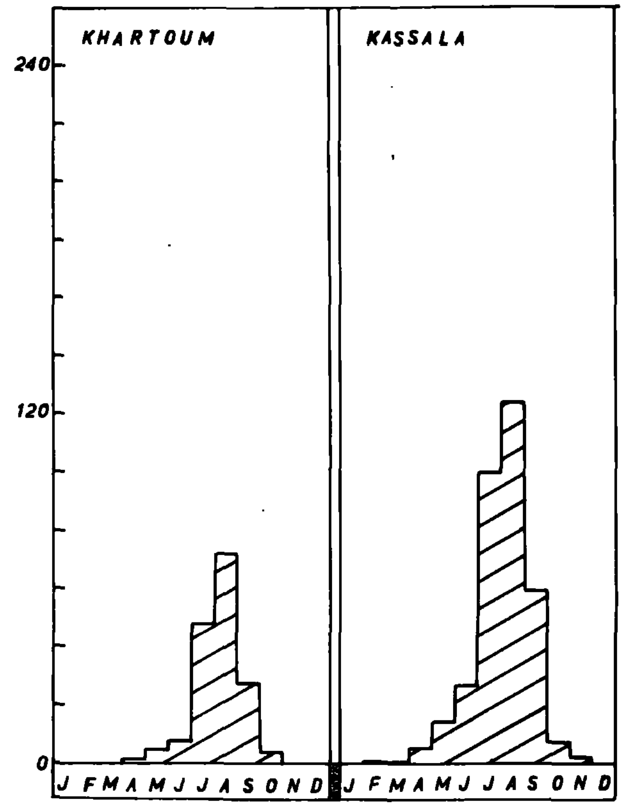


Fig.16 Annual rainfall for Khartoum in m.m.

an annual value of 640 m.m., while Eddueim (15) in the centre has a mean annual rainfall of 323 m.m., and El Fasher (16) in the west has a mean annual value of 287 m.m. If El Fasher (16) is excluded, due to the rain shadow effect of the Jebel Marra region, it is still true that Eddueim (15) receives very much less annual rainfall than that received at Gedaref (20). Further north, Kassala (32) near the eastern border of the Sudan has a mean annual rainfall of 341 m.m. while to the west on the same latitude Khartoum (34) has a mean annual rainfall of 164 m.m. which is in fact less than half the amount received at Kassala, (fig. 16).

These differences between stations on the same latitudes may be explained in terms of the line squalls, whose characteristics have been outlined earlier in this chapter. They tend to disintegrate gradually as they move westwards across the Sudan and thus the rains associated with them decrease to the west. This may explain why the stations near the eastern border of the Sudan, such as Kassala (32) and Gedaref (20) receive much higher annual rainfall than the inland stations to the west, such as Khartoum (34), Eddueim (15) and El Fasher (16), since some of the line squalls affecting the eastern stations may disintegrate well before reaching the stations to the west although on the same latitudes.

THE DISTRIBUTION OF THE MONTHLY AND SEASONAL RAINFALL

It is not a simple task to define a wet month or season, and this is a controversial problem for which there are several approaches. None of the definitions and techniques available seems to be absolutely satisfactory. However, a definition given by Cook, (1946), appears to be suitable for areas like the Sudan in which the amounts of rainfall differ greatly from place to place. Here two criteria are used to define the wet and dry seasons or months. In the wet category is included all the months during which at least 10% of the annual rains fall. A dry month (or season) is that during which less than 5% of the annual rainfall is experienced, whilst any period during which the amount of rainfall received ranges between 10% and 5% of the annual amounts is considered to be a transitional period. All the following discussion will be based on the definition outlined above. In terms of seasonality and influential factors, the Red Sea region differs greatly from the rest of the country, and so it seems more convenient to treat it separately after dealing with the rest of the country.

The months of January and February are safely considered as dry months for the whole country, (fig. 17-20). All the country is absolutely dry except for a little rain that falls in the extreme south, but no where does the amount received, during each of these months, rise above the 2% level of the annual rainfall. In absolute terms the amounts received fluctuate around 25 m.m. By March the amounts of rain received start to increase gradually, and may rise up to 100 m.m. in some places in the southern Sudan, but it is still everywhere less than 10% of the annual rains, (fig. 21-22). A small area in the extreme south east receives about 7% of its annual rains during this month and so it can be considered as experiencing transitional conditions. This area is represented by Nagishot (42) and Boma (10). North of 10° north there is hardly any rainfall during March.

April is the first month that can be considered as a wet or a rainy month, (fig. 23-24). By this month all the areas south of 4° north are receiving at least 10% of their annual rains, and these areas are represented by Yambio (64) and Juba (27). Some rains are experienced up to 15° north but the amounts received do not reach even the 5% level, and so, for these latter areas,

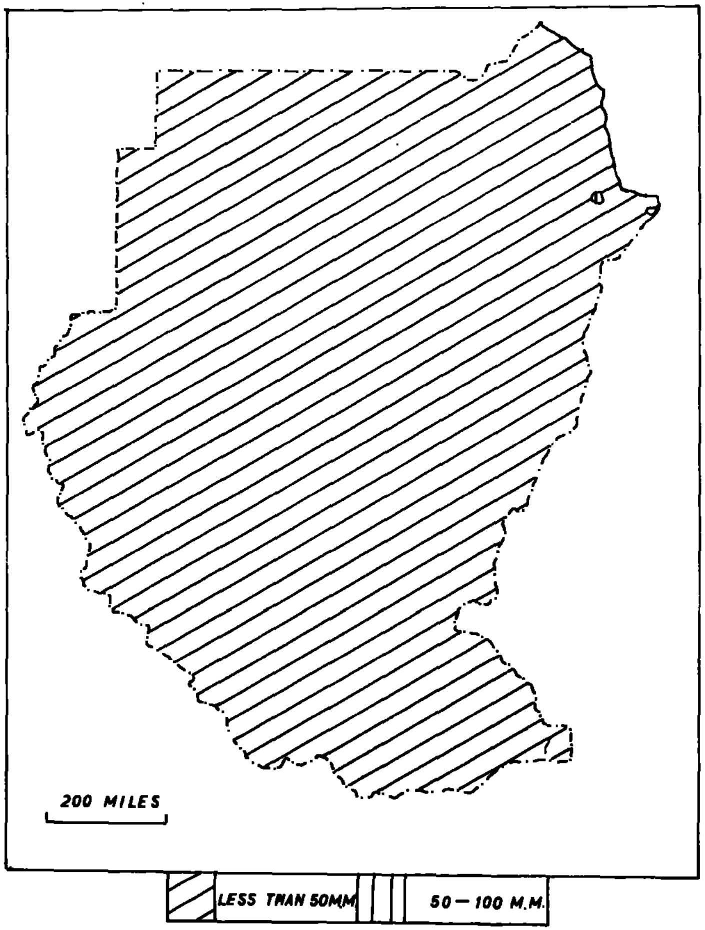


Fig. 17 January isohyets

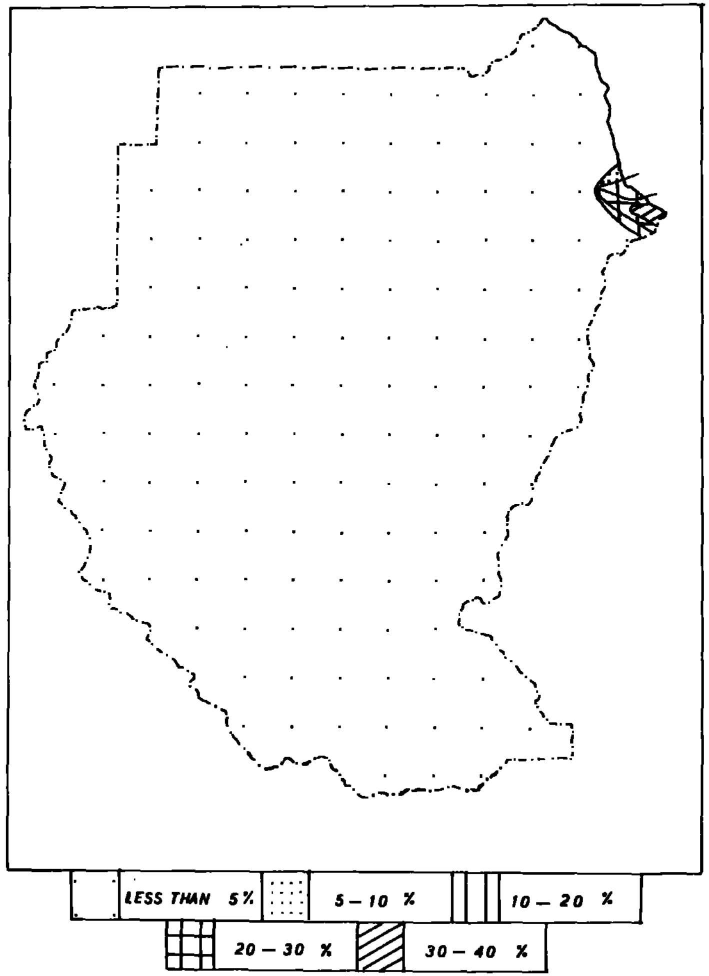


Fig. 18 January isomers

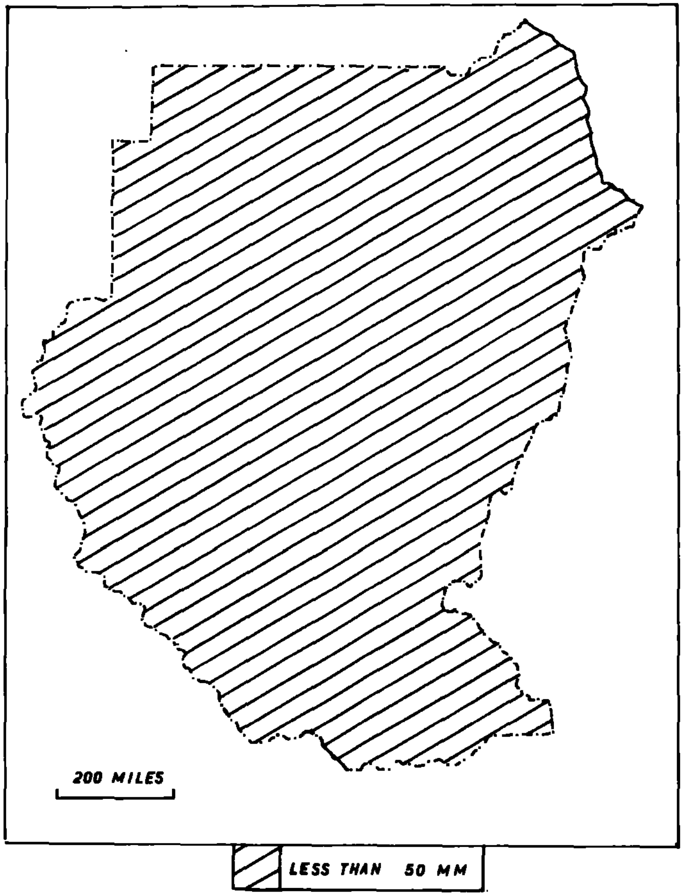


Fig. 19 February isohyets

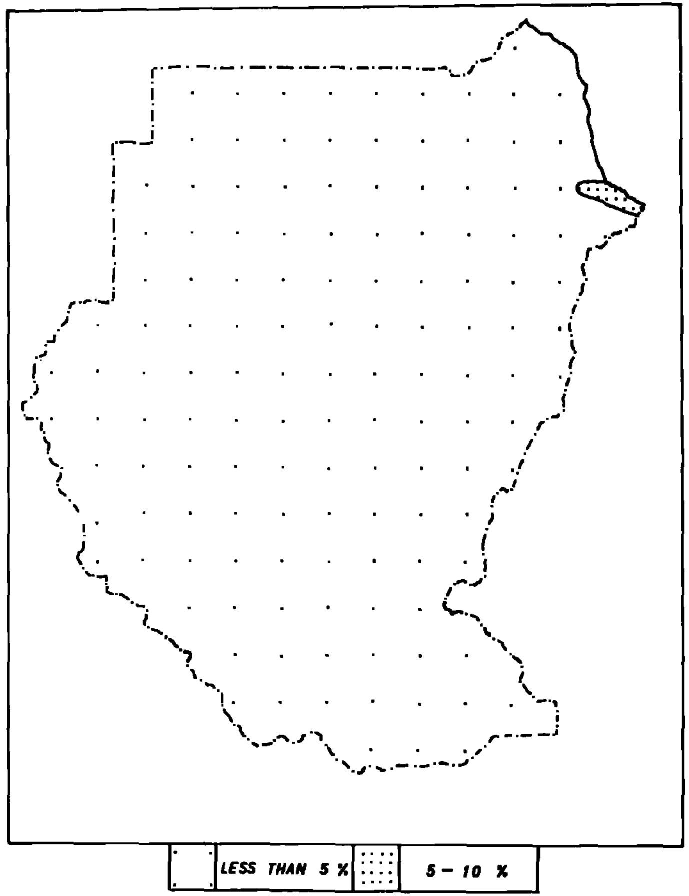


Fig. 20 February isomers

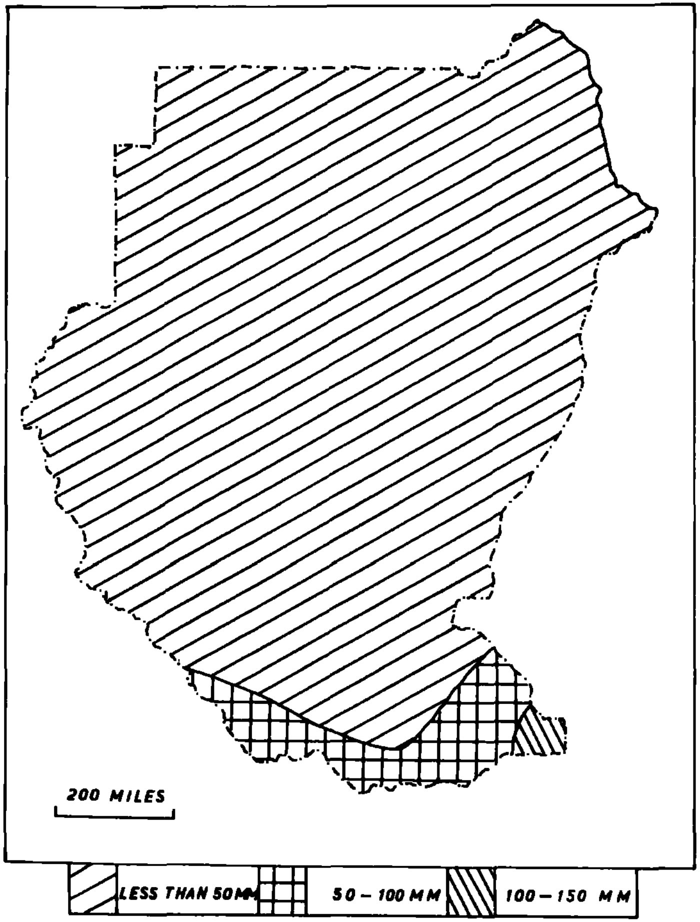


Fig. 21 March isohyets

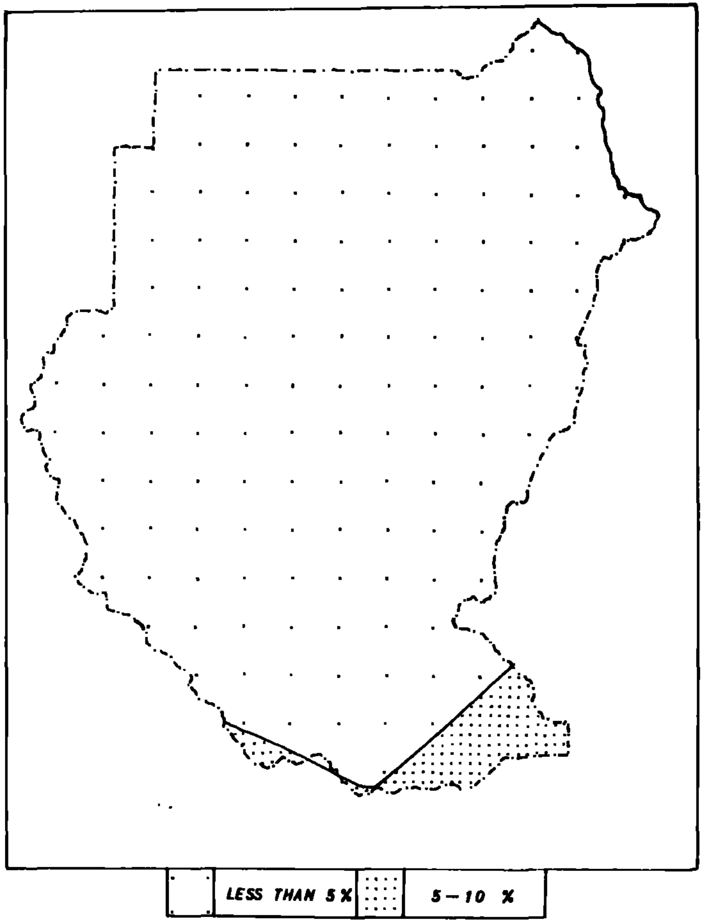


Fig. 22 March isomers

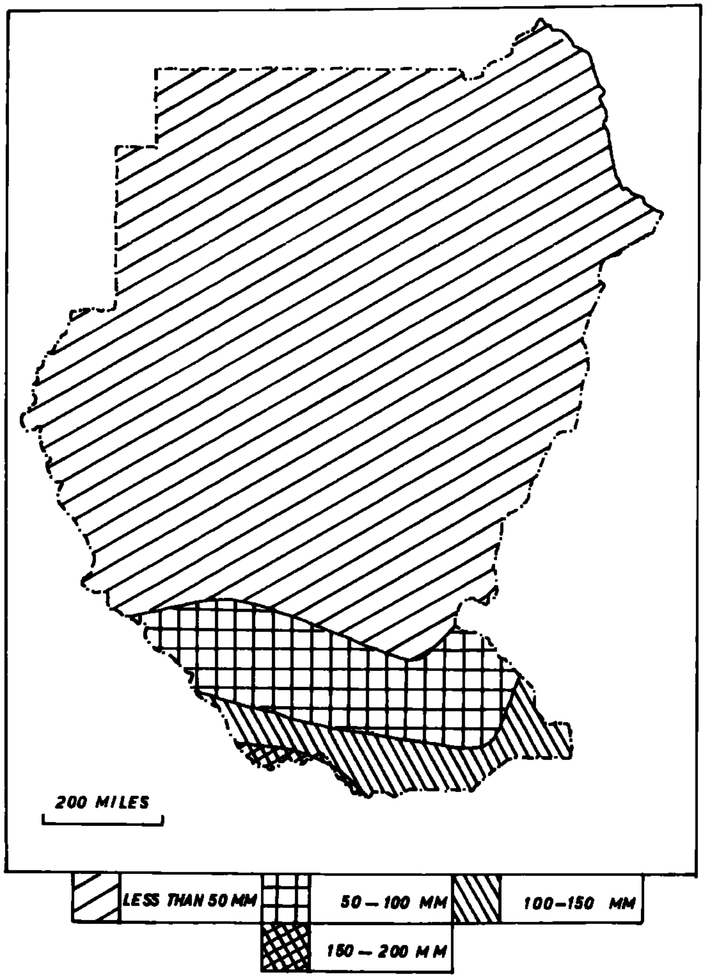


Fig. 23 April isohyets

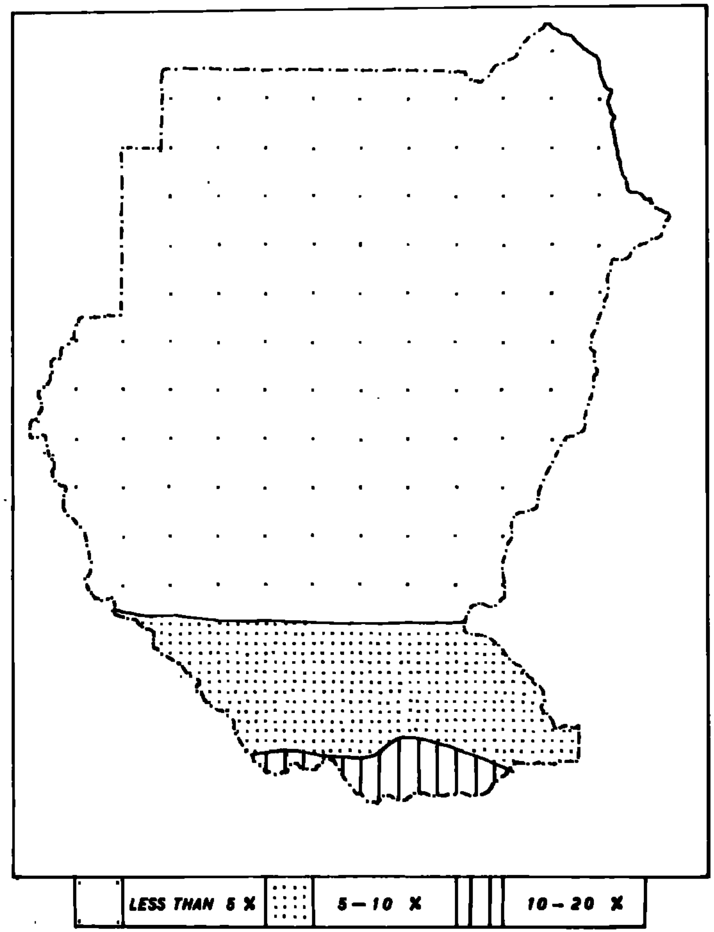


Fig 24 April isomers

April is still a dry month. During May, the 10% isomer advances slowly northward to about latitude 10° north, south of which all stations are receiving more than 100 m.m. of rains, (fig. 25-26). All the stations north of 14° north receive less than 5% of their annual rainfall during this month and so they are still dominated by the dry conditions. The area between the latitudes 10° and 14° north are under transitional conditions, and within this transitional zone the Nuba mountains seem to receive the highest percentages, which are more than 8% in some places such as Kologi (35).

By the month of June, the 10% isomer divides the country into two almost equal parts, (fig. 27-28). This isomer, which coincides with the wet month, advances northward very slowly during June and covers only three degrees of latitude. The transitional zone becomes very narrow. The dry zone is still persisting over the northern part of the country; it lies north of 18° north in the eastern part of the country, and north of 16° north in the west. This is quite obvious since the I.T.C.Z., with which all these rains are associated, tends to lie further to the north in the eastern parts of the continents rather

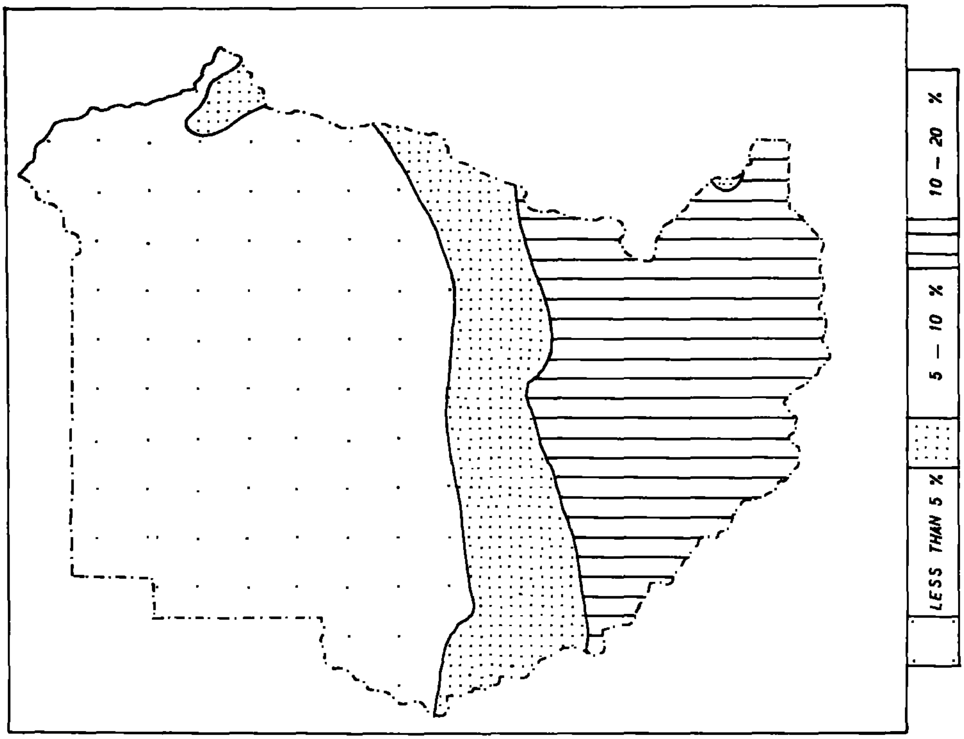


Fig. 26 May isomers

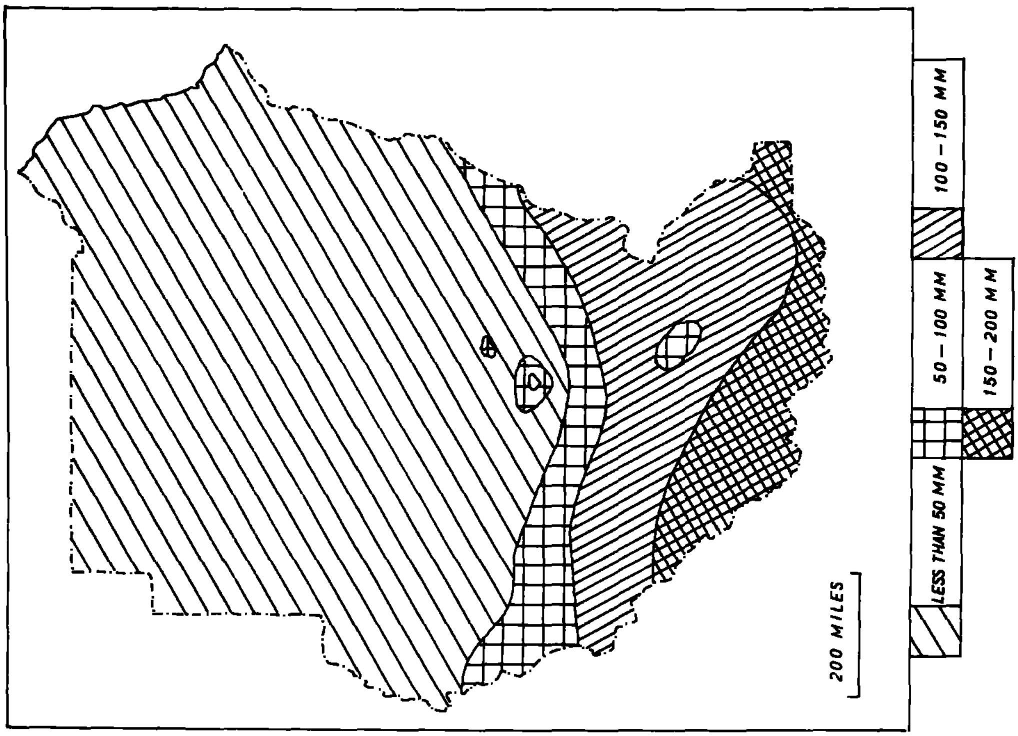


Fig. 25 May isohyets

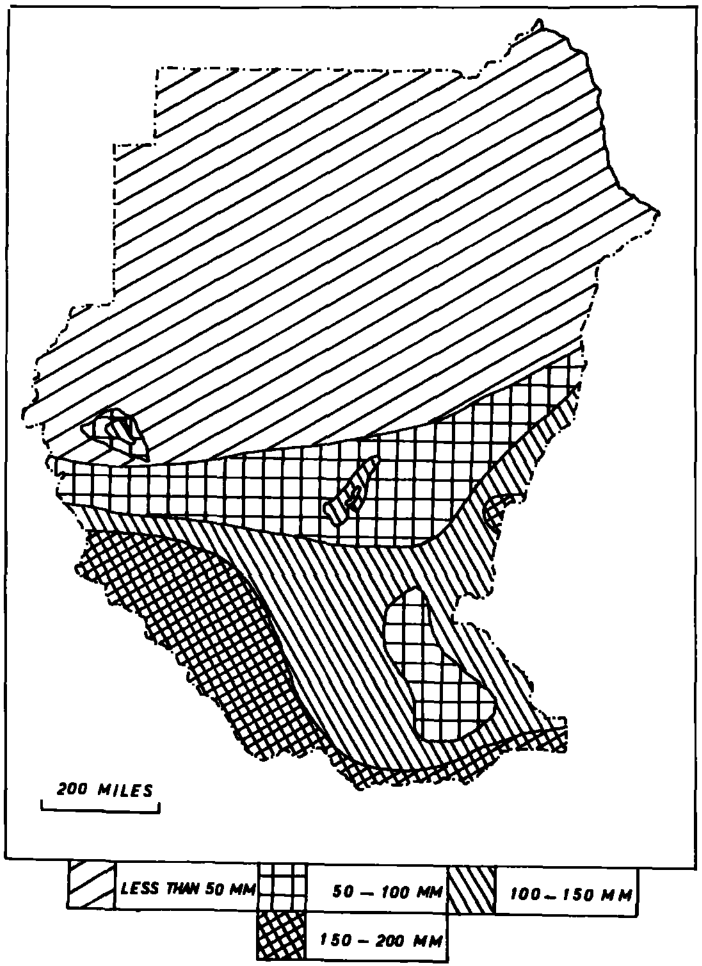


Fig. 27 June isohyets

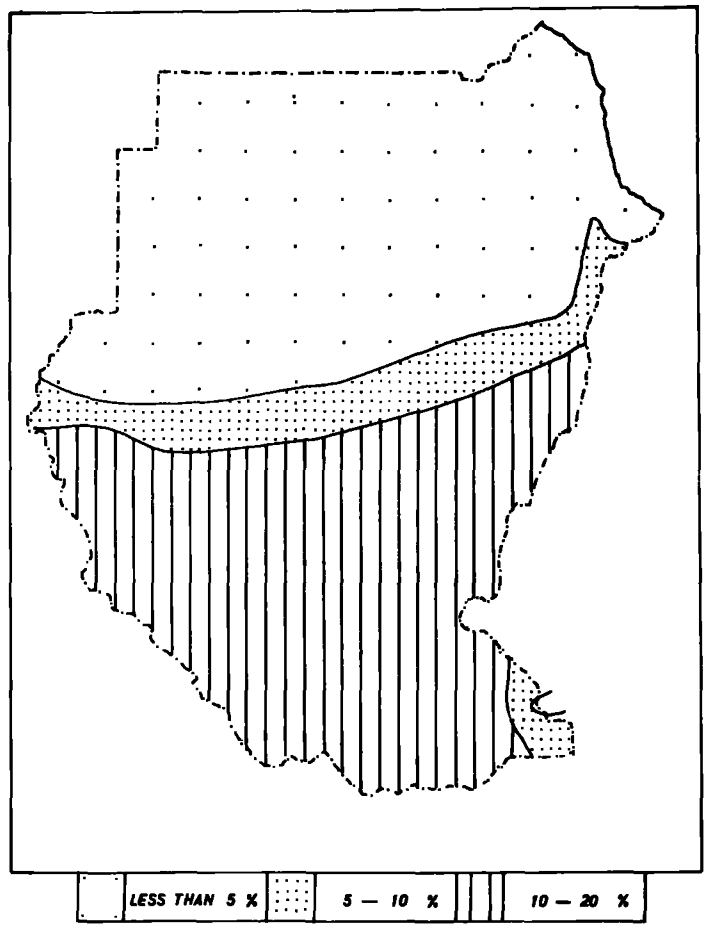


Fig. 28 June isomers

than the west. A feature to be observed during this month is that, in the extreme southern part of the country, both the absolute amounts and the percentages of the rains received tend to decrease in contrast to the rest of the country where both the absolute amounts and the percentages of the rainfall are rapidly increasing. This can be illustrated by the case of Yambio (64), Kagelu (29) and Juba (27).

During July, the rainy zone advances very quickly to cover the whole country, (fig. 29-30). The central Sudan receives very high amounts of rainfall during this month. In absolute terms the amounts received in the central Sudan are comparable to, or even higher than, the amounts received in the southern Sudan. This can be illustrated by the case of Gedaref (20) in the central Sudan which receives 161 m.m. during this month, an amount that is comparable to the 166 m.m. received at Yambio (64), in the extreme south, during the same period. On the other hand, the amount received at Gedaref (20) is actually higher than that received at several southern stations such as Shambe (52), Bor (11) and Malakal (40),none of which receives more than 155 m.m. All the country north of latitude 10° north receives at least 20% of the annual rains during this month. From this latitude the percentage decreases

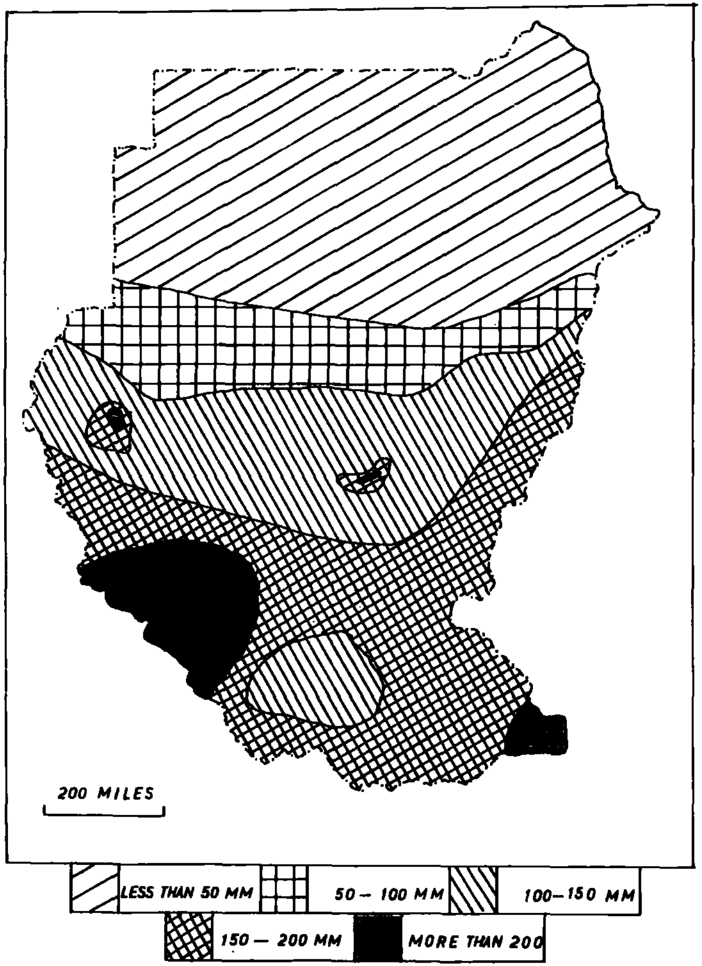


Fig. 29 July isohyets

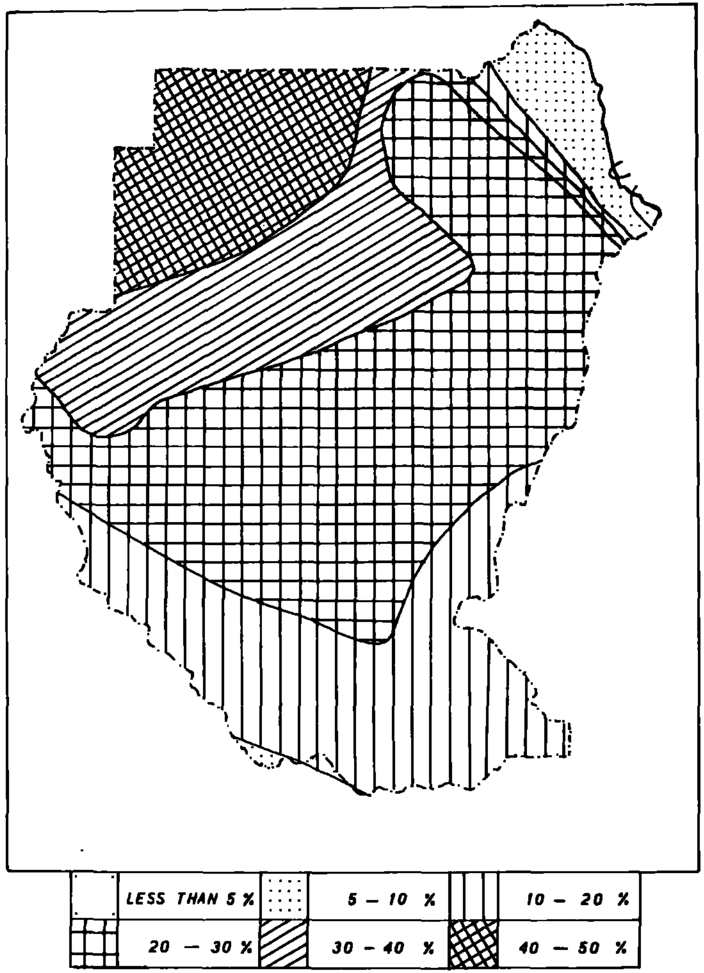


Fig. 30 July isomers

southwards and it is actually less than 10% in the extreme south west. This emphasises the existence of relatively drier conditions over the southern part of the country during the June-July period, as may further be illustrated by (fig. 31). An explanation of this feature may be found in the ideas of Flohn, (1959), which were presented by Bhalotra, (1963). He suggests that a zone of maximum rainfall exists south of the I.T.C.Z., from which the amounts of rainfall decrease both northwards and southwards. During the months of June and July, the I.T.C.Z. is approaching its most northerly position, and the zone of maximum rainfall seems to lie over the central Sudan, from where the amounts of rainfall tend to decrease north and south. These same conditions continue during August which is the rainiest month for the Sudan as a whole, (fig. 32-33). The areas north of 18° north receive more than 50% of their annual rainfall during this month, while the stations south of 8° north receive even less than 20%. In the latter region the percentage is continuously decreasing towards the southern borders. The central Sudan receives between 20% and 50% of its annual rains during this month

By September the rainy zone starts retreating southwards very quickly, (fig. 34-35). All the areas north of 19° north become dry, and the 20% isomer

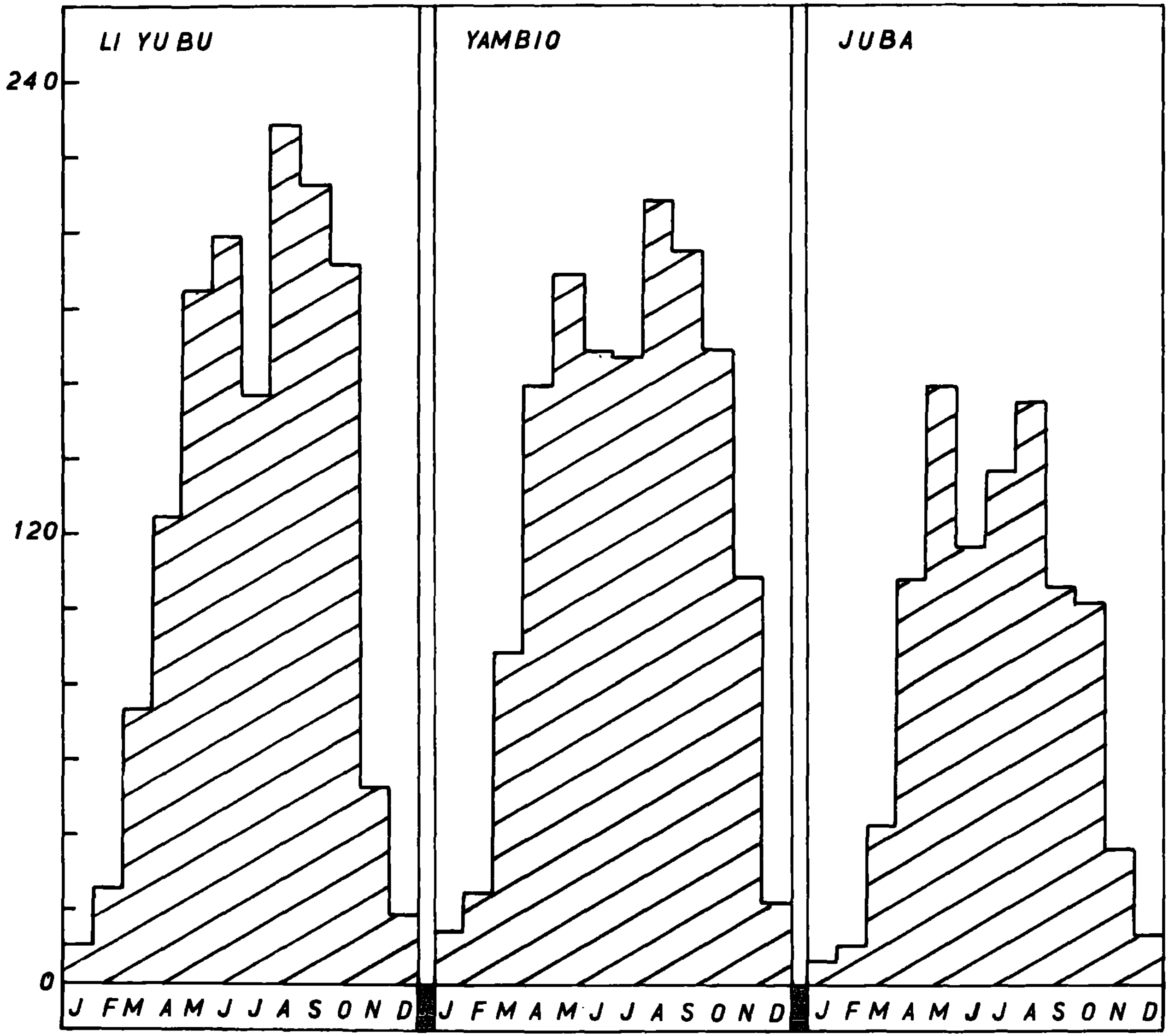


Fig. 31 Annual rainfall of Liyubu, Yambio and Juba in m.m.

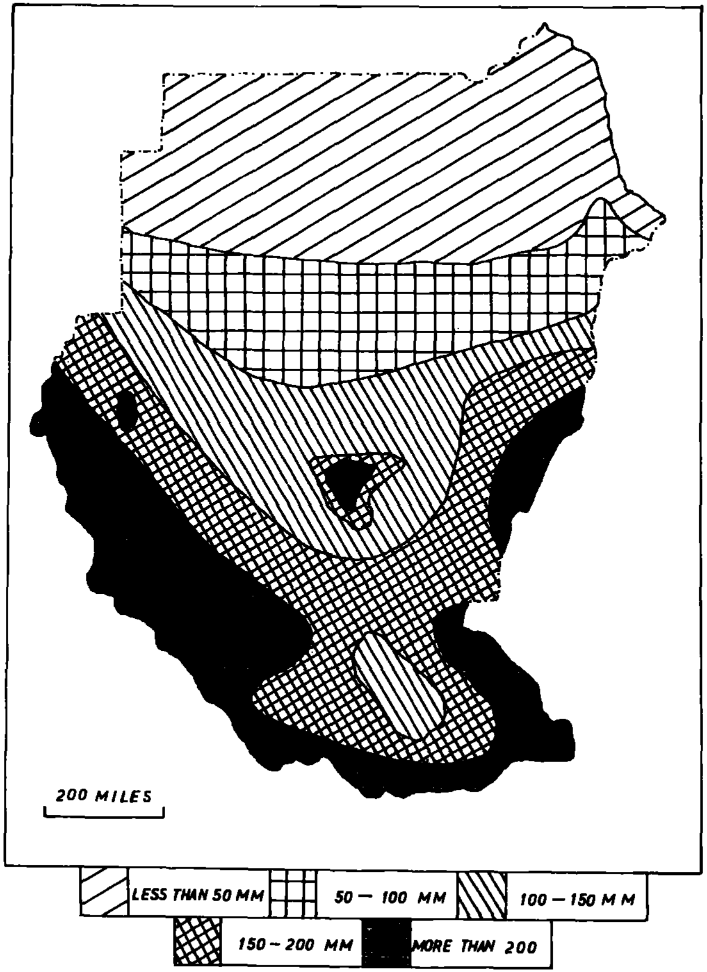


Fig. 32 August isohyets

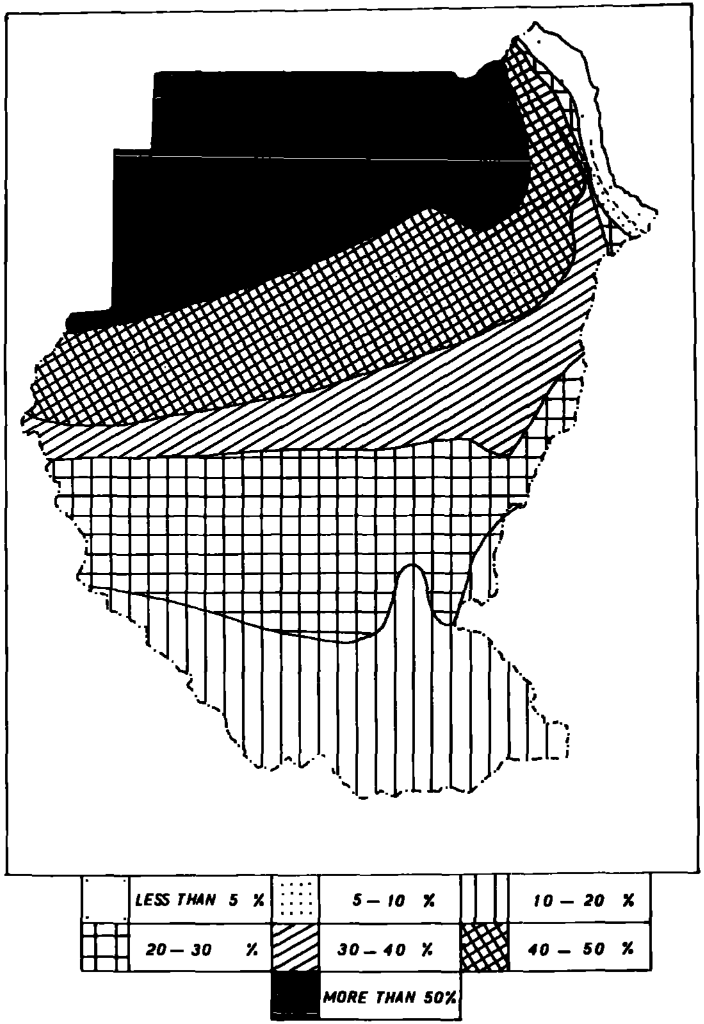


Fig. 33 August isomers

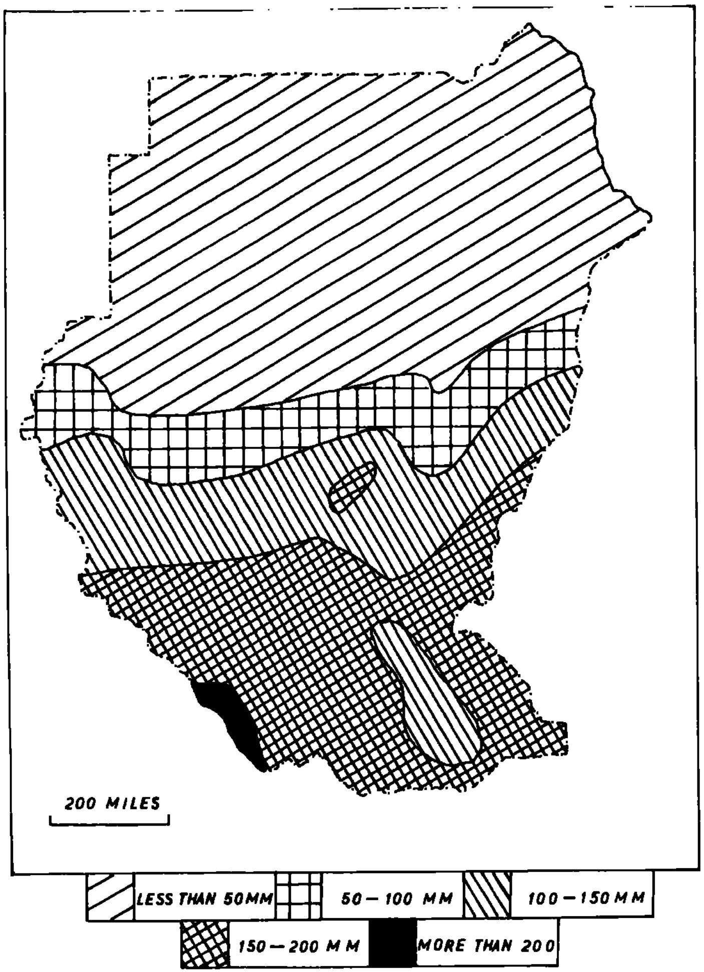


Fig. 34 September isohyets

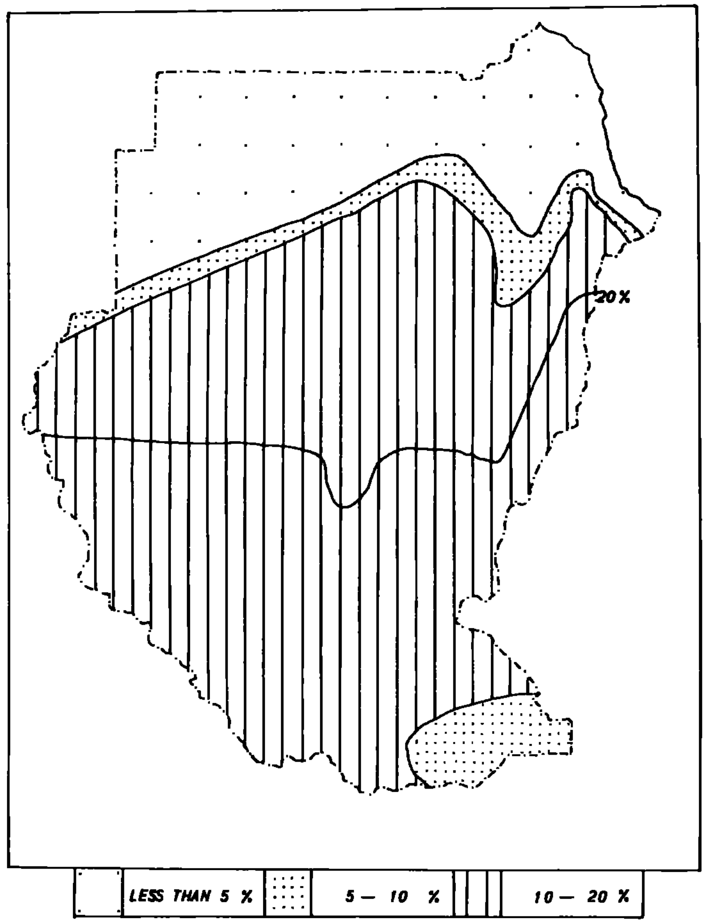


Fig. 35 September isomers

divides the country into two almost equal portions. It runs roughly along latitude 12^{o} north, from where the percentage of rainfall received during this month decreases to the north and to the south. The 20% isomer is nearly coincident with the 100 m.m. isohyet, especially in the central and western parts of the country. In the east the 20% isomer runs further north along the foot of the Abbyssinian plateau. Throughout the Sudan the absolute amounts of rainfall decrease greatly during this month. The rapid retreat of the wet belt continues during October, (fig. 36-37). During October, the wet belt is confined to a narrow triangular zone extending between the south western border and the Nuba mountains. The transitional zone is confined roughly to the southern third of the country, while all the remaining areas are experiencing dry conditions. Absolute amounts of rainfall received in the south are continuously declining. This decline continues throughout the months of November and December, neither of which can be considered as a wet month, (fig. 38-41). All the country becomes absolutely dry except in the extreme south where a little rain may continue to fall during these two months, but no where does it reach even the 5% level, and so even these may be considered dry.

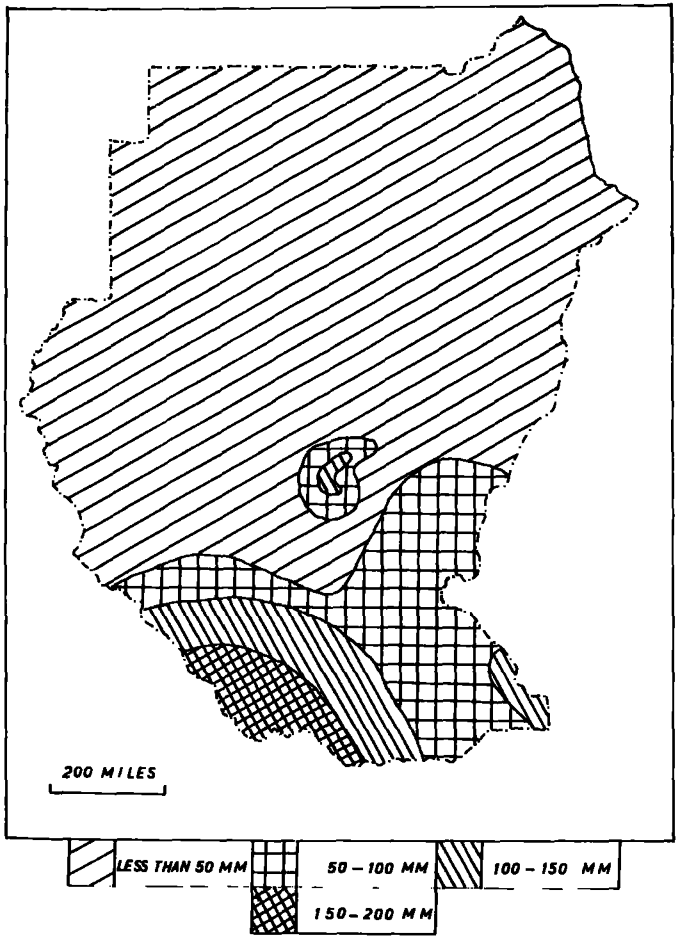


Fig. 36 October isohyets

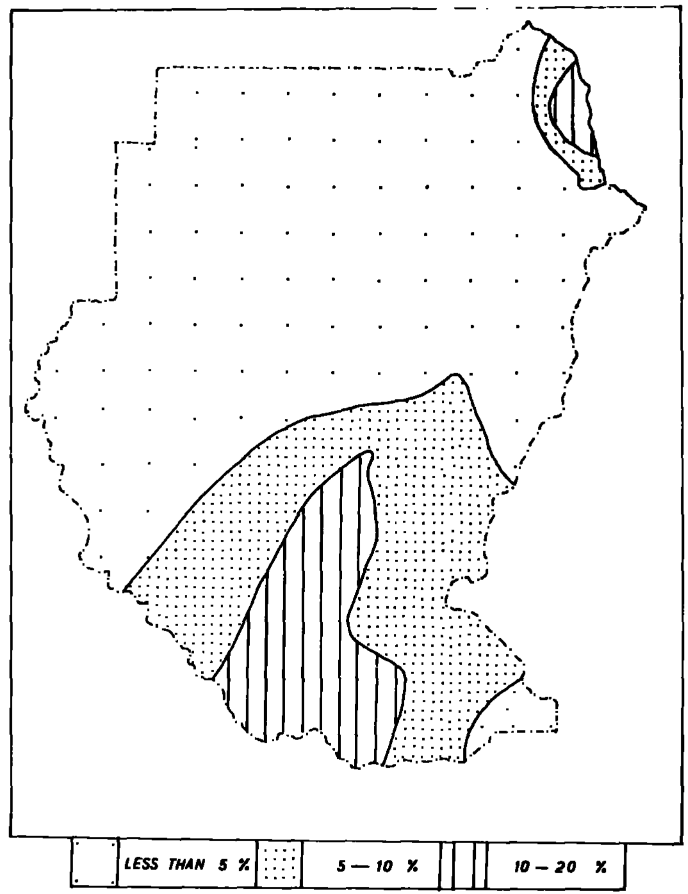


Fig. 37 October isomers

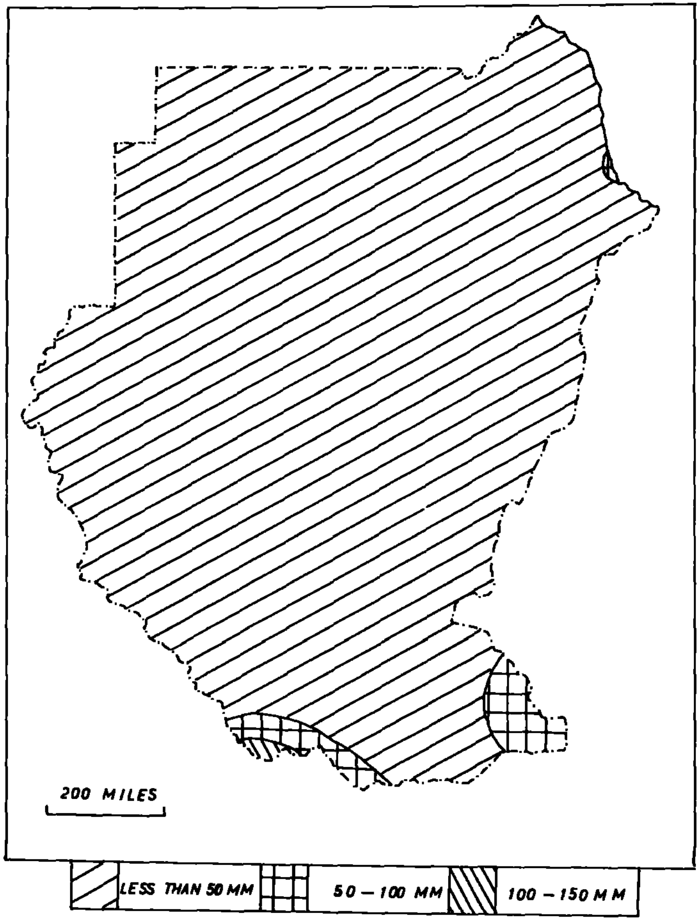


Fig. 38 November isohyets

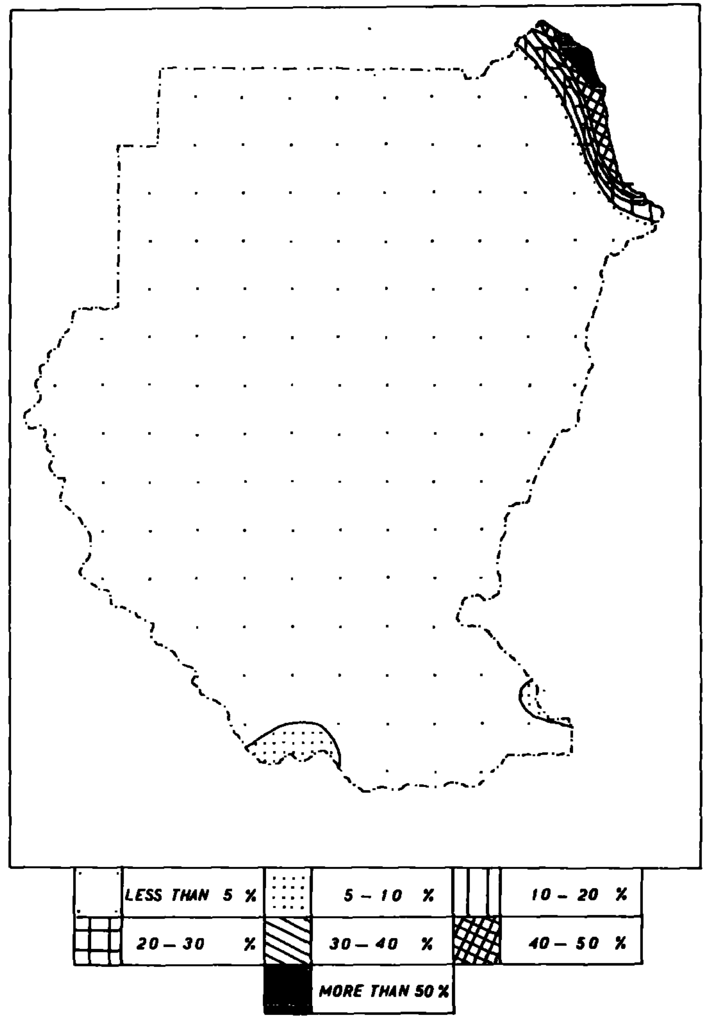


Fig. 39 November isomers

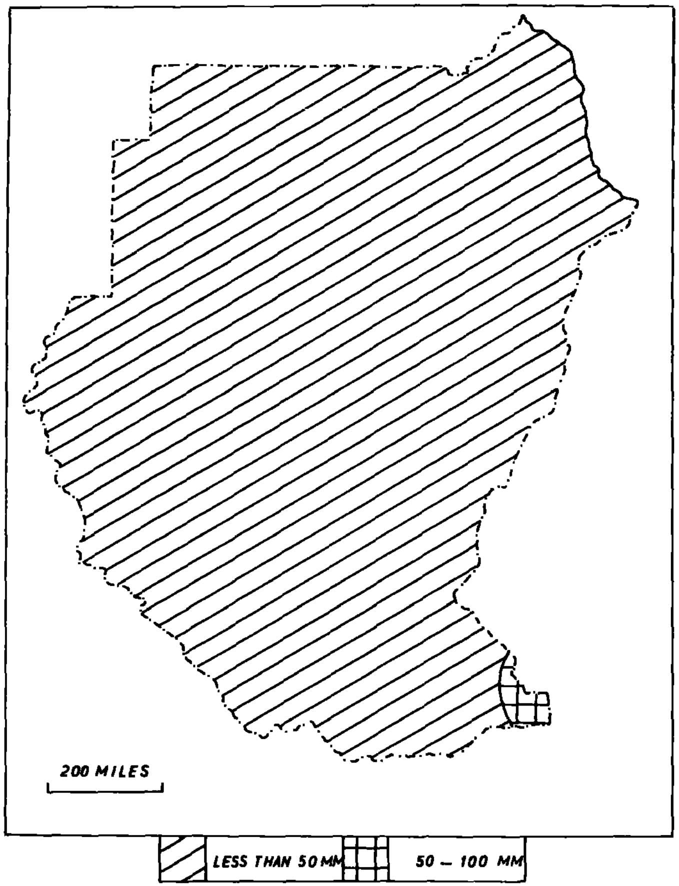


Fig. 40 December isohyets

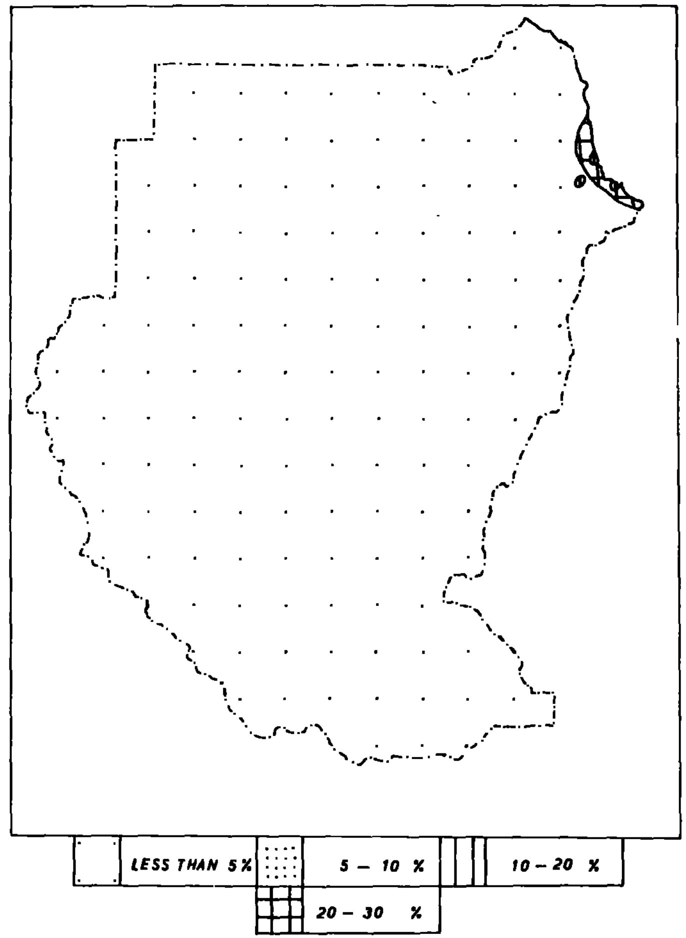


Fig. 41 December isomers

It may be noted that throughout the year, both the monthly isohyets and isomers follow the general pattern of the annual isohyets in running roughly along the latitudes from west to east. They also show some response to the topographical influences of the Jebel Marra region and the Nuba mountains. The effect of the Sudd region is apparent in the maps of the monthly isohyets rather than the isomeric maps.

Both the commencement and the termination of the wet zone differ greatly between one place and the other in the Sudan. The wet zone starts earlier in the south and spreads smoothly and slowly northward, (fig. 42). However, the termination of the wet zone is very rapid, (fig. 43). It may be observed that in the southern third of the country there is a marked difference in the termination of the wet zone between places on the same latitudes. This contrasts with the commencement of the wet zone which affects all the stations on the same latitudes at roughly the same time, throughout the Sudan.

Using Cook's definition of a rainy month, it is possible to take all the months during which at least 10% of the annual rains fall and to treat these as one group that may be called the wet or the rainy season.

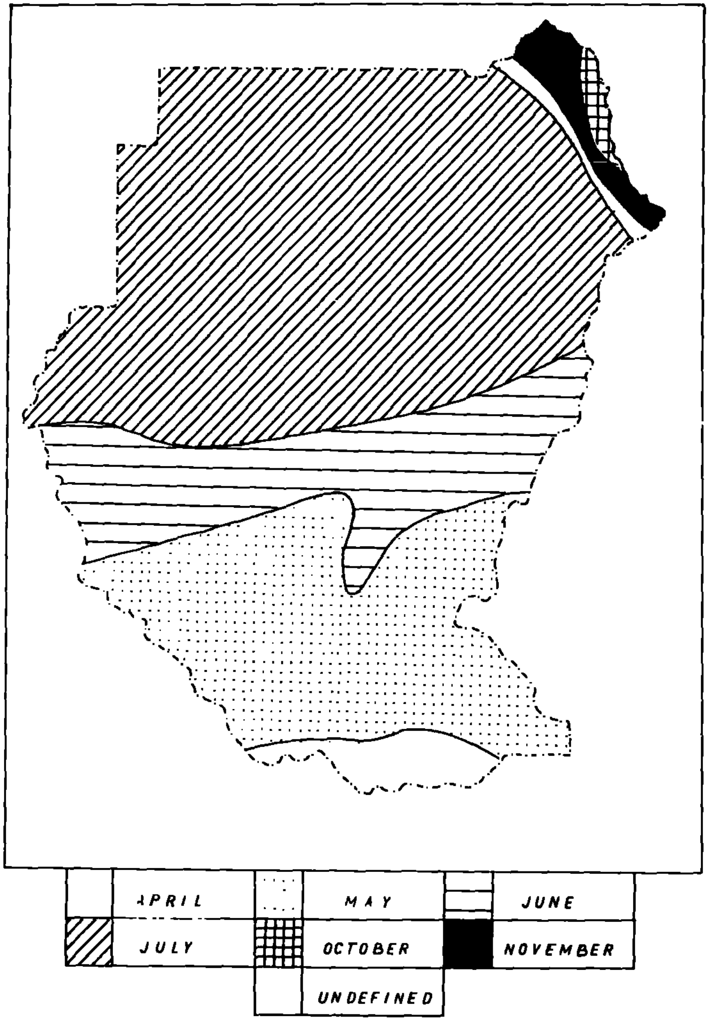


Fig. 42 Commencement of the wet season

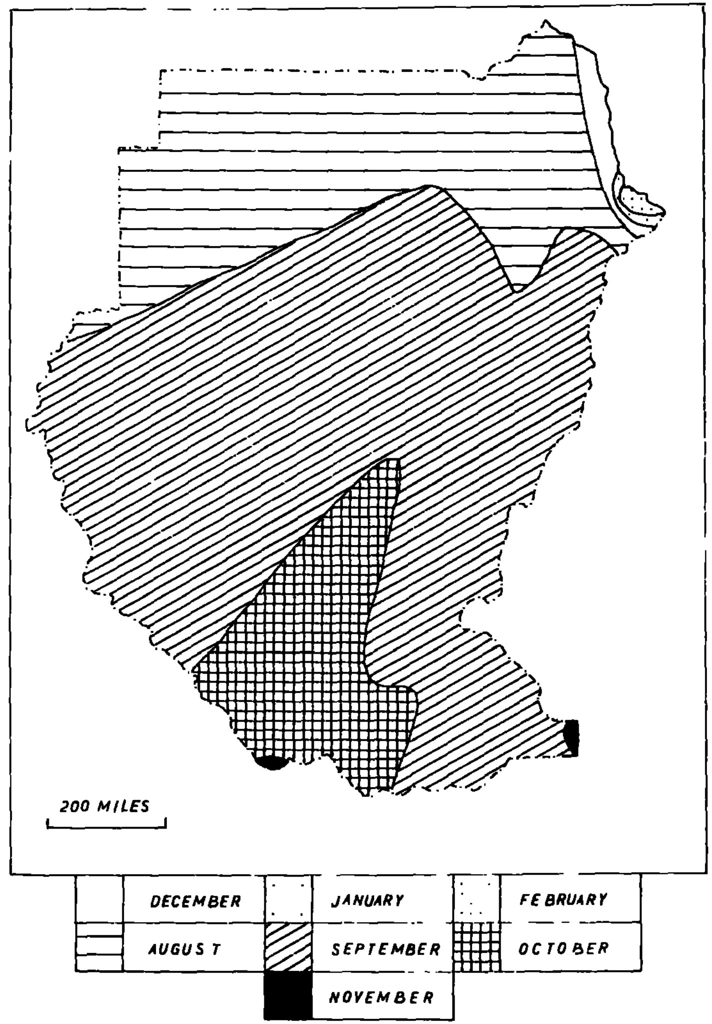


Fig. 43 Termination of the wet season

It is possible to construct the length of this rainy season by superimposing the map of the termination of the wet season over that of the commencement of the wet season. By this method seven rainy or wet seasons can be recognized over the Sudan. The length of these rainy seasons ranges between seven months in the extreme south-west and less than two months in the extreme north, as displayed by figures (44 and 45). Region A has the longest rainy season, equal to at least seven months. Here the rainy season starts during April and continues up to and including October. In regions B and C the rainy season extends to six months, but the seasons are not quite coincident in these two regions. In region B it starts during April and lasts up to September, while in region C it starts during May and lasts up to October. Thus in region B the rainy season starts and terminates earlier than in region C. Region D lies on nearly the same latitudes of region C yet it experiences a rainy season of only five months. It is only in this part of the country that a marked difference in the length of the rainy season is found between places on the same latitudes. The only possible explanation that may be given here is that the shape of region C seems to coincide with the

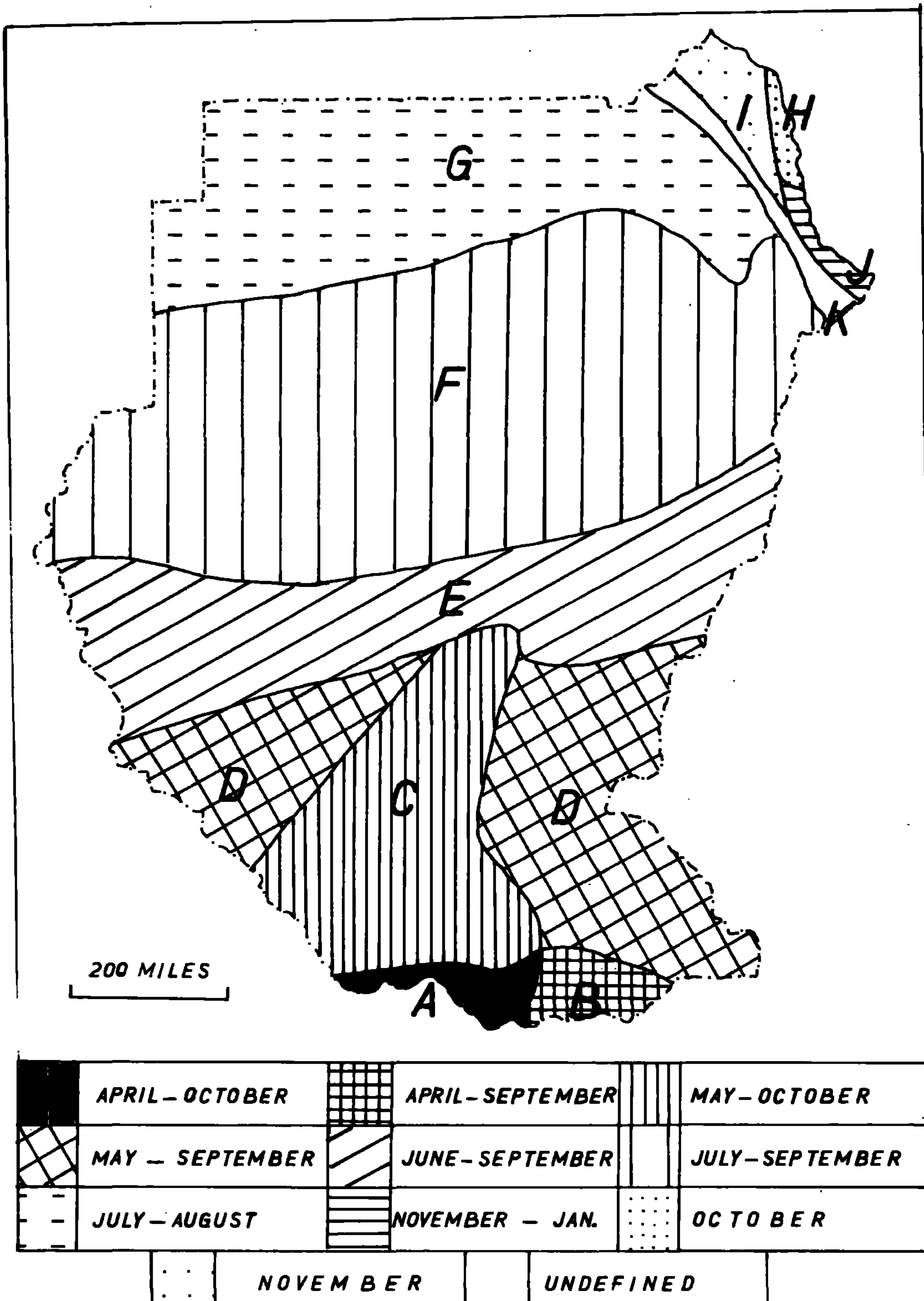


Fig. 44 The rainy seasons

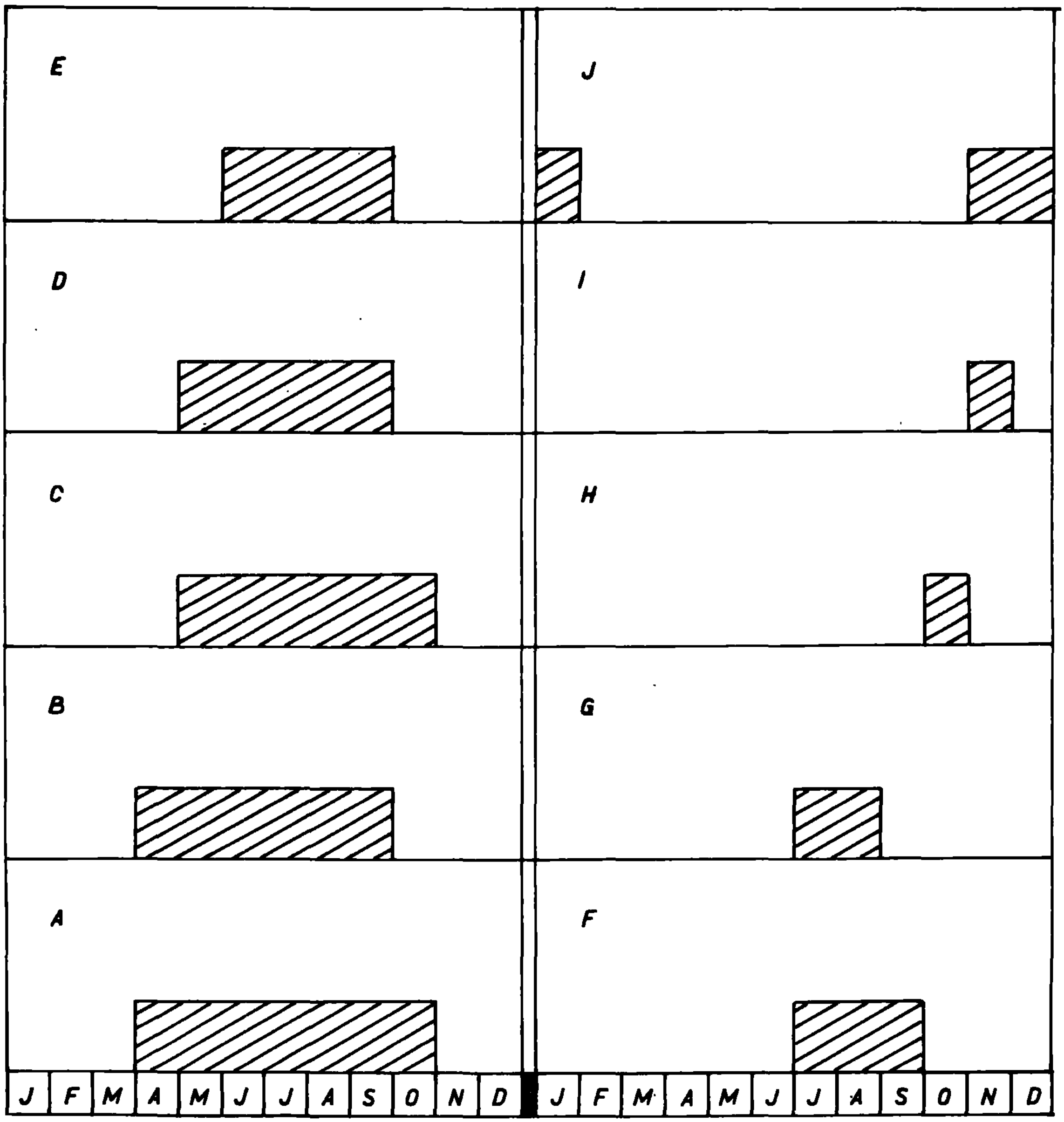


Fig. 45 The length of the rainy seaons

position of the I.T.C.Z., which during its southern retreat leaves the eastern and the western flanks of the country somewhat earlier than the centre, and the latter continues to be occupied by the south western monsoons for some time. In region D the rainy season commences in May, as in the case of region C, but terminates a bit earlier during September.

The rainy seasons tend to become shorter to the north. In region E it is only four months which extend between June and September. Region E is a relatively narrow one that crosses the country from east to west. The largest single region is region F which also extends from east to west over the central Sudan. Here the rainy season is only three months, which further exphasises the tendency of the rainy season to become shorter and shorter towards the north. Here the rainy season starts in July and terminates by the end of September. Region G, in the extreme north, is drawn very roughly due to the lack of observations in the north western part of the Sudan. If these northern areas ever experience a rainy season, it will be between July and August. In all these regions, the commencement of the rainy season is very much slower than its termination.

However, Gregory (1964 and 1965), suggests that it is more desirable to have a group of months that may be considered as the rainy season for the whole country rather than having different rainy seasons for the different parts of the country. These months can be defined as those during each of which at least 10% of the annual rains fall everywhere in the country. The months of July, August and September are the only months that satisfy these conditions, and so they form together what may very roughly be called the rainy season in the Sudan, however confusing the term may be. The wet season isohyets tend to follow the same general pattern of the annual and monthly isohyets. By dividing the total amount of rainfall received during this period, by the number of the months involved i.e. three, it is possible to have a very rough idea about the monthly intensity of rainfall during the general rainy season. The highest intensities are found in the extreme south west and they decrease gradually northwards, (fig. 46). The effects of the Jebel Marra region, the Nuba mountains and the Sudd region are quite similar to those outlined before for the annual conditions. In the eastern central Sudan the effect of the Abbyssinian plateau is very

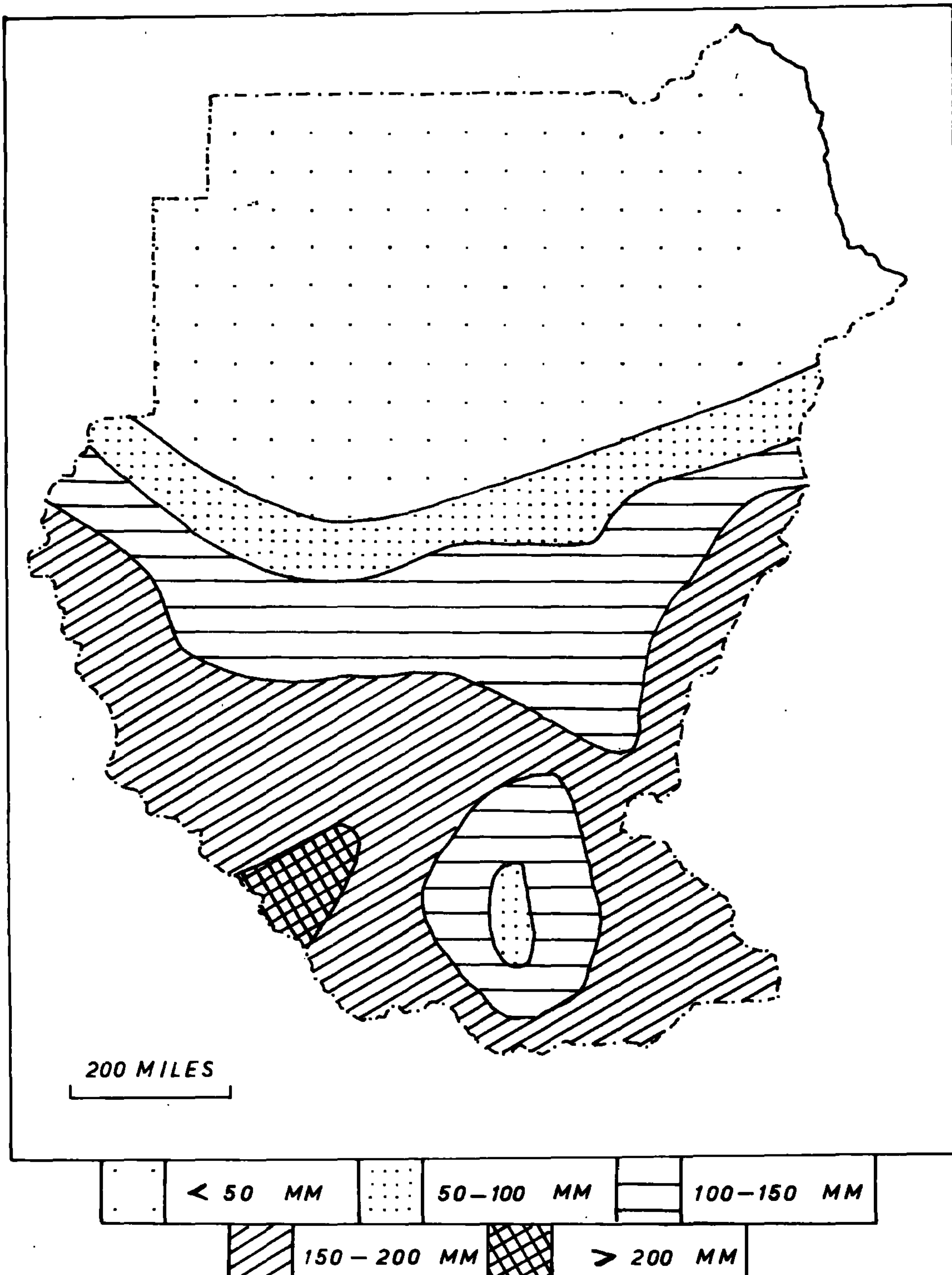


Fig. 46 Monthly rain intensity during the wet season

pronounced in increasing the amounts of rainfall in the eastern border relative to the inland areas on the same latitudes. This can be illustrated by the case of Roseiries (50) and Renk (49), the former near the eastern border and the latter on the same latitude but further inland. During the rainy season the monthly intensity of rainfall at Roseiries (50) is 181.6 m.m. while at Renk (49) it is only 122.6 m.m. During the rainy season the monthly intensity of rainfall is less than 50 m.m. for nearly all the areas north of latitude 15° north. The zone confined by the 50 m.m. and the 100 m.m. isohyets is very narrow but crosses the country rather smoothly from the west to the east.

A better idea about the distribution of the mean rainfall of the generalised wet season, can be obtained by expressing the total amounts of rainfall, received during these particular months, as a percentage of the mean annual rainfall, (fig. 47). This shows that almost three quarters of the country receive more than 60% of the annual rainfall during the period July-September. The central and northern Sudan receive at least 75% of the annual rainfall during this period. The extreme northern areas receive almost all of the annual rainfall during this short period. The southern

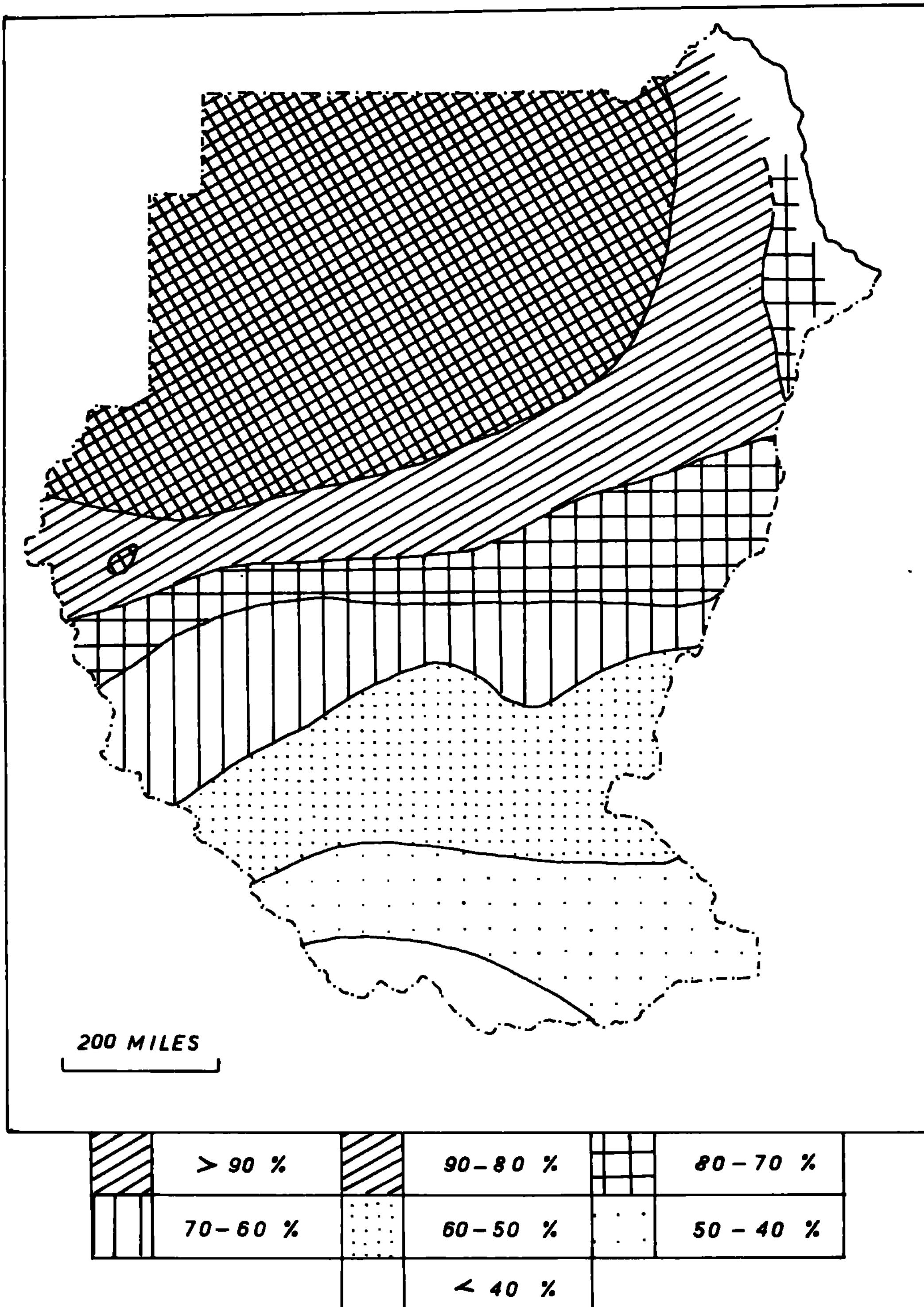


Fig. 47 Wet season rainfall as percentage of annual rainfall

quarter of the Sudan receives less than 60%, a percentage that decreases further towards the south western border where some stations receive less than 40% of the annual rainfall during this period. This distribution shows clearly how the rainfall is confined to a short period in the largest part of the country, whilst it spreads throughout the year, or at least for a longer period, towards the southern borders. In the north east of the country the percentages of the rains received tend to be lower towards the coast rather than on the inland areas on the same latitudes; but they are nowhere less than 75%. This characteristic of the north east emphasises the partial contribution of the winter rains from the Red Sea.

Over the Red Sea coastal area the distribution of the monthly and seasonal rainfall is quite different from the rest of the Sudan. During April, May and June some little rain may fall in this region, but nowhere does it reach even the 5% level, (fig. 23-28). So these months are considered as dry over the coastal region. The highest absolute amounts of rain received during this period fall further inland rather than along the coast. This can be illustrated by the case of Erkowit (17), which receives an average of 10 m.m. during each of these three months; an amount that is never experienced in any of the coastal stations. Such inland rains seem to be associated with the south-western monsoons, flowing across the whole country, rather than with the north eastern trades flowing across the Red Sea.

During July, some coastal stations, such as Port Sudan (47), Suakin (57) and Tokar (59), receive more than 5% of their annual rainfall, (fig. 29-30). Nowhere does the amount received reach the 10% level, and so July can not be classified as a wet month on the coastal area. Further inland slightly higher proportions are received around Erkowit (17) and Gebeit (18), the latter receiving about 25% of its annual rainfall during this month. So, inland the month of July is well within the wet season. The extreme northern part of the coast, around Halaib (25), is absolutely dry. This same pattern continues during August when inland stations receive much higher percentages of their annual rainfall than the coastal stations which generally receive less than 5%, (fig. 32-33). Inland stations may be represented by Erkowit (17), which receives 21%, and Gebeit (18) which receives almost 42% of its annual rainfall during this month. These inland rains are definitely associated with the south western monsoon. In absolute terms, Erkowit (17) and Gebeit (18) receive 50 m.m. and 55 m.m. respectively, while all the stations along the coast receive less than 10 m.m. during the month of August. Throughout the coastal region both the absolute amounts and their percentages drop suddenly during September, (fig. 34-35). The coast itself becomes absolutely dry, and inland, Erkowit (17) receives less than 5% of its annual rainfall and so it is also considered dry.

The picture changes suddenly during October, (fig. 36-37). The proportion received along the coast tends to rise from nil to about 10% around Port Sudan (47) and Arbaat (6). For the rest of the coast, the proportion varies between 5% and 10%, and so the coast can generally be considered as experiencing transitional conditions. The pattern of inland and coastal distribution of the rainfall tends to be reversed during this month. In contrast to the previous months, the coastal stations, such as Port Sudan (47) and Suakin (57), tend to receive higher amounts, in both percentages and absolute terms, than the inland stations such as Erkowit (17) and Gebeit (18). These changes seem to be associated with the intensification of the Saharan anticyclone, and thus the increasing activities of the north-eastern Trades which are associated with this anticyclone.

The tendency towards increasing rains along the coast continues strongly during November, (fig. 38-39). Most of the coastal stations receive more than 30% of their annual rainfall during this month. Halaib (25), in the far north, seems to receive almost 80% of its annual rainfall during November, a percentage that is higher than that received at any other station along the coast. An exception to the tendency towards very high percentages is found in the case of Aqiq (5), in the extreme south, which receives only 18% of its annual rainfall during this month. The reasons behind this are not quite clear, but it may in some way be related to a southward march of the wet zone. Generally, November is the wettest month in the Sudan coastal region, in contrast to the rest of the country for which November is nearly everywhere a dry month.

During December, a sharp drop is noticed in the amounts of rainfall received along the coast, (fig. 40-41). Most of the stations receive less than half the amounts they receive during November. In contrast to this, Aqiq (5) receives about 29% of its annual rainfall during this month, which is the highest percentage received on the coast during this period. Halaib (25) receives less than 10%, while all the stations between these two extremes receive around 20% of their annual rainfall. This pattern of rainfall distribution along the coast, with increasing percentages southwards, may further indicate the southward march of the rainy zone. Thus on the coast the rainy zone marches from north to south, while on the rest of the country it marches from south to north. Inland, Erkowit (17) receives about 12% while Gebeit (18) receives less than 1%. So generally, December can be considered as a rainy month in the southern rather than the northern part of the coast. The sharp drop in the absolute amounts and the percentages continues during January, (fig. 17-18). The case of Aqiq (5) is still an exception to the general pattern. At Aqiq (5) both the percentages and the absolute amounts rise high above those experienced during December. Actually Aqiq receives almost 37% of its annual rainfall during January. For all the stations south of Port Sudan (47), January is considered as a rainy month, since no station in this region receives less than 10%. Inland the percentage received at Erkowit (17) rises to 20%. Throughout February these coastal areas still receive some rainfall, but nowhere does it reach the 10%, and so for the whole coastal area, February is not considered as a rainy month, (fig. 19-20). March is a very dry month in the coastal region, (fig. 21-22).

Some little rain may be received, especially in the southern part of the coast around Aqiq (5), but these are hardly above the 2% level.

In the coastal region the percentage of rain that falls during any single month ranges between zero and 50%. An exception to this, is found in the case of Halaib (25) which receives almost 80% of its annual rainfall during the month of November. Some inland stations, such as Erkowit (17) receive almost equal amounts of rainfall during the months of January and August. The total amount of rainfall received at Erkowit during these two months is equal to 40% of its annual rainfall. Such stations practically experience two rainy periods: the first occuring in the summer, associated with the south-western monsoons, and the other occuring in the winter, associated with the north-eastern Trades. Another feature to be observed is that, unlike the coastal stations, November is not the rainiest month for these inland stations. This can also be illustrated by the case of Erkowit (17) which receives less than 10%, and Gebeit (18) which receives less than 5% of the annual rainfall during this particular month.

Using the technique of superimposing the map of the termination of the wet season upon that of its commencement, it is possible to have a rough idea about the length of the rainy season in the Sudan coastal region. By this method four rainy seasons can be recognized, (fig. 44). Regions H and I have only one month each that may be classified as a rainy month. In region H this month is October, while in region I it is November, when 80% of the annual rains fall around Halaib (25). Further south along the coast lies region J, which has the longest winter rainy season, that extends from November to January inclusive. Region K is largely an undefined region. It is drawn very roughly due to the lack of adequate information about this part of the country. However, the southern portion of this region includes those areas that experience both a summer and a winter rainy period. In fact both region I and K are drawn very roughly, and so their spatial extent can not be considered as reliable.

It is rather difficult to recognize a single common rainy season for the Sudan coastal region. However it is possible to choose the months of November, December and January for this purpose, but this is not applicable to the northern part of the coast (fig. 48). These three months together can safely be considered as the rainy season for the coastal area south of Port Sudan (47)

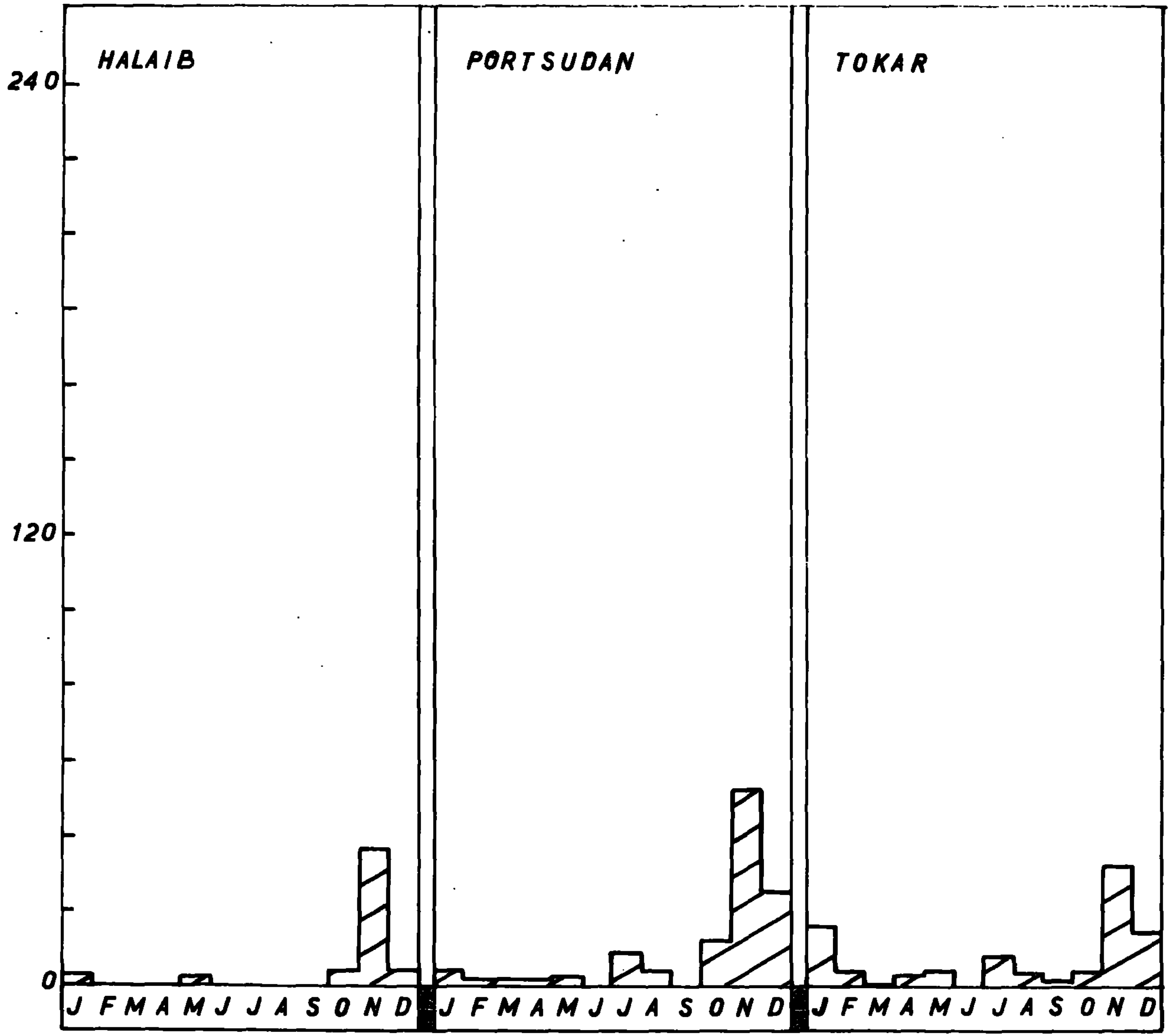


Fig. 48 Annual rainfall for Halaib, Port Sudan and Tokar in m.m.

and so excluding the northern part of the coast as well as the inland stations. The mean monthly intensity of rainfall during this period ranges between 20 m.m. and 40 m.m. Also during these three months at least 60% of the annual rains fall. In the extreme south, this percentage rises to almost 84% around Aqiq (5).

THE VARIABILITY AND PROBABILITY OF THE RAINFALL OVER THE SUDAN

The variability of Rainfall

For an agricultural country like the Sudan, the reliability of rainfall is of great importance. Unfortunately the actual annual and monthly values of rainfall fluctuate considerably around the mean, as is illustrated by (fig. 49). Such an illustration does not help much in the assessment and the evaluation of the degree of variability over the country as a whole. It is for this reason that more detailed statistical methods have been found necessary to be applied in an attempt to evaluate the degree of variability of the rainfall over the Sudan. Twenty stations are used to determine the variability of rainfall, (fig. 50). The selection of these twenty stations is dictated by the fact that these are the only suitable and reliable stations for which detailed records are available for the standard period 1931-1960. Most of the selected stations lie within a belt across the Sudan between latitudes 10° north and 16° north. Within this belt lie the major agricultural areas of the country such as the Gezira scheme and the Managil extension which are the major cotton producing areas of

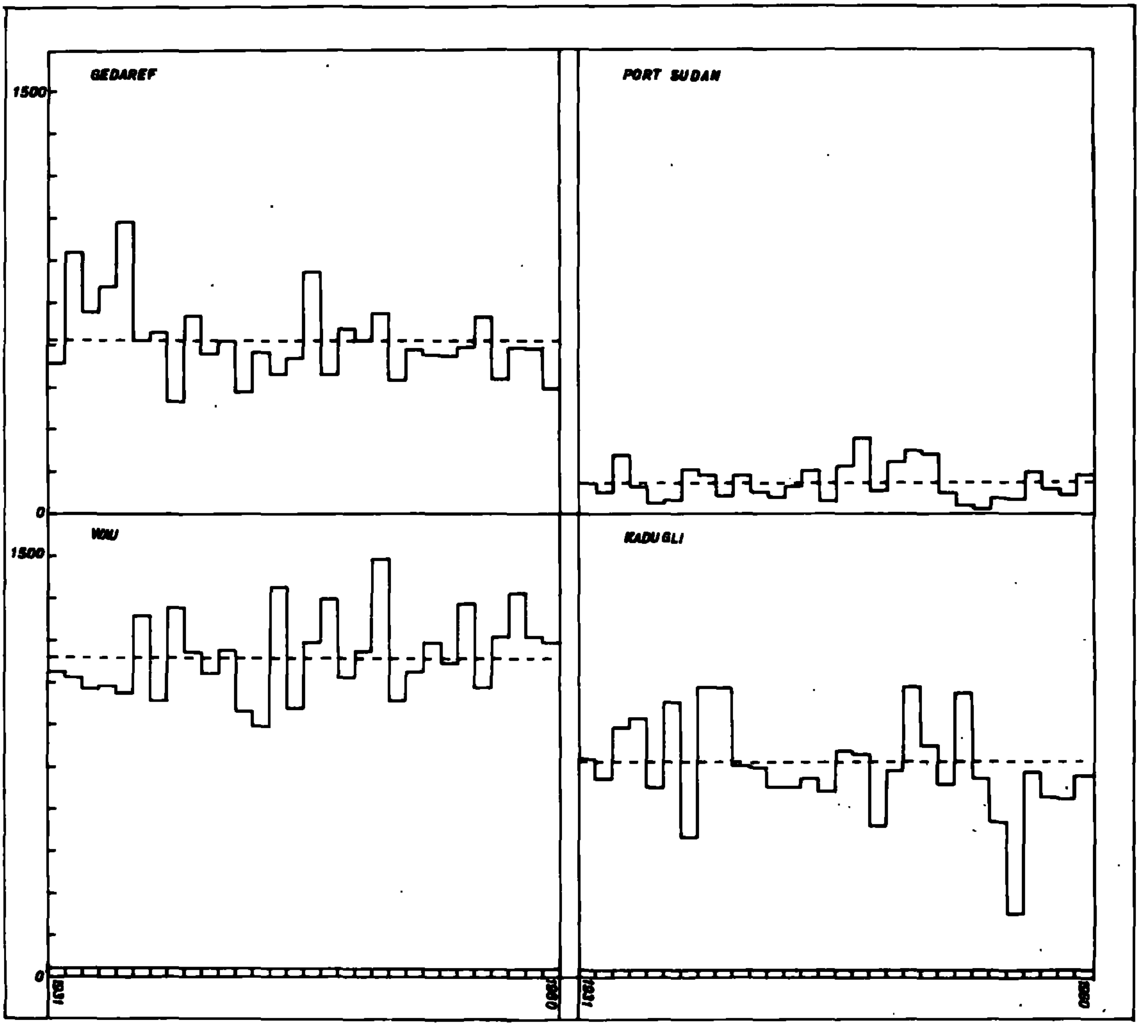


Fig. 49 Fluctuations of the annual rains around the mean in m.m.

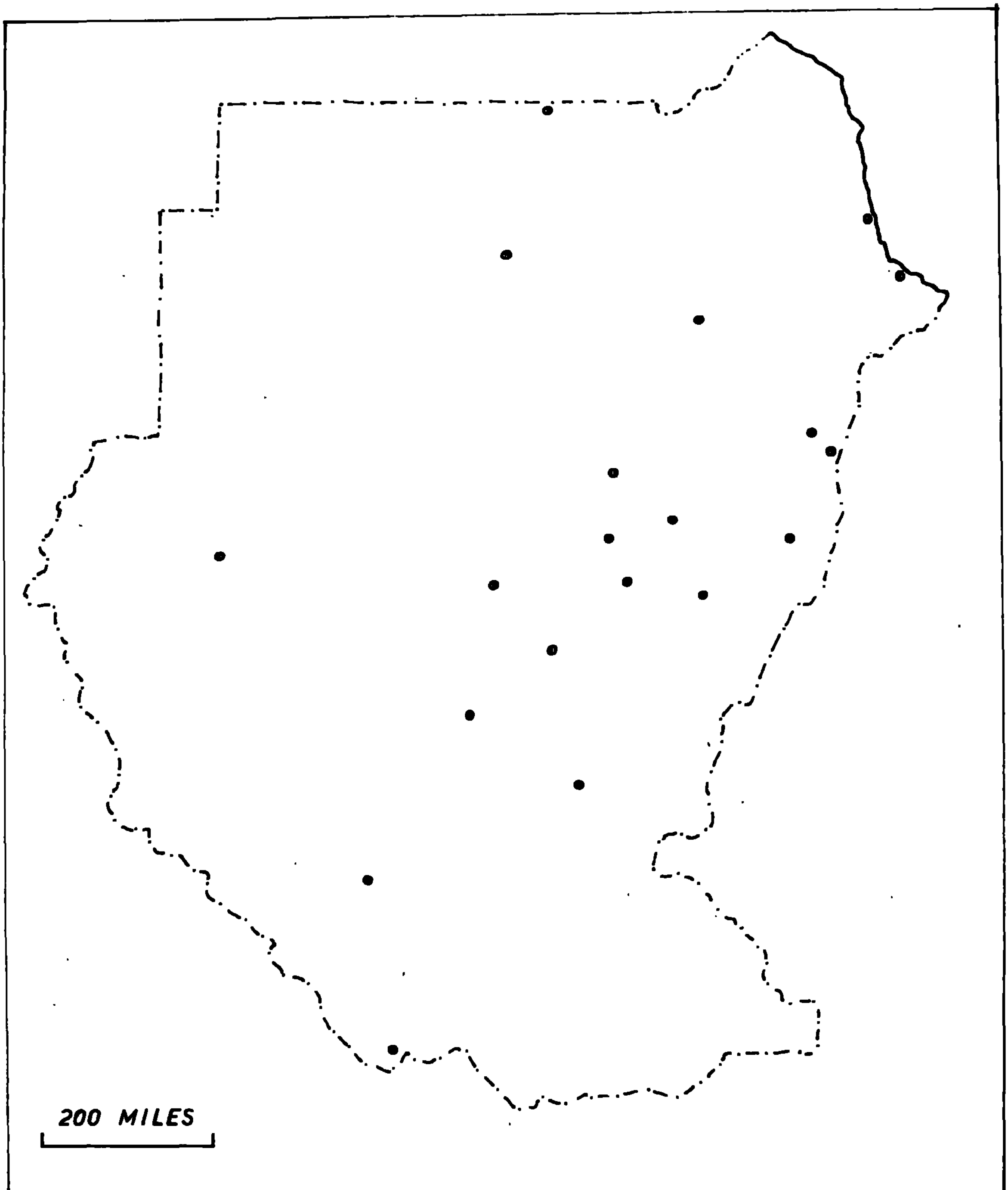


Fig. 50 Stations used for rainfall reliability

the Sudan. Also this region supplies the Sudan with all its requirements of Sorghum, which is the major food crop, and all the gum arabic for which the Sudan is the main exporter. So these agricultural areas are by far the most sensitive parts of the country to the variations in the monthly and the annual amounts of rainfall. Outside the region confined between latitudes 10^{o} north and 16^{o} north, the values given are very approximate, and so cannot be considered as reliable.

A general assessment of the variability of rainfall can be made by calculating the standard deviation of the actual rainfall from the mean values, using the formula:-

$$\sigma = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n-1}}$$

where $(x - \bar{x})$ is the deviation of the actual rainfall from the guessed mean, and n is the number of years used in the calcualtions. The results obtained indicate the values above and below the mean within which the actual amounts of the annual or the monthly rainfall are likely to fluctuate.

At Yambio (64) the annual standard deviation is about 148 m.m. while at Wadi Halfa (61) it is just above 7 m.m. Throughout the central Sudan the annual standard deviation varies between 88 m.m. and 120 m.m. In the Sudan coastal region, the annual standard deviation fluctuates around 60 m.m. The monthly standard deviation tends to increase gradually with the approach of the rainy season, and then drops suddenly with the approach of the dry season. During the general rainy season, i.e. July-September, the values of the monthly standard deviation in the central parts of the country are much higher than in the south. This is a repetition of the pattern outlined in the case of the monthly and seasonal distribution of the rainfall where both the absolute values of rainfall and the isomeric values tend to be higher in the central parts rather than the southern parts of the country during the rainy period July-September.

These results are rather confusing especially from the agricultural point of view. They show that the variability of the rainfall decreases from south to north, i.e. positively related to the amounts of the rainfall, which may indicate that the effects of the rainfall fluctuations are much greater in the south than the north; but actually this is not quite so. However, a much better method for the assessment of the variability of rainfall can be obtained by calculating the coefficient of variation, which is simply the expression of the standard deviation as a percentage of the mean rainfall. This coefficient of variation can be obtained by using the formula:-

$$CV = \frac{\sigma}{\bar{x}} (100)$$

where σ is the standard deviation, and $\bar{x}$ is the mean monthly or annual rainfall.

The annual coefficients of variation over the Sudan present a simple pattern that run in a south-west to a north-east direction, (fig. 51). In the extreme south-west the annual coefficient of variation is less than 10%. This percentage increases slowly towards the centre of the country. All the areas north of 18° north, including the Red Sea region, have a coeffient of variation of more than 50%. At Halfa (61) in the extreme north, the annual coefficient of variation is about 246%.

During the month of January, the extreme south-west and the Red Sea region have coefficients of variation of about 100%, while the rest of the country has an infinite coefficient of variation, (fig. 52). These conditions continue throughout February and March, (fig. 53 and 54). All country north of latitude 6° north has a variability of more than 100%. This degree of variation decreases gradually towards the south-western

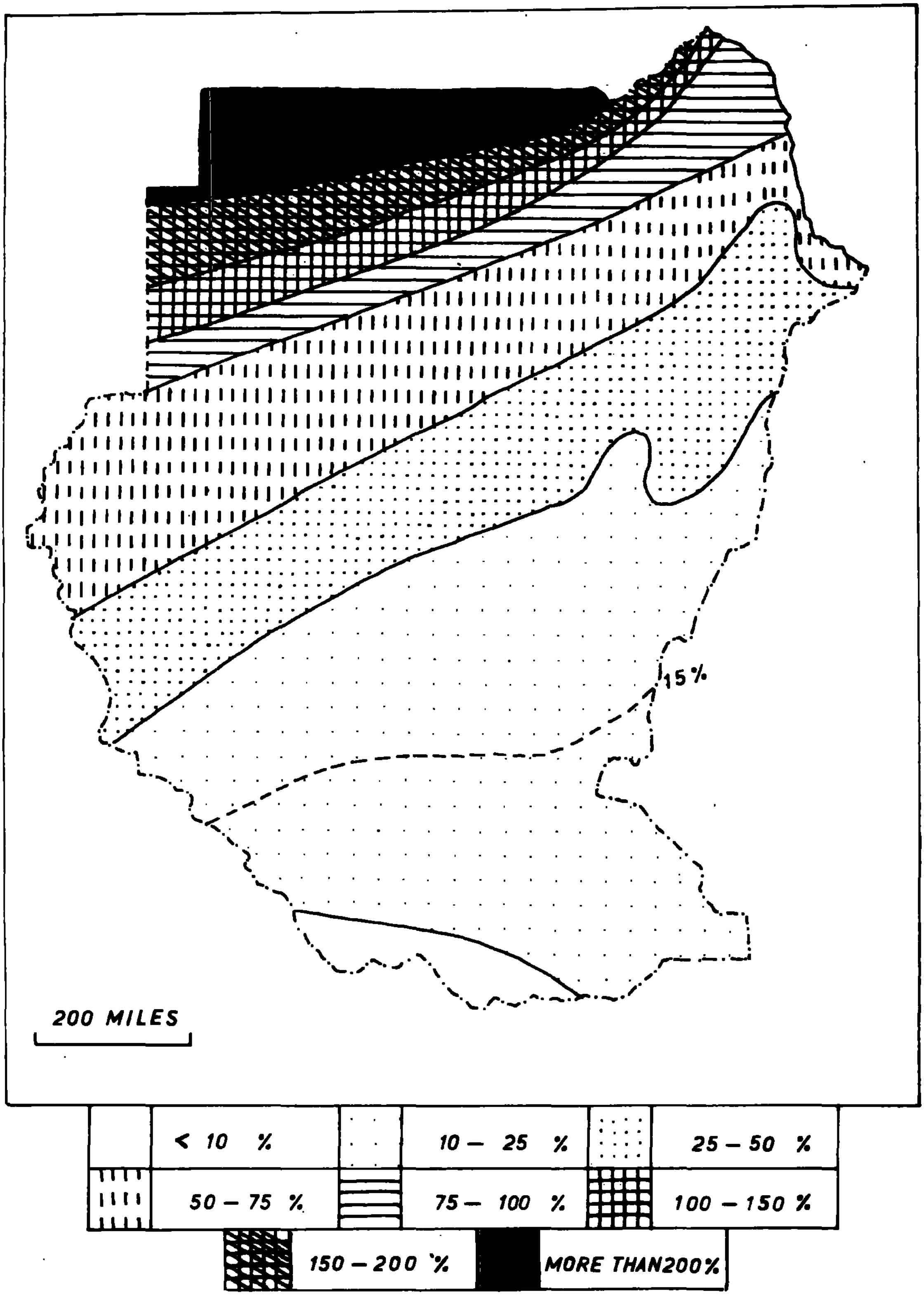


Fig. 51 Annual coefficients of variation

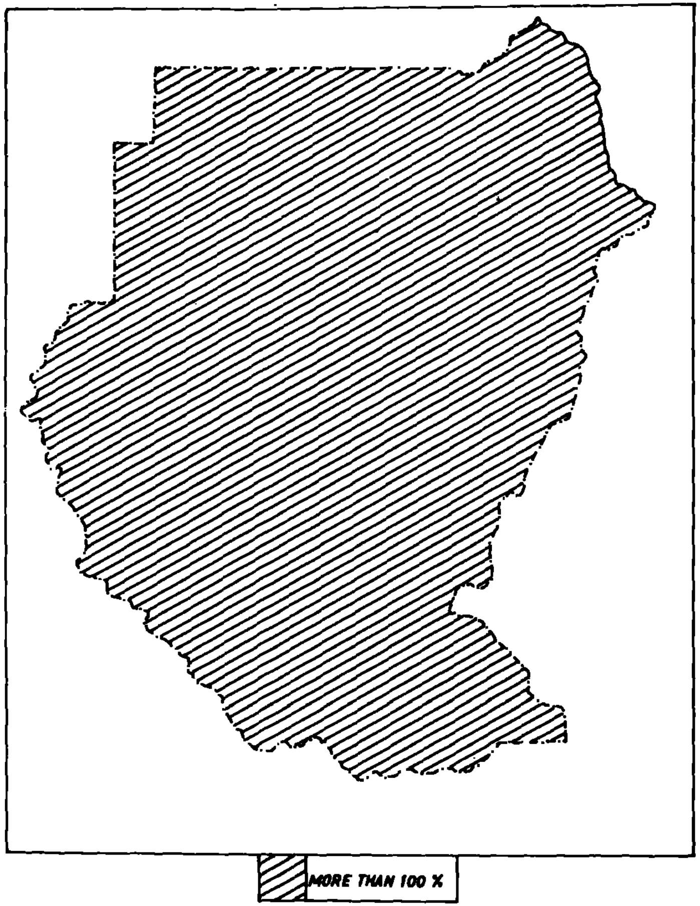


Fig. 52 January coefficients of variation

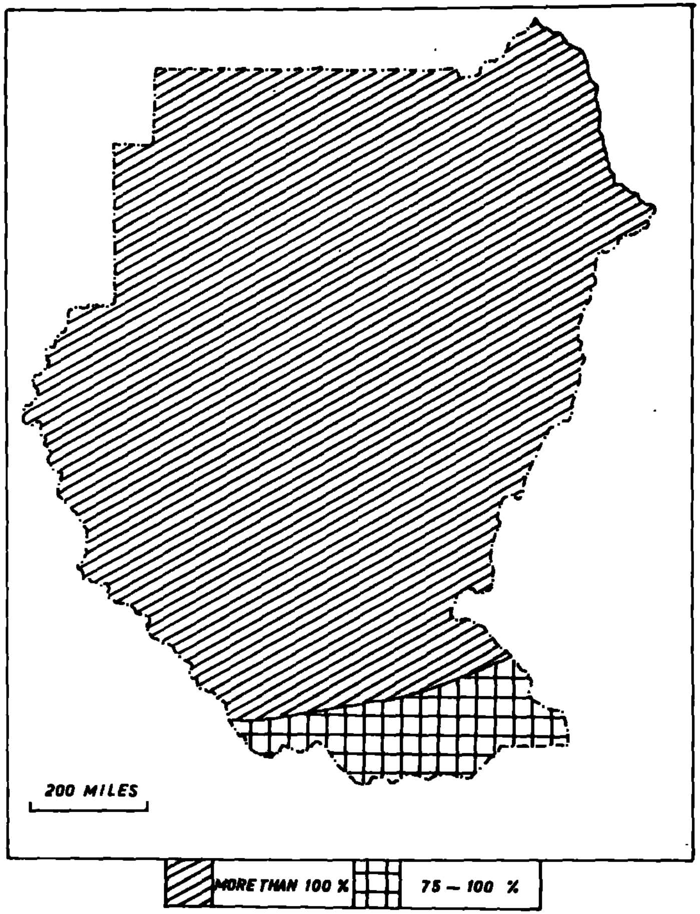


Fig. 53 February coefficients of variation

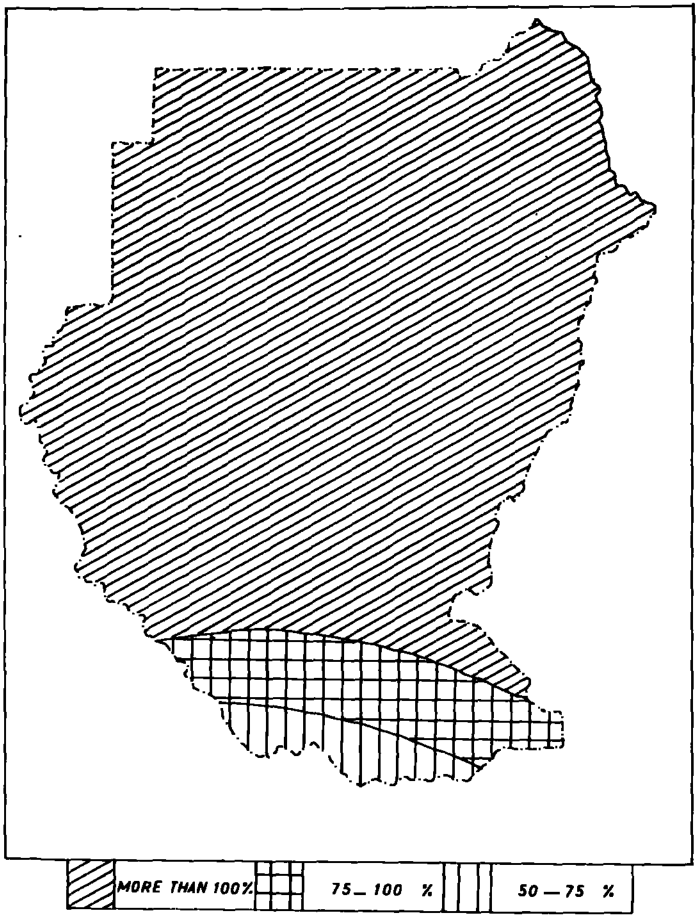


Fig. 54 March coefficients of variation

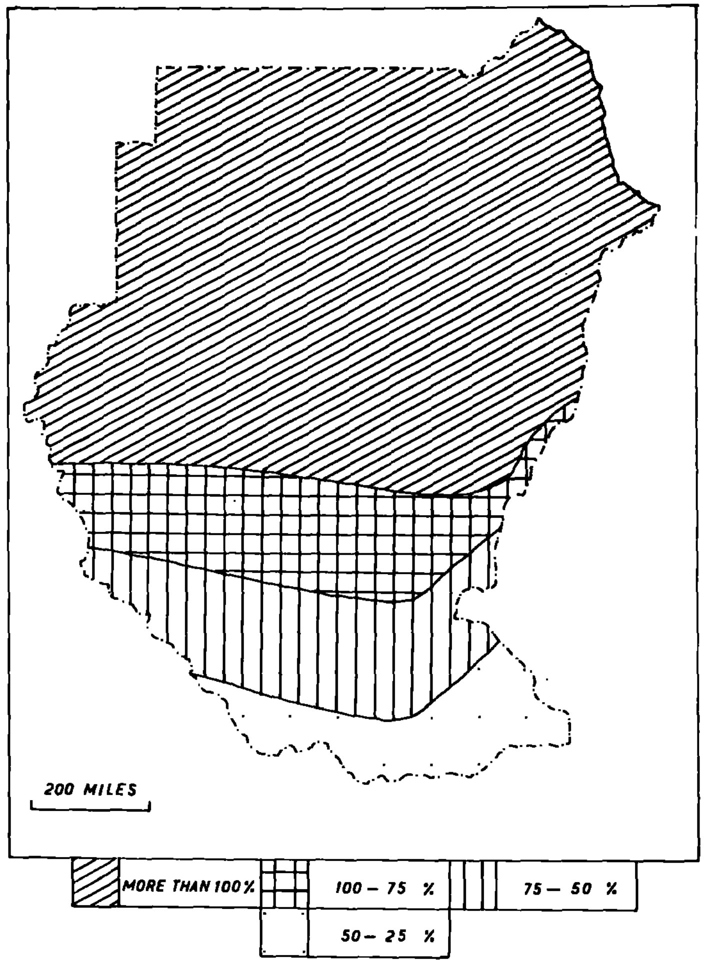


Fig. 55 April coefficients of variation

border. The line indicating the position of the 200% coefficient of variation, assumes a rather peculiar shape which seems to be determined by the presence of the Nuba mountains as well as the Abbyssinian plateau.

By April the extreme south has a coefficient of variation of less than 50%, while in the central Sudan the coefficient of variation ranges between 80% and more than 200% (fig. 55). The degree of variation seems to decrease gradually with the advance of the rainy season, (fig. 56-57). During June, Yambio (64) in the extreme south has a coefficient of variation of only 37%. For no obvious reasons, the areas coincident with the White Nile in the central Sudan, seem to have higher coefficients of variation than the adjacent lands on the same latitudes. This can be illustrated by the case of Kosti (36) on the bank of the White Nile, which has a coefficient of variation of 88% during June, while Gedaref (20) has a coefficient of 54%, and El Obied (46) a coefficient of 73%, in spite of the fact that these three stations lie on nearly the same latitude.

During July, the coefficient of variation is less than 50% over the southern half of the Sudan, (fig. 58). It seems to drop to less than 25% in the south-eastern parts of the country. The northern third of the country still has a coefficient of variation of more

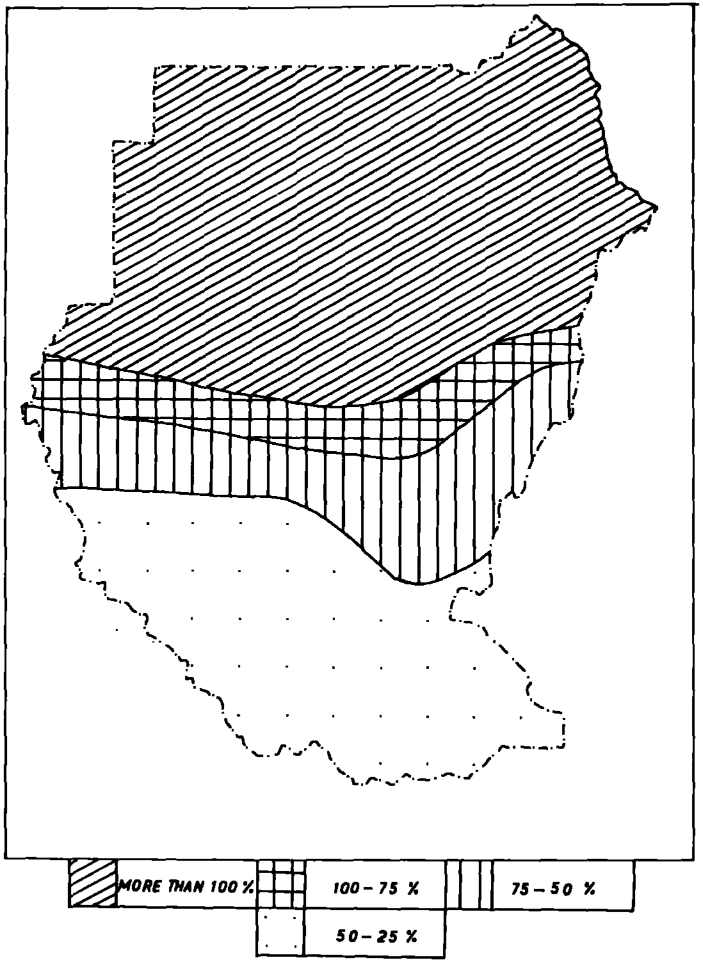


Fig. 56 May coefficients of variation

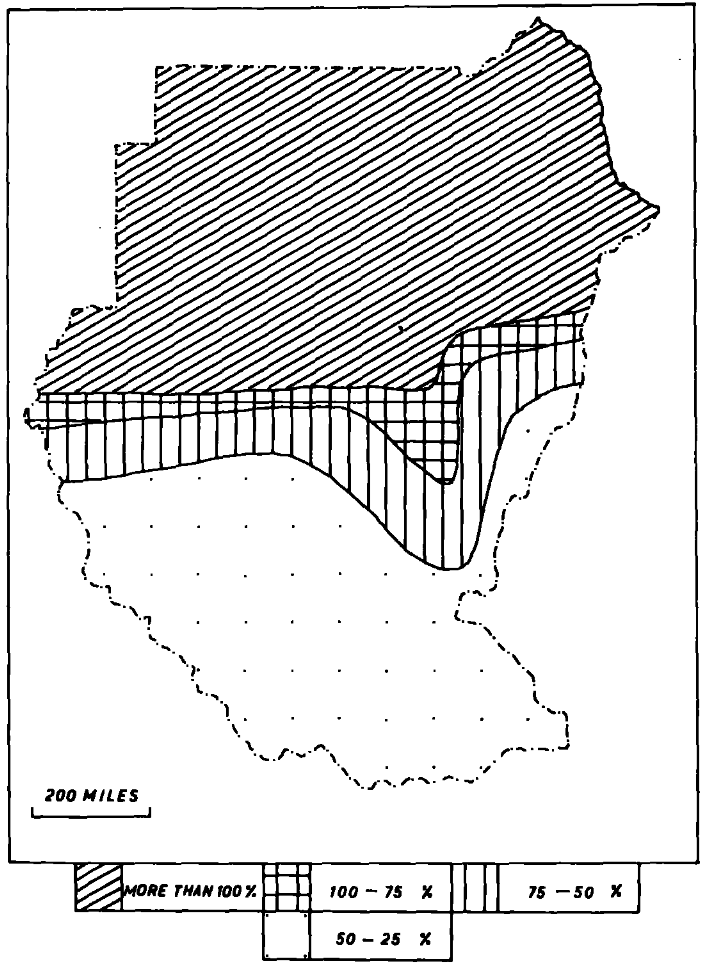


Fig. 57 June coefficients of variation

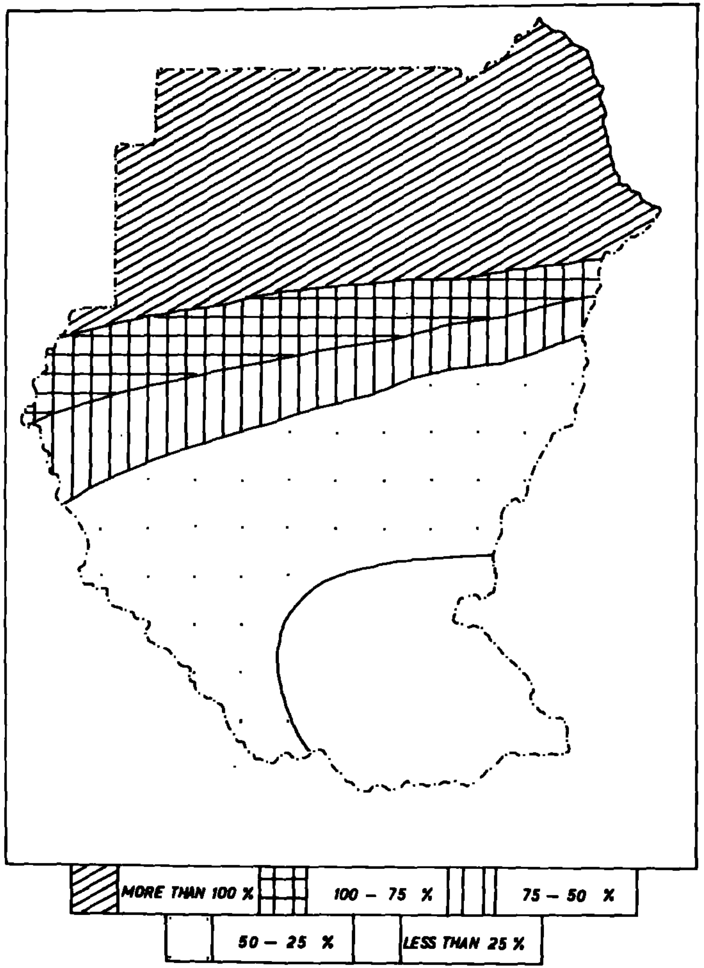


Fig. 58 July coefficients of variation

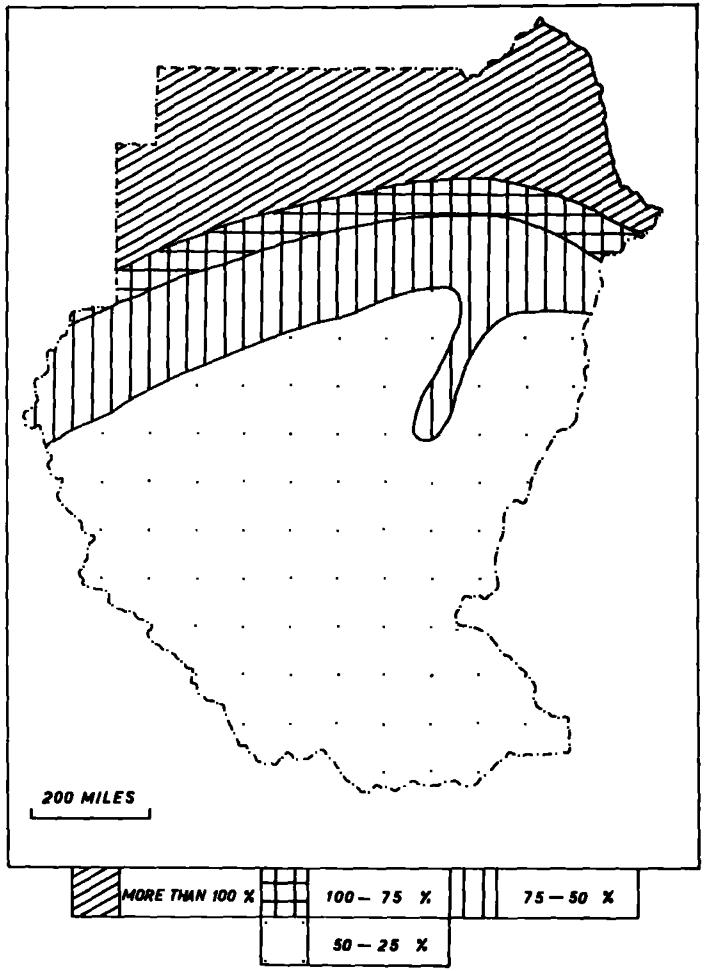


Fig. 59 August coefficients of variation

than 100%. Unlike the case of June, all the stations on the same latitudes appear to have similar coefficients of variation. The Red Sea region is not markedly different from the inland areas on the same latitudes. This picture does not change much during August, which is the rainiest month for all the country except the coastal region, (fig. 59). A narrow tongue of relatively higher coefficients of variation, exists over the central Sudan and tends to disrupt the smooth and simple distribution of the coefficients of variation.

By September, the coefficients of variation start to increase gradually over the whole country, but more markedly over the central Sudan, (fig. 60). In the extreme south the coefficient of variation is around 35%, while in the central Sudan it varies between 50% and 70%. The tongue of relatively higher coefficients of variation tends to become more prominent during September. Unfortunately the reasons behind this phenomenon are not clear. During October, only the southern third of the country has a coefficient of variation of less than 50%, while in the northern third, it is everywhere more than 200%, (fig. 61). Over the central parts of the Sudan, the coefficients of variation are evenly distributed between 50% and 200% but they still show a tendency towards relatively

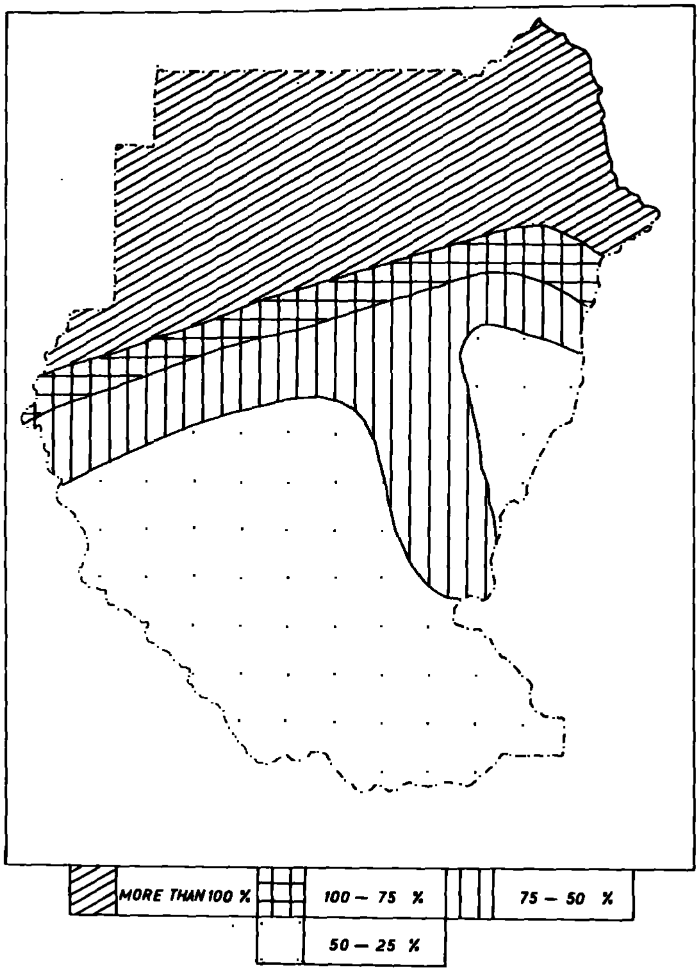


Fig. 60 September coefficients of variation

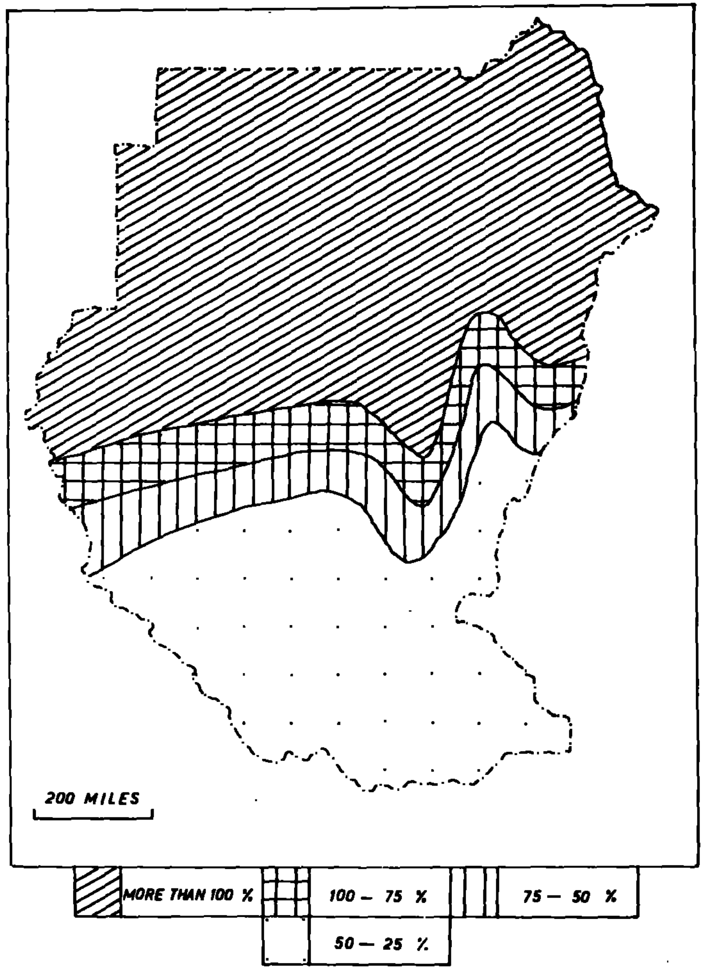


Fig. 61 October coefficients of variation

higher values coincident with the White Nile rather than the adjacent areas on the same latitudes.

During November, the central Sudan has a coefficient of variation of more than 200% while the Red Sea region and the southern third of the country have lower values, (fig. 62). In the Red Sea region, the coefficient of variation is everywhere more than 100%. Such rapid increases in the coefficients of variation continue throughout December, (fig. 63). Except for the southern margin of the country and a very small strip on the Sudan coast, the coefficient of variation is everywhere more than 100% during the month of December; it is infinite over most of the country.

So generally both the annual and the monthly coefficients of variation seem to be negatively related to the mean rainfall over the Sudan. Their distribution tends to follow the general pattern of the isohyets and the isomers. However, the effects of the Jebel Marra region, the Nuba mountains, the Red Sea mountains and the Sudd region are hardly felt in the case of the coefficients of variation. This indicates that the degree of rainfall variability is only affected by, or related to, the latitudes north of the Equator, rather than by any local effects, such as the above mentioned

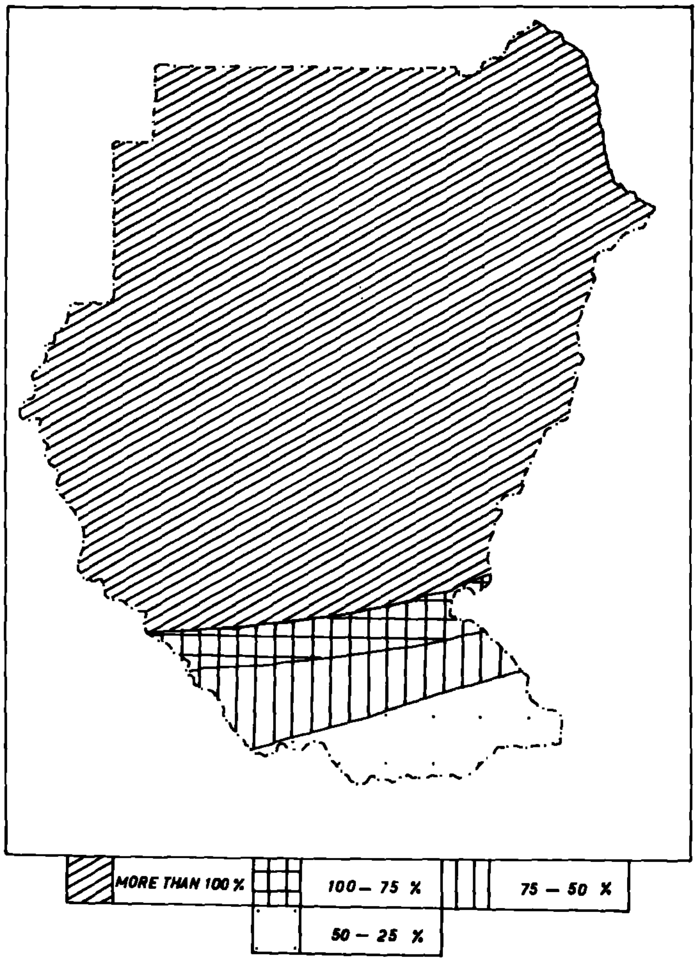


Fig. 62 November coefficients of variation

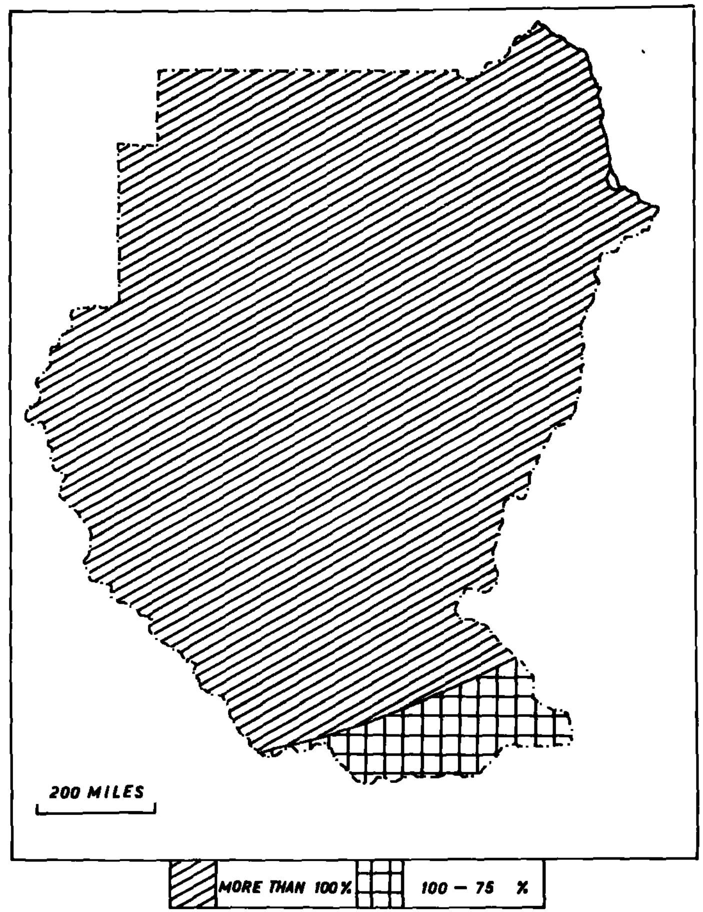


Fig. 63 December coefficients of variation

ones, which exert some influences on the smooth distribution of the isohyets and isomers.

The Probability of Rainfall:-

From the agricultural point of view, the percentage probability of receiving certain critical values of rainfall is of great significance. This can be determined by following the pioneering works of Glover, Robinson and Henderson on East Africa (1953 and 1954). Their method of calculation is based on the assumption that the distribution of the annual rainfall coincides with the normal frequency curve. This assumption may also be considered true in the case of the Sudan where the annual distribution of the rainfall over the country, especially in the central parts, is not markedly different from the normal frequency curve, (fig. 64). However, not being quite coincident with the normal curve, this is liable to present some unaccuracy in the results obtained. Nevertheless these results give some idea about how the pattern of the percentage probability of receiving certain critical values is likely to be.

The choice of the critical rainfall values is not governed by any restricted measures. For the present purpose, irrigation necessity has been used to determine the critical values for the rainfall probability. The values of 100 m.m. and 500 m.m., which are used for

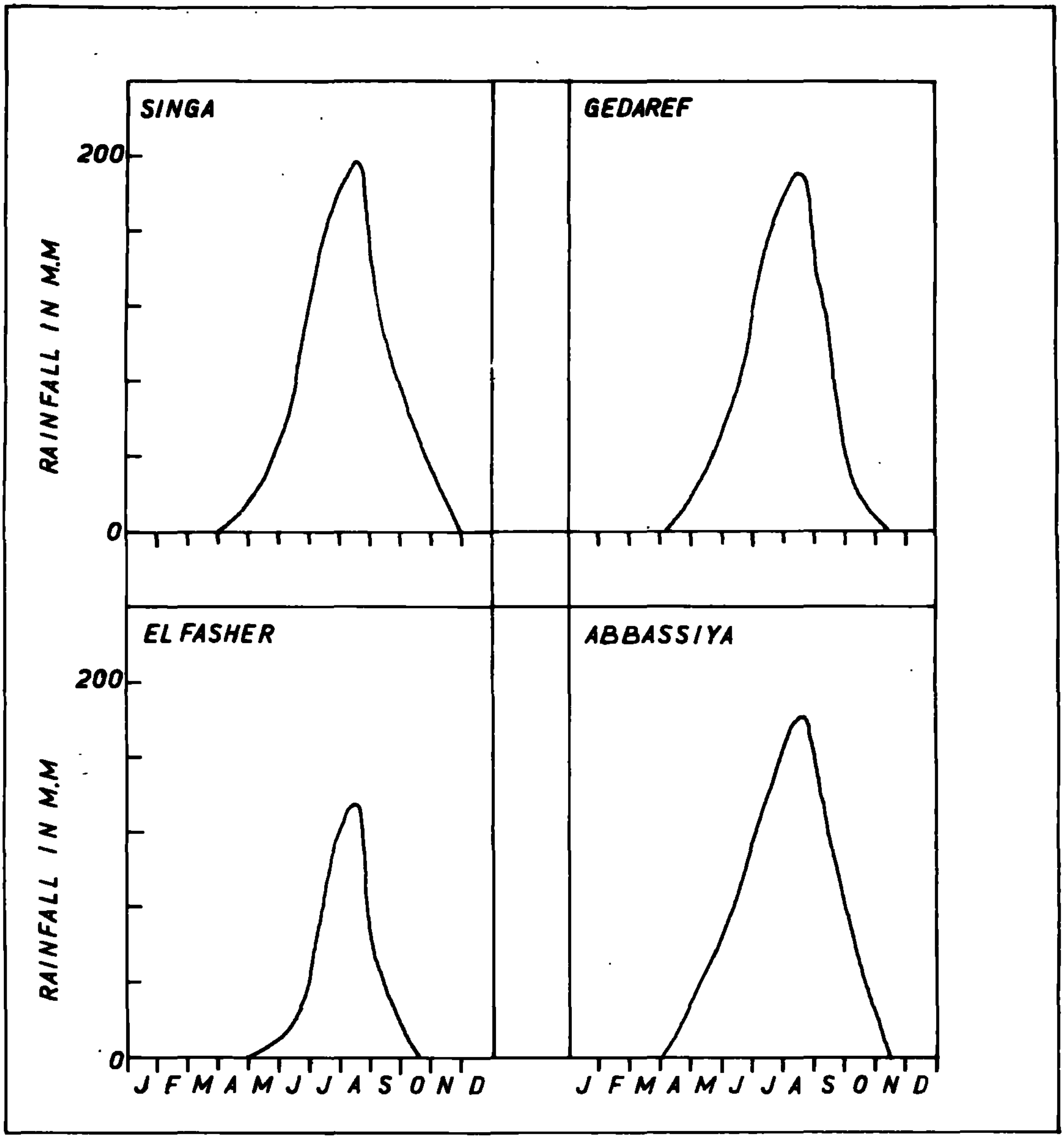


Fig. 64 Examples of rainfall frequency curves in central Sudan

the present purpose, are those suggested by Mr. Allan, who was a former Director of the Sudan irrigation Department, and his Development Assistant, (Tothill, 1948). They suggest that an annual rainfall value of less than 100 m.m. is deficient for all crops and so irrigation becomes essential. Also they suggest that an annual value of 500 m.m. is sufficient for the practice of rain cultivation and irrigation may only be used in the drought years.

So an attempt is made here to show the distribution of the percentage probability of receiving less or more than 100 m.m. and 500 m.m. respectively, In the southern two thirds of the country the percentage probability of receiving more than 100 m.m. of rainfall annually, is generally more than 50%; a percentage that rises within a short distance to about 100%, (fig. 65). The probability of receiving more than 100 m.m. of rainfall annually, decreases gradually northwards from about latitude 16^{o} north reaching less than 1% in the extreme north. This indicates that irrigation is essential for all the areas north of latitude 16^{o}north; south of which rain cultivation is possible in varying degrees depending on the nature of the crop itself and whether its germination

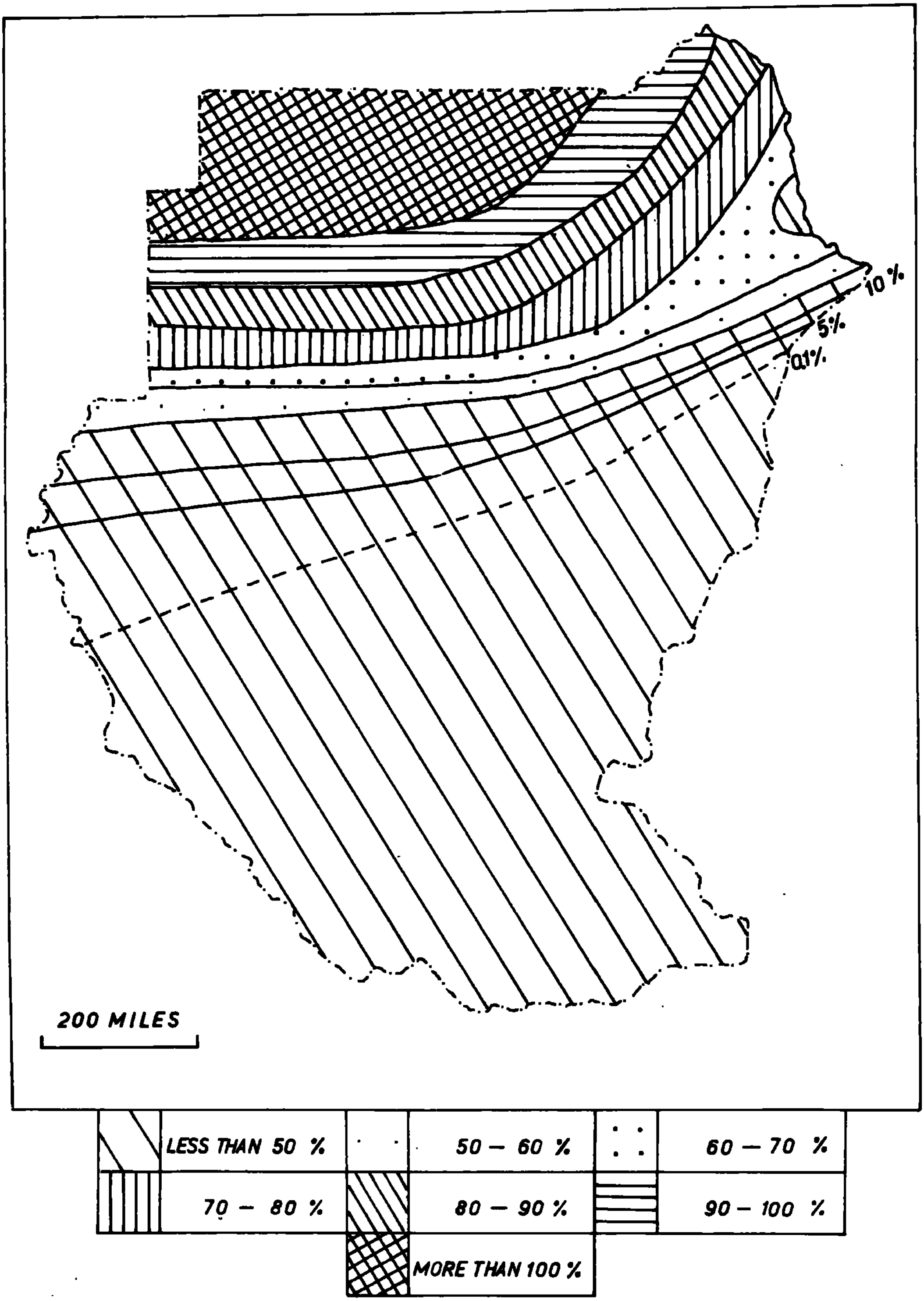


Fig. 65 Percentage probability of receiving less than 100 m.m.

continues beyond the rainy season. This can be further assessed by determining the percentage probability of receiving more than 500 m.m. of rainfall annually, a value that is suggested to be sufficient for the growing of all crops, (fig. 66). Almost all the southern half of the country has more than 50% probability of receiving more than 500 m.m. of rainfall annually. This percentage increases sharply to the south, and within a short distance it rises to almost 100%. The percentage probability of receiving more than 500 m.m. of annual rainfall is at least 100% for all the areas south of 8° north. North of 16° north it is an impossibility to receive an annual value of 500 m.m. or more. A feature to be observed is that the areas near the Abbyssinian plateau have higher percentage probabilities of receiving 500 m.m. annually, than the inland areas on the same latitudes. This may be due to the fact that these eastern areas are likely to receive much higher rainfall as a result of the line squalls that form over the Abbyssinian plateau, sweep over the Sudan and disintegrate gradually westwards.

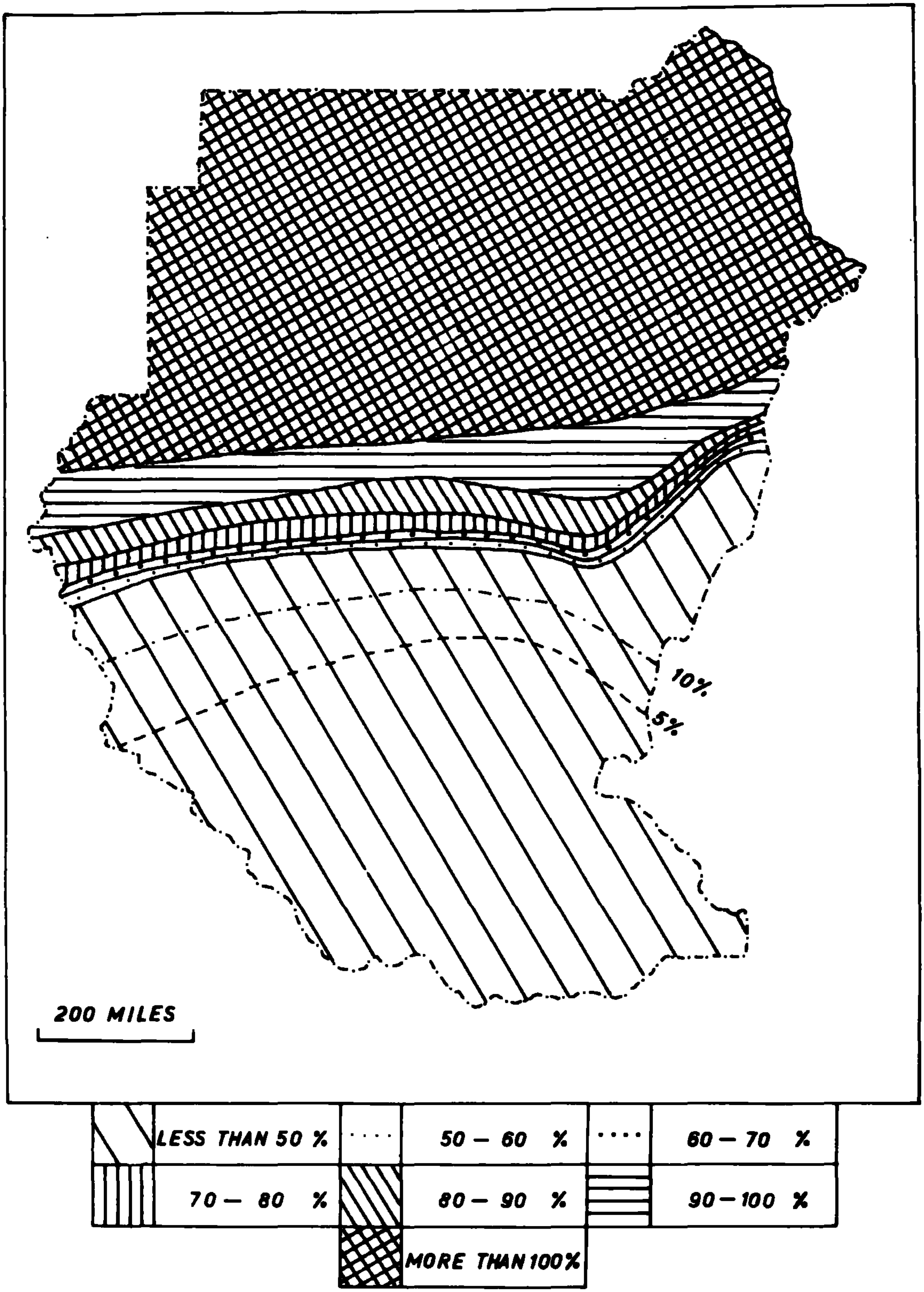


Fig. 66 Percentage probability of receiving less than 500 m.m. of annual rainfall

A MULTIPLE REGRESSION ANALYSIS

The rainfall over the Sudan, as everywhere else, is the outcome of a combination of several atmospheric factors. Here an attempt is made to analyse statistically the causal relatiohships between the rainfall and four of these factors. For the present purpose, a random sampling by digits and tables has been carried out to select fifteen representative stations, (fig. 67). The Red Sea coast has been excluded from this analysis since it has its own peculiarities and it differs in many respects from the rest of the country. It should be admitted that the present attempt is following the steps of Gregory (1965) on Sierra Leone.

The four factors under consideration are:-

a : The I.T.C.Z.
b : The relief
c : The monsoons
d : The line squalls.

These factors are the same ones used by Gregory, (1965). It is thought that these factors may be suitable for the Sudan especially because no other factor seems to be of greater influence on the distribution of the rainfall over the Sudan. It is generally believed that the rainfall over the Sudan is associated with the movements of the I.T.C.Z. and the monsoonal winds, the effects of which are influenced by the relief. Also the line

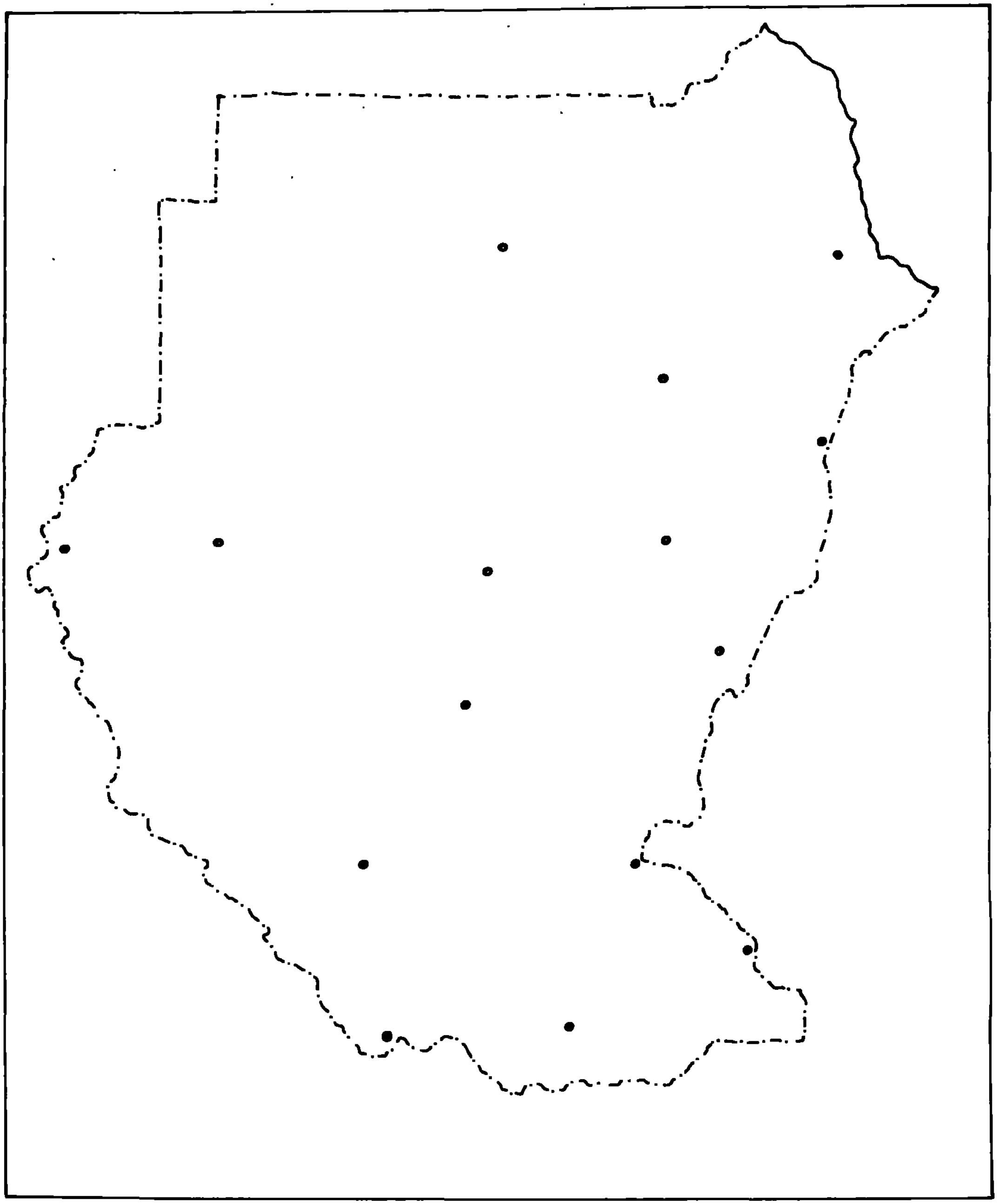


Fig. 67 Stations used for the multiple regression analysis

squalls seem to play an important part in the distribution of the rainfall especially in the central parts of the country. It is from these reasons that come the selection of the four factors mentioned before. These four factors are transferred to spatial terms so that factor -a- is represented by the latitudes since its advance and retreat may generally be considered as coincident with the latitudes. Factor -b- is represented by the altitude/the distance inland from the south-western border which emphasises the fact that the general effects of the relief on the distribution of rainfall decrease as the distance inland increases. Factor -c- is represented by the distance inland from a line based on the south-western border of the Sudan. The location of this base line generally symbolises the position from which the monsoonal winds enter the Sudan and for convenience it is used instead of the Gulf of Guinea from which the monsoonal winds start affecting the whole of North Africa. Lastly, factor -d- is represented by the longitudes east of Greenwich, since the effects of the line squalls seem to change in relation to the longitudes.

Some indication of the relationships between the rainfall and each of these factors, can be obtained by calculating the product moment correlation coefficients

TABLE NO. 4

THE CORRELATION COEFFICIENTS BETWEEN THE RAINFALL AND FOUR SPECIFIC FACTORS

THE FACTORS	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
I.T.C.Z. FACTOR	-0.593	-0.723	-0.783	-0.875	-0.949	-0.881	-0.808	-0.761	-0.858	-0.898	-0.717	-0.566	-0.951
RELIEF FACTOR	+0.430	+0.673	+0.669	+0.709	+0.569	+0.490	+0.229	+0.236	+0.480	+0.631	+0.763	+0.264	+0.565
MONSOONAL FACTOR	-0.485	-0.637	-0.699	-0.814	-0.898	-0.859	-0.821	-0.784	-0.846	-0.872	-0.632	-0.451	-0.914
DISTURBANCE LINE FACTOR	+0.092	-0.012	-0.018	-0.082	-0.098	-0.115	-0.262	-0.307	-0.173	-0.147	-0.021	+0.132	-0.150

Significance levels:- 5% = 0.59 , 1% = 0.69 , 0.1% = 0.79

using the formula:-

$$r = \frac{\frac{\Sigma xy}{} - \bar{x}.\bar{y}}{\sigma x.\sigma y}$$

where x is the mean rainfall, and y is the factor under consideration. These correlation coefficients are shown in table number (4) and figures (68-71). A significance test has been carried out to find whether the coefficients obtained are due to chance or whether they express the real relationship between the mean rainfall and each of these factors. For this purpose a students'$t$test has been carried out, the results of which are shown in the form of the significance levels in figures (68-71).

For the annual conditions, the rainfall has the largest correlation coefficient with factor -a-, i.e. the I.T.C.Z. This correlation coefficient is equal to - 0.951. In spatial terms, this indicates that the annual rainfall is very highly negatively correlated with the latitudes north of the Equator. This correlation coefficient is very significant statistically since it is actually less than the 0.1% level of significance. Factor -a- seems to be succeeded in importance by factor -c- which is the monsoonal factor. The latter factor with a correlation coefficient of - 0.914, is also

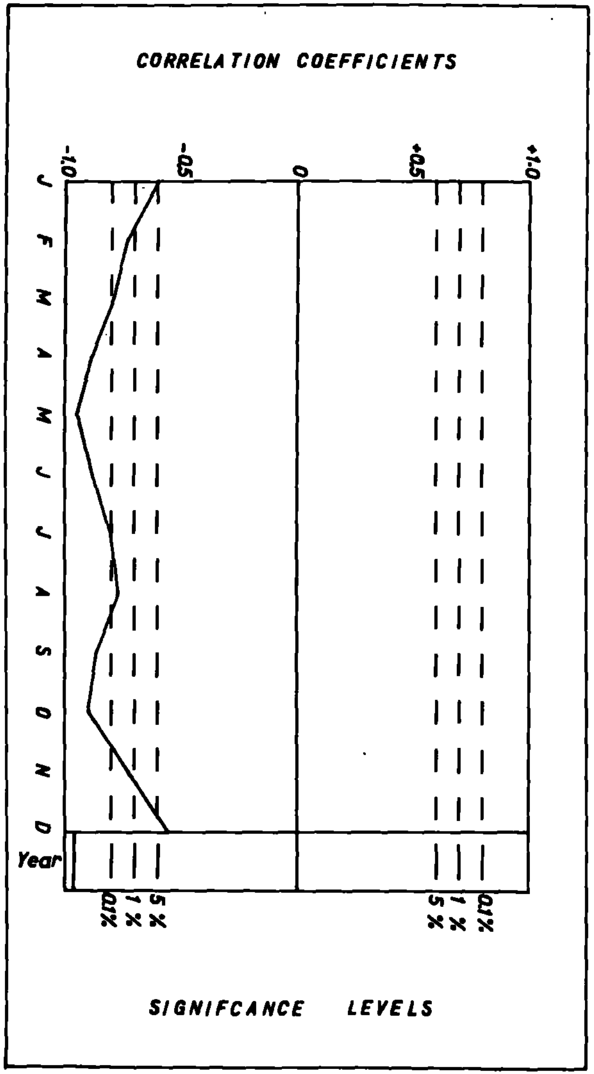


Fig. 68 Correlation coefficients:
Rainfall & Latitudes

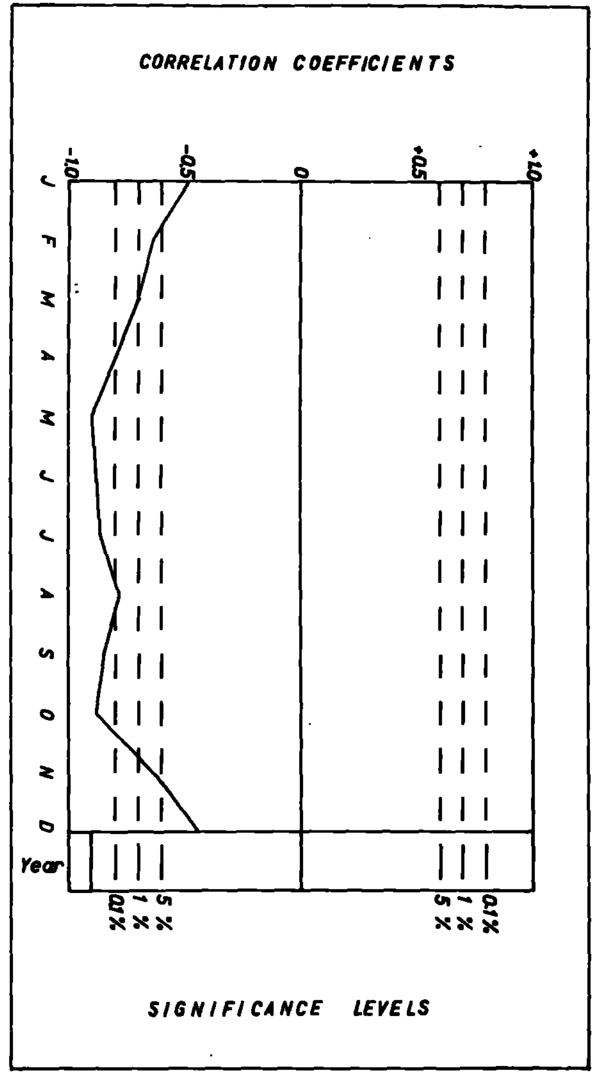


Fig. 69 Correlation coefficients:
Rainfall & Distance inland

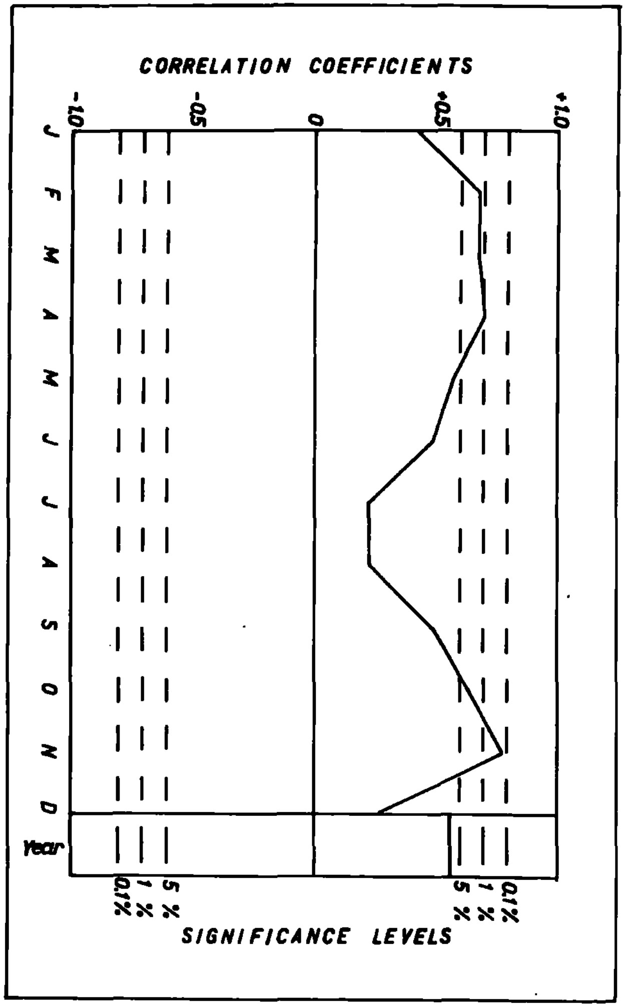


Fig. 70 Correlation coefficients: Rainfall & altitude/distance in-land

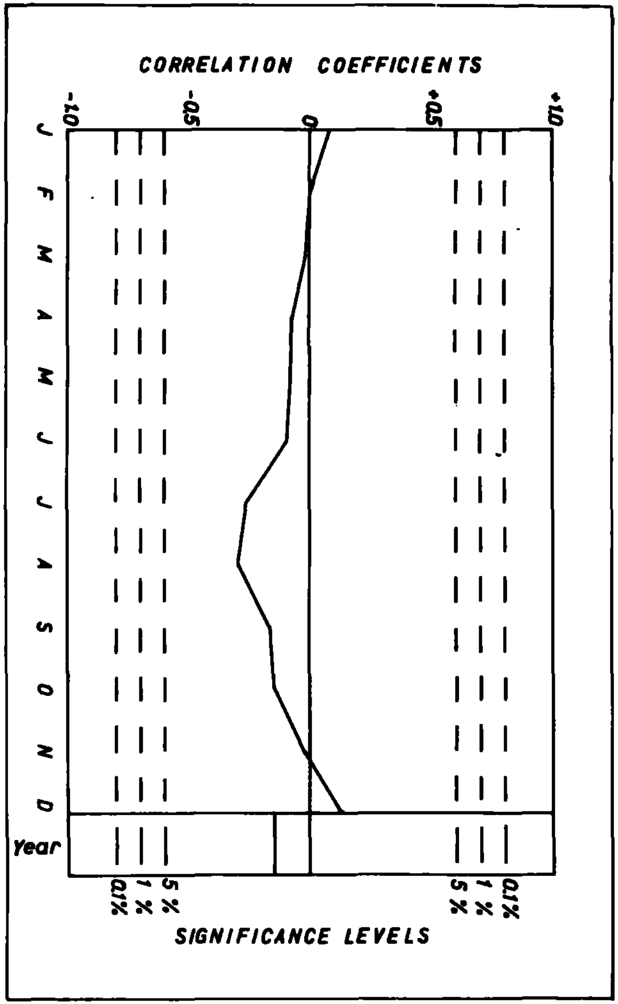


Fig. 71 Correlation coefficients: Rainfall & longitudes

very highly negatively correlated with the annual rainfall, and it is also highly significant. The relief factor, -b-, has a positive correlation with the annual rainfall of +0.565 which just fails to reach the 5% level of significance, and so the reliability of this correlation coefficient should be considered with some caution. Factor -d-, i.e. the line squalls factor, has the lowest correlation coefficient with the annual rainfall, which is only - 0.150. Such a correlation coefficient is largely insignificant statistically and so very unreliable. This general pattern of the relationships between the annual rainfall and the four factors under consideration, can further be emphasised by constructing the regression lines of the annual rainfall on each of these factors using the formula:-

$$b-\bar{b} = r \cdot \frac{\sigma b}{\sigma a} \cdot (a-\bar{a})$$

where a is the mean annual rainfall, b is the factor under consideration and r is the correlation coefficient. This linear regression analysis also indicates that a closer relationship exists between the mean annual rainfall and factors -a- and -c- rather than factors -b- and -d-, (fig. 72-75).

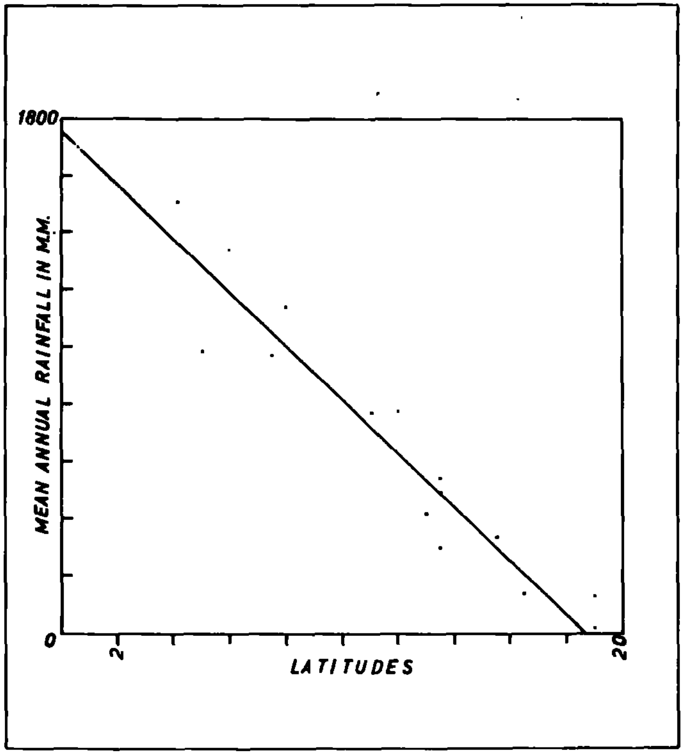


Fig. 72 Regression line: Rainfall /latitudes

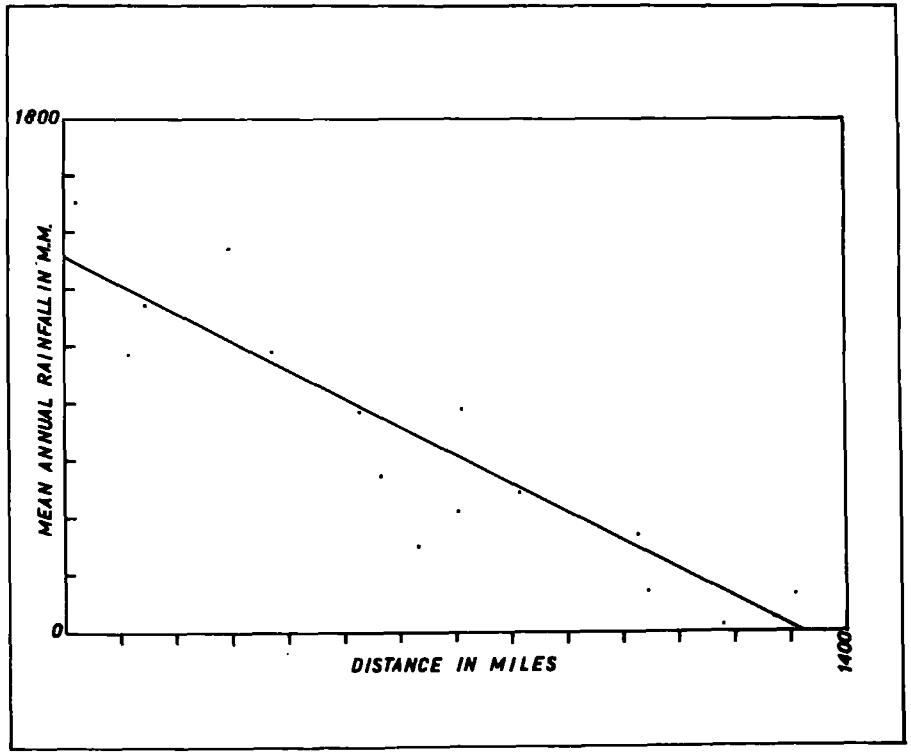


Fig. 73 Regression line: Rainfall/distance inland

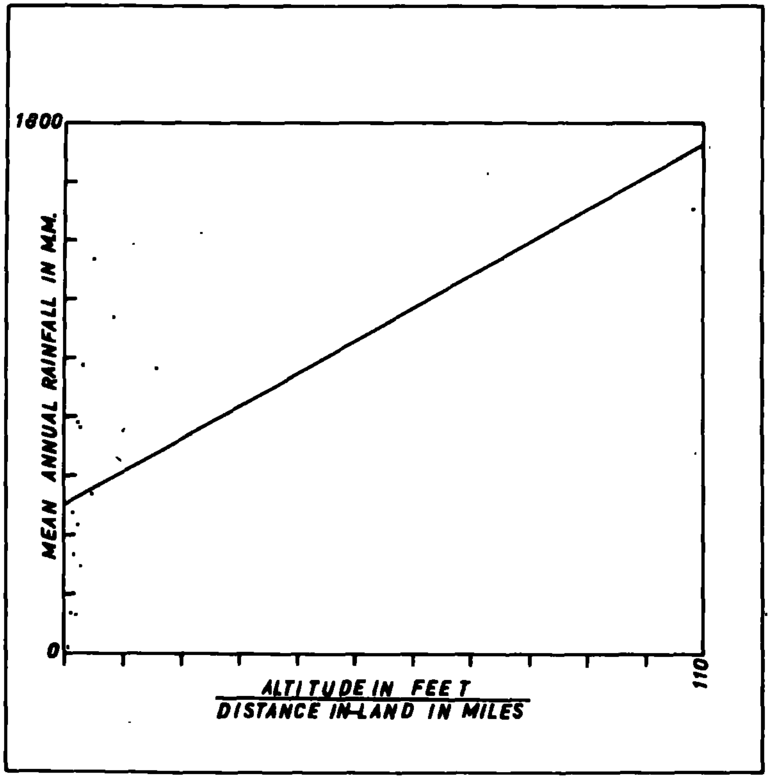


Fig. 74 Regression line: Rainfall/altitude/distance inland

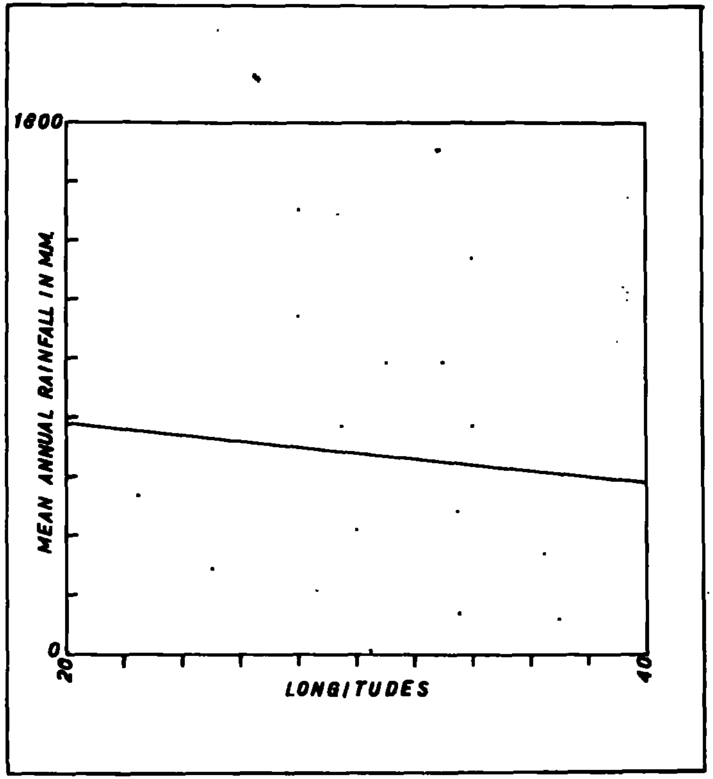


Fig. 75 Regression line: Rainfall/longitudes

With the exception of December and January, a highly negative correlation coefficient exists between the mean monthly rainfall and factor -a- throughout the year. This correlation coefficient is very significant in the period April-July inclusive and also in the period September-October. These two periods are coincident with the advance and retreat of the I.T.C.Z. over the Sudan. During the rest of the year, these monthly correlation coefficients fluctuate between the 5% and the 0.1% levels of significance, which indicates that they can also be considered as reliable coefficients. The highest monthly correlation coefficient between the rainfall and factor -a- is equal to - 0.949, which is experienced during May. The lowest monthly correlation coefficient is equal to -0.566, and this is experienced during December. The latter correlation coefficient just fails to reach the 5% level of significance.

The relief factor, -b-, has a positive correlation coefficient with the mean monthly rainfall throughout the year. These coefficients hardly reach the 0.1% of significance. In the period February-April, they fluctuate between the 1% and 5% levels of significance. They remain insignificant and therefore unreliable throughout the period May to September. They again attain a reliable level between October and November. This indicates that the relative significance of the relief factor is confined to the transitional periods rather than the proper rainy periods when other factors seem to be of much greater importance. The highest monthly correlation coefficient between factor -b- and the mean monthly rainfall is +0.763, which is experienced during November, while the lowest monthly correlation coefficient is only +0.229, which is experienced during July.

Factor -c-, i.e. the monsoonal factor, is negatively correlated with the mean monthly rainfall throughout the year. These correlation coefficients seem to be very highly significant during the period April to October inclusive, when it hardly rises above the 0.1% level of significance. Between November and January they rise sharply above the 5% level of significance and so they are unreliable. The mean monthly rainfall of February and March are also highly negatively correlated with the distance inland from the south western border. In the latter two months the correlation coefficients fluctuate between just above the 0.1%, and just below the 5% levels of significance. The highest monthly correlation coefficient between the rainfall and factor -c- is experienced during May and it is equal to - 0.898. It may be noted that the month of May also experiences the highest correlation coefficient between the mean monthly rainfall and the I.T.C.Z. factor, but the latter is slightly higher and so relatively more significant. The lowest monthly correlation coefficient in the case of the monsoonal factor is - 0.451 and it is experienced during December.

The correlation coefficients between the mean monthly rainfall and the line squalls, i.e. factor -d-, is very insignificant and so unreliable. Throughout the year they fluctuate above the 5% level of significance. However, except for December and January, they show a tendency towards a negative correlation, but this is an unreliable correlation.

A further analysis on these lines, shows that these annual and monthly correlation coefficients between the mean rainfall and the four factors under consideration, are not actually as they seem to be. A certain degree of intercorrelation appears to exist between each of these factors and all, or at least some, of the rest. This intercorrelation between the four factors can easily be determined from the accompanying table of the annual and monthly correlation matrixes, (table no. 5).

Table No. 5

THE ANNUAL CORRELATION MATRIX

A

	a	b	c	d
a	-a	-0.497	+0.966	+0.206
b			-0.504	-0.247
c				+0.435

JANUARY CORRELATION MATRIX

B

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

FEBRUARY CORRELATION MATRIX

C

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

MARCH CORRELATION MATRIX

		a	b	c	d
D	a		-0.498	+0.965	+0.214
	b			-0.504	-0.246
	c				+0.444

APRIL CORRELATION MATRIX

		a	b	c	d
E	a		-0,498	+0.965	+0.213
	b			-0.504	-0.247
	c				+0.443

MAY CORRELATION MATRIX

		a	b	c	d
F	a		-0.498	+0.965	+0.214
	b			-0.504	-0.246
	c				+0.444

JUNE CORRELATION MATRIX

G

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

JULY CORRELATION MATRIX

H

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

AUGUST CORRELATION MATRIX

I

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

SEPTEMBER CORRELATION MATRIX

J

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

OCTOBER CORRELATION MATRIX

K

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

NOVEMBER CORRELATION MATRIX

L

	a	b	c	d
a		-0.498	+0.965	+0.214
b			-0.504	-0.246
c				+0.444

DECEMBER CORRELATION MATRIX

M

	a	b	c	d
a		-0.498	+0.965	0.214
b			-0.504	-0.246
c				+0.444

In the case of the annual rainfall a high positive correlation exists between factors -a- and -c- which is equal to $+0.966$. This correlation coefficient is very significant statistically. A very low and insignificant correlation coefficient exists between factors -a- and -d-, which is equal to -0.206. This latter insignificant correlation between factors -a- and -d- is quite obvious since there is no logical spatial relationship between the latitudes and the longitudes. Another important, although not significant, intercorrelation exists between factors -b- and -c-. This is rather obvious since factor -c- has an important role in the determination of factor -b-, as outlined before. In the monthly conditions also the largest inter-correlations exist between factors -a- and -c-, and the lowest intercorrelations exist between factors -a- and -d-. Except for very minor and insignificant differences, the monthly intercorrelation matrixes are constant throughout the year and they are nearly equal to the annual correlation matrix as is displayed by the table number (5).

To eliminate, or to allow for, these intercorrelations between the four factors, a partial regression analysis has been carried out. It is through this partial regression analysis that a series of equations can be produced to express the closest possible relationship between the mean rainfall and the four factors under consideration. For the mean annual rainfall, the equation produced is as follows:-

$$x = +306.5 - 4.33_a + 2.565_b - 1.072_c + 33.83_d$$

where x is the mean annual rainfall, -a- the latitude, -b- the altitude/distance inland, -c- the distance inland from the south-western border, and -d- is the longitude. An annual multiple correlation coefficient of + 0.947 exists between the actual mean annual rainfall and the annual values that can be derived from the annual partial regression equation. This equation shows that the four factors under consideration contribute together up to 92.76% of the mean annual rainfall over the Sudan, of which 90.48% seems to be contributed by factor -a- alone. The monthly partial regression equations and the percentage contribution of the four factors are shown in tables (6) and (7) respectively.

The table number (7) shows clearly that the latitude and the monsoonal factors are the most important contributors to the rainfall over the Sudan. Each of them tends to dominate over the country during a certain part of the year. The significance of the

Table No. 6

THE MONTHLY PARTIAL REGRESSION EQUATIONS

***

1. January:-

$$x = +60.01 -5.437_a +4.594_b +5.997_c -1.0_d$$

2. February:-

$$x = +58.17 -5.429_a +0.155_b +5.54_c -0.818_d$$

3. March:-

$$x = +142.7 -13.89_a +0.432_b +0.128_c -1.49_d$$

4. April:-

$$x = +46.14 -7.13_a +0.755_b -90.24_c +2.32_d$$

5. May:-

$$x = -41.12 +1.378_a +0.41_b -0.18_c +6.48_d$$

6. June:-

$$x = -355.3 +27.22_a +0.309_b -0.497_c +13.4_d$$

7. July:-

$$x = +54.8 +8.79_a -0.497_b -0.262_c +4.462_d$$

8. August:-

$$x = +181.6 +4.519_a -0.532_b -0.221_c +2.185_d$$

9. September:-

$$x = -182.7 +18.36_a +0.259_b -0.381_c +9.571_d$$

10. October:-

$$x = -207.6 +15.1_a +0.609_b -0.316_c +8.846_d$$

11. November:-

$$x = +189.9 - 18.02_a +0.671_b +0.189_c -2.783_d$$

12. December:-

$$x = +144.6 -12.93_a -1.747_b +0.141_c -2.391_d$$

x = Rainfall, a = Latitude, $b = \frac{\text{altitude}}{\text{Distance inland}}$, c = Distance inland

d = longitude

Table No. 7

THE PERCENTAGE CONTRIBUTION OF THE FOUR FACTORS TO THE MEAN ANNUAL AND MONTHLY RAINFALL

	The total percentage contribution of the four factors	The most important single factor	The percentage contribution of the most important single factor
THE YEAR	92.76%	a	90.48%
JANUARY	54.01%	a	35.14%
FEBRUARY	73.88%	a	52.24%
MARCH	78.50%	a	61.35%
APRIL	89.15%	a	76.55%
MAY	93.95%	c	80.61%
JUNE	87.83%	c	73.84%
JULY	73.63%	c	67.40%
AUGUST	65.06%	c	61.45%
SEPTEMBER	79.22%	a	73.68%
OCTOBER	90.31%	c	76.11%
NOVEMBER	82.54%	b	58.23%
DECEMBER	50.15%	***	-

a = I.T.C.Z. factor
b = Relief factor
c = Monsoonal factor
*** = No single factor dominates

monsoonal factor is confined to the period May-August inclusive. The relief factor seems to be the most important single contributor to the mean November rainfall. During December none of the four factors seems to dominate the scene, and it may also be noted that December is the month that witnesses the lowest percentage contribution of the four factors to the mean monthly rainfall. During the rest of the year, the latitude factor is the most important single contribution to the mean monthly rainfall, and this may explain the fact that the most southerly stations in the country experience some rainfall throughout the year. It may also be noted that whenever the latitude factor is the most important contributor, the relief factor is always the second in importance. The retreat of the rainy season witnesses a struggle between the I.T.C.Z. and the monsoonal factors, towards the position of the overall predominance. This may be recognised by the replacement that takes place between these two factors in the months of September and October.

As the percentage contribution of the four factors indicates, these factors do not explain all the rainfall over the Sudan. A certain degree of error is presented by factors other than those under consideration. This situation produces some differences between the actual mean rainfall and the rainfall amounts that can be calculated by using the partial regression equations. Such differences are known as the residuals and they are shown by figures (76-78), for the annual, August and January conditions. August and January are chosen as examples of the monthly conditions, since they are respectively the rainiest and the driest months in the Sudan. Generally as the residuals increase, the reliability of the partial regression equation decreases.

The distribution of the residuals over the Sudan tends to follow roughly the longitudes in contrast to the isohyets and isomers which show a tendency towards following the latitudes. The annual residuals, as displayed by (fig. 76) emphasise the role of the Abbyssinian plateau, the Jebel Marra region, the Nuba mountains and the Sudd region, in the distribution of the annual rainfall over the Sudan. In the Jebel Marra region and the Nuba mountains, the positive residuals in the west and the negative residuals in the east, emphasises the presence of a rain shadow east of these regions. The negative residuals over the Sudd region also emphasises the rèlative dryness of this region in comparison to the outer regions to the east and west which have positive residuals.

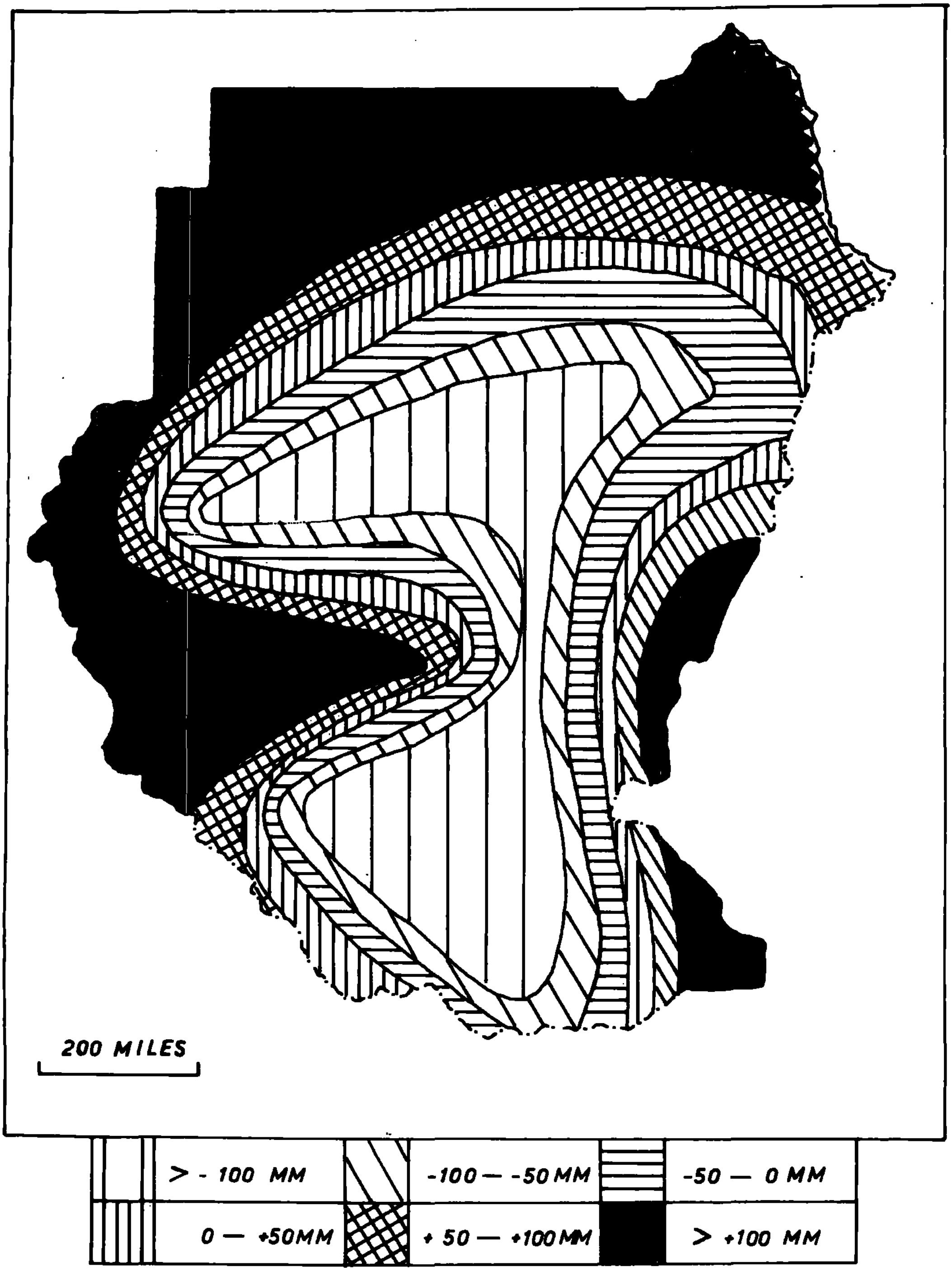


Fig. 76 Annual residuals

The August partial regression equation seems to be more reliable than the annual equation. Throughout the Sudan, the August residuals are well below the 100 m.m. level and in the central parts of the country, the residuals may be within just 5 m.m. of the actual mean August rainfall, (fig. 77). Also the tendency of the residuals to follow the longitudes is more apparent in the case of the August residuals. However the partial regression equations for the dry months, which are represented by January, (fig. 78), seem to be very unreliable since they tend to produce very high residuals which range between 600 m.m. in the extreme southern, and 7000 m.m. in the extreme northern parts of the country.

The existence of these residuals illustrates that factors other than those under consideration contribute to the rainfall over the Sudan, however small their contribution is. With some caution, local temperature may be suggested, as an important additional contributor to the Sudan rainfall, especially in the southern parts of the country where convectional activities are likely to occur throughout the year.

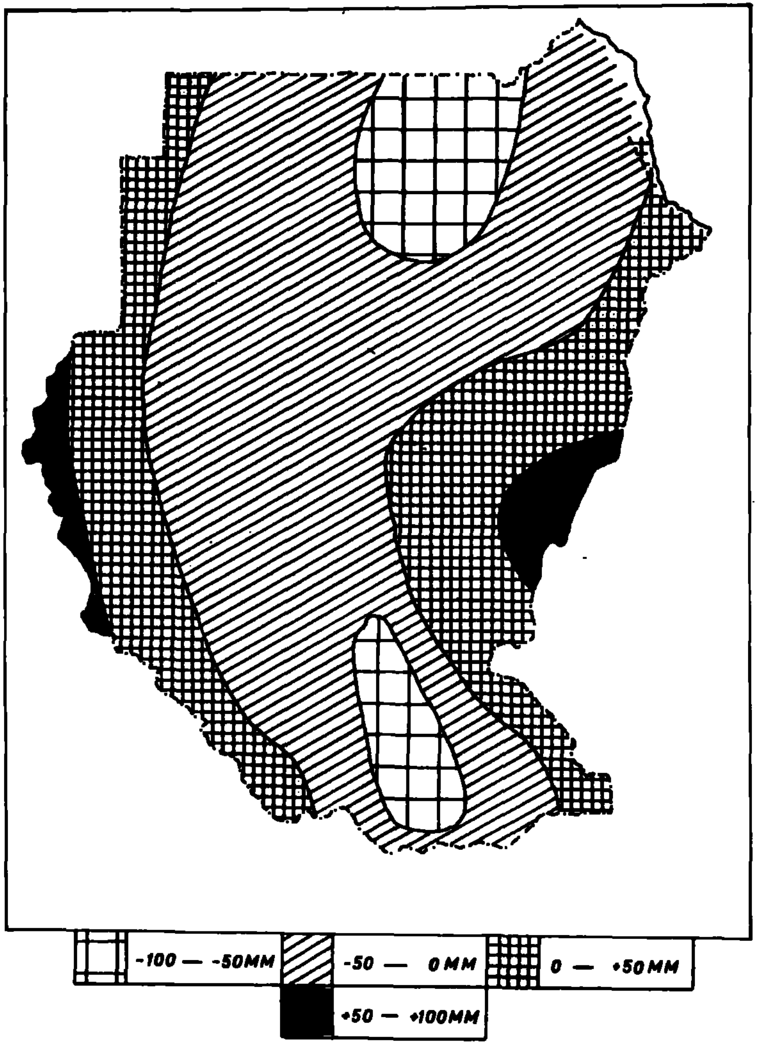


Fig. 77 August residuals

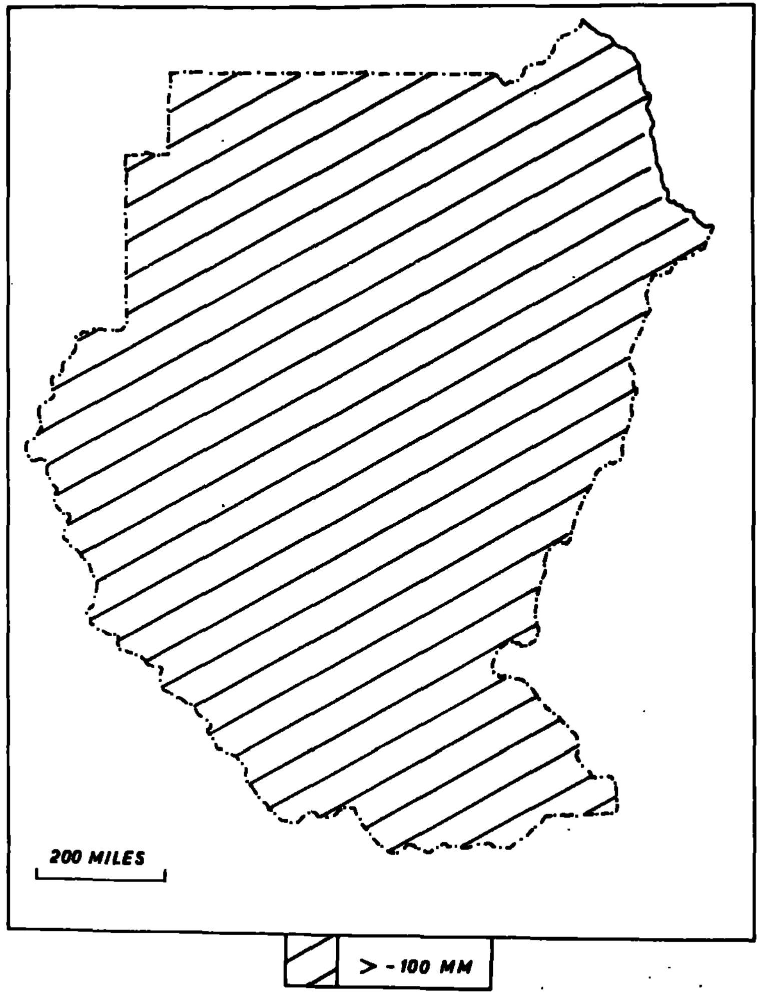


Fig. 78 January residuals

CONCLUSION

Within the Sudan, the general pattern of agricultural production is generally related to the characteristics of the annual and monthly rainfall, and the present work is mainly a cartographic representation of these characteristics. In general, the distribution of the rainfall over the country is fairly simple, except for some local complications exerted by the Red Sea mountains, the Jebel Marra region, the Nuba mountains and the Sudd region, together with the apparent effects of the line squalls on the central parts of the country. It is the local condition of each individual area that gives rise to these local characteristics. Otherwise, the mean rainfall over the Sudan decreases steadily from the south to the north showing a negative correlation with the latitudes.

The variability of the rainfall seems to be negatively correlated with the amounts of rainfall. The degree of variation decreases steadily with the advance of the rainy season, and this is rather fortunate since it is during the proper rainy season that the rainfall variability is the most undesirable because it may have disastrous effects on crop yields.

However, irrigation would appear to be necessary for all the areas north of 16° north, whilst south of this latitude, rain cultivation seems to be possible in varying degrees. Furthermore, this result seems to coincide with the ideas of Barbour, (1959), when he stated that irrigation is essential for all the areas north of Khartoum (34). The reliability of the rainfall over the eastern portion of the country is greatly influenced by the Abbyssinian plateau. In the central Sudan, the percentage probability of receiving certain amounts of rainfall generally increases towards the eastern borders. This indicates that the potential for rain cultivation is much greater in the eastern rather than the western parts of the country on the same latitudes. This indicates that the eastern central Sudan has greater potential for rain cultivation than the west, but this is restricted by the nature of the crops themselves and whether their germination extends beyond the rainy season. In the latter case, irrigation will be essential after the termination of the rainy season.

The multiple regression analysis is the first application of this very useful statistical method to the rainfall conditions in the Sudan. It is through this analysis that the causal relationships between the rainfall over the Sudan and the atmospheric factors can be explored. The four factors considered in the analysis, seem to explain about 93% of the annual rainfall over the Sudan. This indicates that a residual of about 7% is contributed by factors other than the latitude, the longitude, the distance inland from the south western border, and the altitude/distance inland. In the dry months the little rains received are confined to the extreme southern parts of the country which are naturally hotter than the northern parts. It is for this reason that temperature may be considered as an important additional contributor to the rainfall over the Sudan. Rainshadow effects may also explain some of the residuals in the Jebel Marra area and the Nuba mountains. The anomaly of the Sudd region is further emphasised by this statistical analysis, but still no further light can be thrown on it.

The series of partial regression equations is of great importance since it may help in the determination of the rainfall values in the remote parts of the country which lack any climatological observations, although it should be re-emphasised that the reliability of these equations is much greater for the rainy months rather than the dry months. This is fortunate however, since the rainfall values of the wet months are of much greater significance than those of the dry months, especially from the agricultural point of view.

Appendix I

THE INDEX OF THE STATIONS USED IN THE WORK

1. Abbassiya
2. Abu Gubeiha
3. Abu Hamad
4. Akobo
5. Aqiq
6. Arbaat
7. Aroma
8. Atbara
9. Aweil
10. Boma
11. Bor
12. Derudeib
13. Dilling
14. Dongola
15. El Dueim
16. El Fasher
17. Erkowit
18. Gebeit
19. Gebeit mines
20. Gedaref
21. Geneina
22. Geteina
23. Guldo
24. Haiya
25. Halaib
26. Heiban
27. Juba
28. Kadugli
29. Kagelu
30. Karima
31. Kas
32. Kassala
33. Kebkabiya
34. Khartoum
35. Kologi
36. Kosti
37. Kurmuk
38. Kutum
39. Liyubu
40. Malakal
41. Muglad
42. Nagishot
43. Ennahud
44. Nasir
45. Nyala
46. Obied
47. Port Sudan
48. Rashad
49. Renk
50. Roseiries
51. Sennar
52. Shambe
53. Shendi
54. Singa

* Sinkat

55. Sodari
56. Station No. 6
57. Suakin
58. Talodi
59. Tokar
60. Um badr
61. Wadi halfa
62. Wad Medani
63. Wau
64. Yambio
65. Zalingei

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ABSTRACT

The rainfall over the Sudan is mainly controlled by the distribution of the pressure systems within and adjacent to the African continent. During the winter, north-easterly trade winds blow over the country and they are very dry except on the Red Sea coast. In the Summer, the winds over the Sudan are south westerlies and they are associated with all the summer rains over the country.

The distribution of the annual rainfall is fairly simple, and decreases steadily from south to north. Some local complications are imposed by various upland areas and the Sudd region, together with the effects of the line squalls in the central Sudan. The pattern of the monthly and seasonal rainfall is similar to the annual conditions in its simplicity and response to the local topographical effects. Excluding the Red Sea region, seven rainy seasons can be recognized. However, July, August and September can be considered as the general rainy season, whilst the Red Sea coastal area is the only part of the country that experiences winter rains. Variability of rainfall tends to decrease both southwards and with the advance of the rainy season.

A multiple regression analysis shows that the latitude, longitude, distance inland from the south west border and the relief factor, explain almost 93% of the annual rainfall over the Sudan. The latitude and the distance inland are the most important contributors, each of which tends to dominate the country during a certain part of the year. They are succeeded in importance by the relief factor, while the line squalls influence appears to be very insignificant.