A study of the climate of the Sudan with special reference to agriculture

Ahmed, Badr El Din Yousif Mohammad

A STUDY OF THE CLIMATE OF THE SUDAN WITH SPECIAL REFERENCE TO AGRICULTURE

By

Badr el Din Yousif Mohammad Ahmed
B.A.(Hons),University of Khartoum

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ABSTRACT

The study of the climate of the Sudan is important as it helps in understanding many socio-economic activities, particularly agriculture, as well as helping to understand the role of climate in the formation of physical features.

Chapter one outlines the scope of the study and the methods and techniques used. Chapter two describes the physical environment of the Sudan to provide a background for the study of climate and its relationship with agriculture. The climate of the Sudan is described in Chapter three and the different climatic elements, together with the factors affecting them are analysed. Distribution maps of the climatic phenomena over the Sudan are shown. Following the description of the individual climatic elements over the Sudan, climatic regionalizations of the Sudan are attempted in Chapter four. Amongst these classifications factor analysis is applied to the Sudanese climatic data.

Chapter five deals with the assessment of daily rainfall in the Sudan from satellite imagery. The importance of daily rainfall to many aspects of life in the Sudan, particularly agriculture, led to this trial.

This study pays a special consideration to the relationships between climate and agriculture. The importance of agricultural phenomena and the key role played by climate in it necessitate the investigation of such relationships. Chapter 6 explores agriculture in the Sudan as an introduction to the detailed study of the climate-agricultural relationships made in the consecutive chapters. Chapters seven, eight and nine give a detailed study of the relationships between climatic variables and cotton, sorghum, sesame and groundnut yields as examined by using a variety of statistical methods.

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GLOSSARY AND ABBREVIATIONS

AVCS	Advanced Vidicon Camera System
ERTS	Earth Resource Technology Satellite
ESSA	Environmental Satellite Services Administration
Essa	Environmental Survey satellite
FAO	Food and Agriculture Organization (of the United Nations)
fd	feddan, agricultural land measurement = 0.42 hectare or 4,200 square metres
Ghazal Gzt	Ghazal Gawazat (Fig. 1.1)
I.T.C.B.	Inter Tropical Cloud Band
I.T.C.Z.	Inter Tropical Convergence Zone
Kantar	weight measurement unit, for cotton 1 kantar = 315 lb.
Kg.	Kilogram
Landsat	Land satellite (formerly ERTS)
MSS	Multispectral Scanner
NOAA	National Oceanic and Atmospheric Administration (U.S.A.)
Saqiya	Persian water-wheel, an old irrigation method
SGB	Sudan Gezira Board (Gezira Scheme)
Shaduf	Counter-weight lever, an old irrigation method
Station 6	A railway station in northern Sudan (Fig. 1.1)
TIROS	Television and Infrared Observation Satellite
WMO	World Meteorological Organization
Z	Local time, Sudan Z = GMT + 2 hrs.

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CHAPTER ONE

INTRODUCTION

This thesis analyses the climate of the Sudan using variety of graphical and multivariate statistical techniques, and then relates crop production, principally of cotton, sorghum, sesame and groundnuts, to climatic variables.

The importance of studying climate in general is that it plays a very important role in the physical environment and the cultural aspects of any country, region or locality. Development planning in any aspect of socio-economic activity pays special attention to climate. Climatic study is of particular importance because climate, unlike many other factors, cannot be completely controlled. It is important to understand climate in order to realize the magnitude of its effect as well as to help to modify that effect and adjust cultural activities accordingly.

Among the many workers who considered the climate of the Sudan, besides the climatologists and the meteorologists are the agronomists. El Tom (e.g. 1966-1971) concentrated his researches and most of his studies on the rainfall climatology. Others, like Oliver (1965), and Pedgley (1969), also made short studies of rainfall in the Sudan. El Fandy (1949; 1950) and Bhalotra (1959, 1960; 1963) approached the climate of the Sudan from the viewpoint of the meteorologists. Satakopan (1965), Oliver (1969) and Adam (1973) did some studies on the problem of evapotranspiration. Agronomists like Jackson (1969) made some experimental studies on the effect of some climatic elements on cotton at particular research localities in the Gezira scheme in the Sudan. The present study, unlike all the others, combines the study of the characteristics of the climate with the application of climatic elements to the main agricultural crop yield by means of statistical methods in different areas of the Sudan.

Agriculture is one of the most important cultural activities affected by climate. In the Sudan the agricultural sector contributes 41% of the country's GDP, 90% of the total value of domestic exports, as well as involving 80% of the labour force (Hoyle, 1976). Different types of agriculture as well as different crops in different areas show different reactions to climatic and weather performance and the need to investigate such reactions appears essential.

Many factors other than climate affect agriculture and crop yield. These factors are soil, water supply and technology, represented by mechanization, pest and disease control, and the other agricultural management aspects. Although these factors are crucial in agriculture and crop yield, the interest of this study is concentrated on the effect of the climatic factor alone. This is not intended to minimize the influence of the other factors. Many difficulties stand on the way of including other variables affecting agriculture and crop yield in statistical model quite apart from the difficulty of designing a totally comprehensive multivariate model, there is a lack of, and difficulty in obtaining statistical data on :

(1) Soil characteristics and soil moisture;

(2) Efficiency of irrigation, water management and inundation control;

(3) Actual dates of sowing, harvest and growing season calendars;

(4) Pests and disease control;

(5) Efficiency of harvest;

(6) Weed control;

(7) Types and methods of fertilizer applications;

(8) Land and/or crop rotation.

Added to these, agricultural and agrometeorological stations are absent from the majority of the areas, and even when they do exist the data on crops and environments are inadequate for accurate statistical analysis. There are no measurements of variables such as rainfall and temperature concurrent with the phenological stages of the plant growth. Wang (1972) maintains that even when data on the environment are available, the environmental elements influencing the growth and the development of crops are not fully known. Because of all these difficulties the study in this thesis is concentrated on using the most generally available relevant climatological data and then testing their significance.

The main interest of this study is to apply the climatic factor to agriculture, and to crop yield in particular, to elucidate the statistical relationships between these variables. The effects of climatic factors on agriculture in Sudan has not been satisfactorily studied previously. This study considers climate as an initial variable in models erected for crop yield to obtain a first relationship approximation and from which relationships between climatic variables and crop yield can be determined through further experimental studies and a fuller collection of appropriate data concerning climate and other factors. If the whole range of climatic and production data had been available consistently even for all the existing stations the effects of technological and management change could have been analysed. Such time trend effect in fact can only be indicated.

In the study of the general aspects of the climate of the Sudan 61 meteorological stations have been selected (see Fig. 1.1 and Table A.1 - Appendix) and they are arranged from north to south in the tables. There is some concentration of these stations along the Nile and in the Gezira scheme area. There is almost a complete absence of meteorological stations in the northwestern quarter of the country occupied by the desert. The period selected for study is 1941-1970 within which the meteorological stations differ in their ages and the consistency of their records.

The sources of the meteorological data are those published by the Meteorological Department of the Sudan Ministry of Defence. These are the Annual Meteorological Reports for the period 1950-1975 which contain the monthly averages or total values of climatic elements, climatic normals for the period 1941-1970 for 23 stations, and the monthly and annual agrometeorological reports for the period 1964-1978 for 4 stations. Added to these are the unpublished data extracted also from the Meteorological Department records. Interpolations based on these sources are also made for some of the climatic variables used in this study. The crop yield statistics for the period 1950-1978 were obtained from the publications of several departments of the Ministry of Agriculture of the Sudan, and from the Sudan Gezira Board (SGB) publications and files on the Gezira scheme.

Statistical methods, mainly correlation and regression,

Fig.1.1 LOCATION OF METEOROLOGICAL STATIONS USED IN THE STUDY

have frequently been applied in this study. They are described in detail in Chapters 5 and 6 where they are fundamental to the discussion and the model building in Chapters 5, 7, 8 and 9. The main advantages and shortcomings of these methods are also listed.

The computer programs SYMAP and SYMVU described by Muxworthy (1972) were used to produce maps and block diagrams for many climatic elements for the climatic normal period 1941-1970 as well as for mapping other phenomena of this study. The Symap program has the advantage of quick and more accurate drawing of isolines for value distribution. Although these isolines are given according to the upper and lower limits of the values of the studied phenomena in relation to the number of levels desired, isolines of round figure values can be interpolated from the map produced. Another feature of these Symaps is the artifact phenomenon where in areas such as north western Sudan where recording stations are rare or even absent then isolines values are derivative of the mathematical procedure of the program. The implied interpolation is only valid in terms of the program's logic but may not match the real situation on land.

Chapter 2 deals with the physical environment of the Sudan to furnish a basic knowledge about the country. This knowledge is particularly important for the study of climate and agriculture as the study deals with continentality, tropicality, and size, as well as dealing with relief, geological structure, drainage systems, soils and vegetation cover.

An exploration of the general aspects of the climate of the Sudan is given in Chapter 3. The principal purpose of such a survey is to provide statements of the different elements of the climate of the country. This is also useful in approaching the climate-agriculture relationships discussed later. An account of the relationships between the climatic elements, the nature of these relationships and the factors controlling them are also given. The main aspects discussed are radiation, temperature, pressure and wind system, cloud cover and sunshine, relative humidity, rainfall and evaporation. The tropicality, continentality, relief and pressure and wind systems are the main factors affecting the climate of the Sudan. In the study of each element the number of stations included is governed by the data available. Within the study period, 1941-1970, the data for some stations cover almost the whole period for most of the climatic elements, whereas in some other stations only short records for some of the climatic variables are available.

Chapter 4 is allocated to climatic classification in order to make simplification and generalization of the knowledge about the climate of the Sudan described in Chapter 3. Three of the conventional climatic classification methods, Köppen's and Thornthwaite's (1931; 1948), together with a new factor analysis method were applied to the Sudan. Köppen's method depends on a moisture index from the relationship of rainfall to temperature. Thornthwaite developed two methods:

(1) the 1931 method which provided a better moisture index from precipitation and temperature relations than Köppen's method, and

(2) the 1948-55 method which introduced the concept of potential evapotranspiration. This method has been applied in many regions of the world.

The factor analysis method was used to provide an objective climatic regionalization of the Sudan presented by cluster analysing the scores provided by this method. The computer programs of factor/cluster analysis are described in the Statistical Package for the Social Sciences (SPSS) manual (Nie et al., 1970). The region's boundaries were drawn using the Symap computer program previously mentioned.

The importance of rainfall, and daily rainfall in particular, in many aspects of life such as agriculture was the reason of paying it particular attention in Chapter 5. The network of the raingauges throughout the Sudan is imbalanced with a concentration along the Nile, contrasting with wide dispersion in many other places. There is an almost complete absence of raingauges in the northwestern desert area of the country. The use of meteorological satellite imagery to fill the gap in the data, as well as to help the estimation and the prediction of the daily rainfall in the Sudan is discussed. The Barrett (1970) model is adopted for such estimations, and modifications of the model are suggested. These trials are followed by a final assessment of the method's application to the Sudan.

Following the climatic aspects of the Sudan, Chapter 6 describes the agricultural phenomena and the methods to be used in the climate-crop yield relationship analysed in the succeeding chapters. The first section of the chapter is concerned with agriculture and includes agricultural systems, agricultural development and the variations in crop yield of different crops. The second and related section deals with the use of Landsat satellite imagery in monitoring agricultural land use. The use of such a technique could give improved evaluations of agricultural activity, production and productivity if correctly applied and fully developed. The final section of this chapter gives information about the area and the data selected for the climate-crop yield relation study as well as the problems related to the study of such relationships. The area selected for the study is confined to the regions of central and eastern Sudan where both extensive and intensive agriculture take place, and where relatively reliable data can be expected to be found. The study includes the irrigated, rainfed and flooded types of agriculture. The data provided for climate-crop yield lie within the period 1950-1978. Regions and localities differ in consistency for climatic variables and crop yield records. Sometimes no more than 13 cases were obtained. The four crops chosen for the study are cotton, sorghum, sesame and groundnuts. Cotton is the most important cash crop followed by groundnuts and sesame. Sorghum is the main subsistence crop in the country. The growing season for irrigated and flooded cotton starts in late July and early August and ends in April the following year, while for the rainfed cotton it starts in late June and ends in January the following year. The other crops' seasons lie approximately between late June and December. The rainy season (approximately July to September) coincides with the first part of the growing season.

The study of the climate-cotton relationship is considered in Chapter 7 with a concentration on some climatic variables' relationship with cotton yield only. There is a difficulty of obtaining reliable weighted data for the other stages of the crop development. The whole area of the study is first taken as a single unit, then split into the irrigated area of the Gezira scheme (Wad Medani - Dueim - Kosti) and the rainfed area (Gedaref, Kadugli). Within these regions a temporal study is made by splitting the period 1951-1970 for the Wad Medani-Dueim area into two decades. The relationships for these decades are compared with each other to inspect any suggested effect of technological change over time on the climate-cotton yield relationships. The regions were then split into local centres of cotton production and some of them are studied to show the local difference in climate-cotton yield relationships. The localities chosen are Wad Medani, Kosti, Kadugli and Aroma and they represent different types of agricultural practices. Multiple regression is used to evaluate the influence of climatic variables on crop yield. Fisher's (1924) second degree polynomial regression is applied to examine the effect of the change of rainfall throughout the rainy season on cotton yield. Stepwise regression is applied to analyse the effect of climatic variables on cotton and to produce formulae for cotton yield estimations from climatic data.

In Chapter 8 similar procedures to those in Chapter 7 are followed in studying the relationships between climate and sorghum yield. Correlation and regression analyses are presented, together with estimations of sorghum yield from models provided by the regression procedures. Within the study area two regions are mainly considered : the irrigated region (Wad Medani - Dueim - Kosti) and the rainfed region (Gedaref - Abu Naama - Kadugli). At the local level the following centres are considered, Kosti, Gedaref, Singa, Abu Naama and Aroma. These areas represent different types of agricultural practices.

The oil seeds, sesame and groundnuts, are chosen for the investigation of climate-crop yield relationships in Chapter 9. Although these two crops are grown in many areas in the Sudan, few data sets could be obtained (Ministry of Finance and Economics, 1964). The relationships studied for sesame are for Dueim, Gedaref and Abu Naama. For groundnuts the study is for only Wad Medani and Kosti. The same methods followed in Chapter 7 and 8 are also followed here finishing with crop yield estimations.

Finally Chapter 10 gives a summary of conclusions reached from the study. In that Chapter an assessment of the methods, the models and the results is made. The potential uses of the models and the value of the study are discussed. The problems faced in this research and the possibility of improving the results and the models are also discussed.

CHAPTER TWO

PHYSICAL ENVIRONMENT OF THE SUDAN

2.1 General

In this chapter the general physical environment of the Sudan will be discussed. It is important to provide this knowledge to stand as a basic background to a general understanding of the climate of the Sudan, as the physical environment is closely related to climate. It will be seen that the Sudan, besides its continentality and tropicality, contains physical factors which have a noticeable effect on climate. Of these factors the low relief contrast and the vast extension of the country across a range of latitude are of particular importance. The geological structure and its role in water contents and water movement and hence in vegetation distribution is also considered as it also partially reflects physical response to climate and weather. The physical environment has a particular importance in relation to local climate and the role it plays will be discussed later in Chapter 3.

Sudan is the largest country in Africa and it is the twentieth largest in the world. Its lands are equivalent to 8.3% of the African continent and 1.7% of the world's landmass. It covers an area of 2,505,805 sq. kms. The country extends approximately between latitudes 3°N and 23°N, and longitudes 22°E and 38°E. Sudan is bordered by the lands of 8 African countries (see Fig. 2.3) and has only a short coastline along the Red Sea in the extreme north east. The Red Sea coastal area is a vital one for the country because it is the only sea outlet to the rest of the world. The Red Sea separates the country from its ninth neighbour, Saudi Arabia.

2.2 Relief

Sudan lacks the extensive mountain ranges that are effective in other countries as climatic barriers. Gradual transition is the normal situation rather than abrupt change. There are some relatively higher areas, but they are not extensive enough to have a significant effect on the overall climate of the country (Fig. 2.1). It is noted that about 50% of the country's land lies between 1,200 and 500 metres above sea level, 45% between 500 and 300 metres and only 2% lies below 300 metres. The sum of those areas leaves only 3% of the country's land higher than 1,200 metres (Barbour, 1961). It is also noted that except for small areas, most of the country is included in the Nile Basin. One of the areas outside that basin is that which lies to the west of the Chad-Nile watershed in western Sudan. The other is the narrow coastal area of the Red Sea. The country is generally a vast rolling plain which includes the Nile and its tributaries.

The highest area in the Sudan is the Imatong area in the south eastern corner near the border with Uganda. It is a small area in which Mount Kineti has a peak rising to 3,190 metres. The next highest is the Marra Mountains area in the western Sudan roughly covering 110 km. from north to south and about 50 km. from east to west and its southern part has peaks rising over 3,088 metres. The so-called Nuba

Mountains of southern Kordofan in central Sudan are in fact a group of scattered hills of which the highest peak is only 1,524 metres. They rise above a raised plateau 610 m. above sea level. The last of the relatively higher areas is the Red Sea hills of the extreme north east. The hills are an elongated series running close to the sea and leaving only a narrow coastal strip 24 to 32 kilometres wide. The general level of the hills is roughly 915 metres in which Jebel Asotriba is 1,200 metres high (Andrews, 1948; Barbour, 1961).

A look at the situation of relief surrounding the Sudan can give an idea of the expected influence of those areas on the climate of the country. To the south there are the mountains of Kenya of more than 1,830 metres with a number of peaks more than 3,000 metres. The highest is Mt. Kilimanjaro (5,895 m.) at the Tanzania-Kenya border. Uganda's height is generally less than 1,829 metres at the Lakes area, but on its border with the Congo there stands the high Ruwenzori mountain (5,199 m.). The Sudan-Congo border is of an approximate height of 900 metres.

To the west and the north of the Sudan, the lands are generally low and they are almost completely occupied by the Sahara desert which is mostly a low plateau. The only significant ridges of more than 900 metres range between latitudes 20^{o}N and 25^{o}N and longitudes 5^{o}E and 20^{o}E of which the most famous are the Tibesti (3,800 m.) and the Ahaggar (3,000 m.).

To the east of the Sudan there is the extensive Ethiopian plateau which runs in a north-south direction with

Fig.2.1 RELIEF (after Barbour,1961)

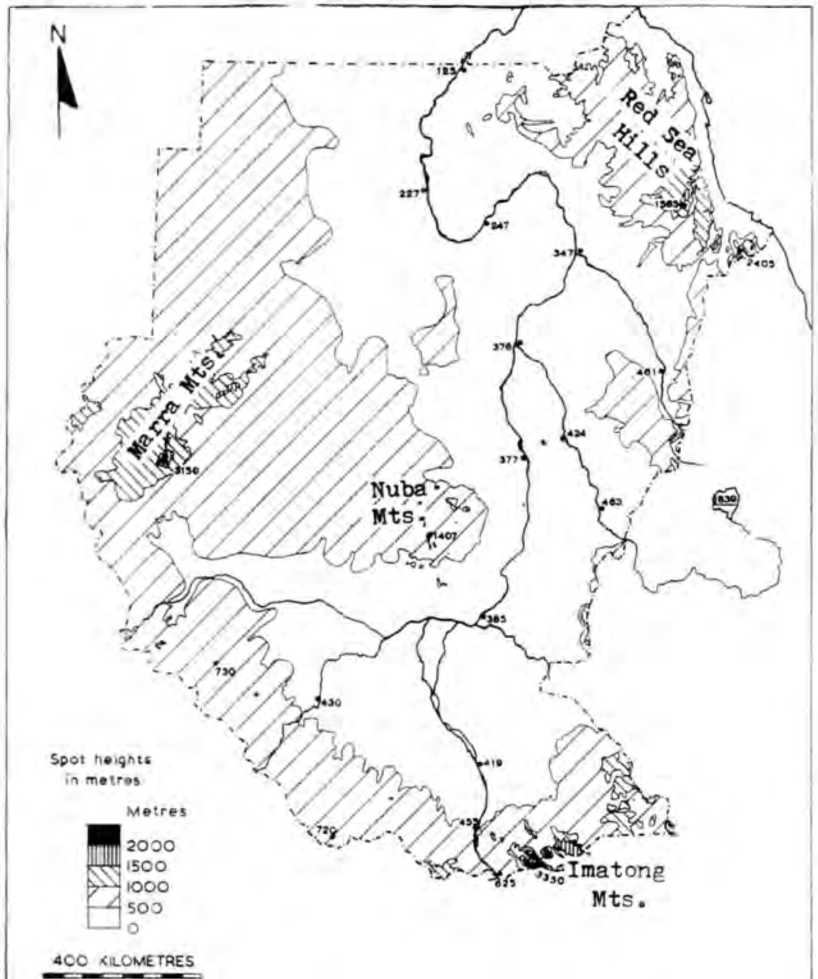
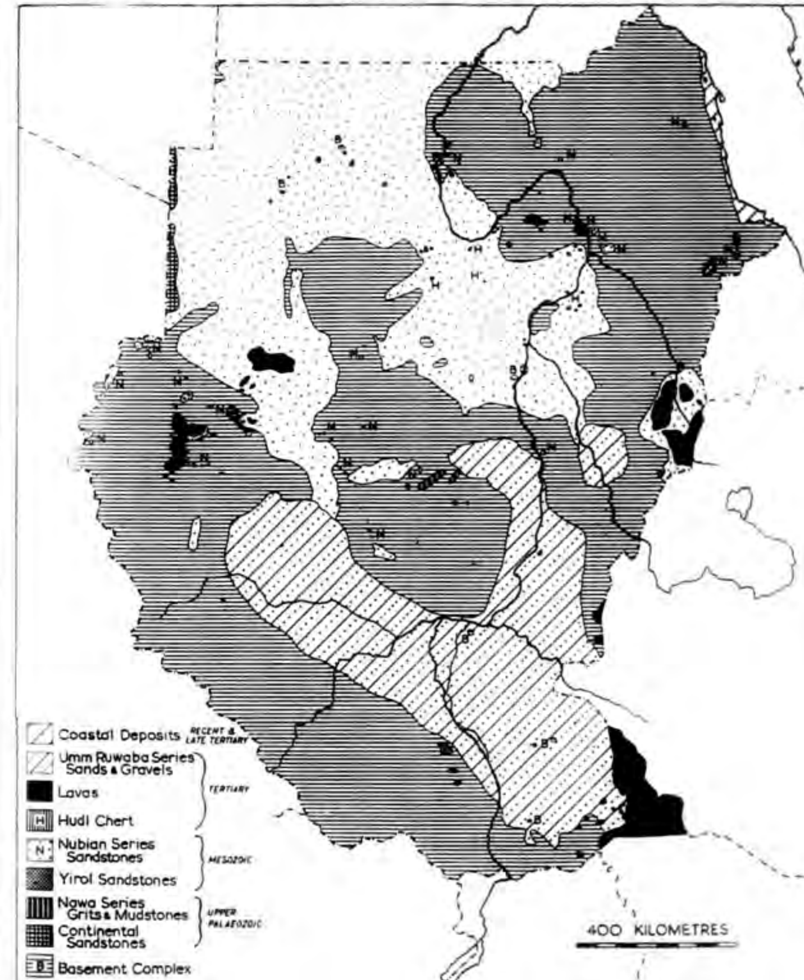


Fig.2.2 GEOLOGY (after Barbour, 1961)



a general relief range between 1,829 and 2,438 metres. It has tracts more than 3,000 metres high and some peaks in the western part more than 3,960 metres high. The plateau declines southwards to the Somali desert and in the north, in Eritria it declines eastward to the Red Sea (Bhalotra, 1963; Thorp, 1975).

2.3 Geological structure

Because geological structure is very important in relation to the hydrological cycle between the earth and the atmosphere, and because it can affect both physical and cultural aspects of a region, a brief account of it will be given in this section.

The most extensive geological formation in the Sudan, apart from the superficial deposits, is the Basement Complex occupying 49% of the whole country. This contains the oldest rocks, which are of Pre-Cambrian age. Much of the Basement Complex is covered by superficial deposits but they appear on the surface in many places. The exposed rocks of this type are mainly the hills of Equatoria, the Nu ba Mountains of Kordofan and the Sabaluka Jebels north of Khartoum. The Basement Complex is characterized by being a non-water bearing formation (see Fig. 2.2).

The Nubian series are marine formations, mainly sandstones and mudstones, horizontally bedded and characterized by their ability to bear water. They are an extension of the same marine formation of Egypt that covers large areas of the Sahara. This Paleozoic formation rests on the older Basement Complex. A conspicuous example of this succession is shown on Jebel Rauwian, north of Khartoum, where the Nubian sandstones cap the Basement Complex rocks of the mountain.

Following these older formations, the Hudi Chert rocks (dark silica) were formed in the Tertiary period. They are only localized in northern Sudan in Jebel Nakhara. This formation is basalt laid upon the Nubian formation. They are solid rocks with a greater ability to resist erosion compared with other rocks beneath them. The Tertiary period also witnessed small scale volcanic activity which resulted in the formation of the Marra and Meidub mountains of Darfur. Their rocks are also basaltic.

The latest solid formations are those of the Umm Ruwaba series which are extensive in the south but completely masked by superficial deposits. This formation, together with the Basement Complex and the Nubian sandstones, occupies 97% of the Sudan (Whiteman, 1971). The Red Sea coast is in most cases formed of unhardened sedimentary rocks (Worral, 1957; Saeed, 1971).

Over most of these formations superficial deposits have been extensively laid down in recent times. These deposits are the laterites of Equatoria Province, the sand qoz of Kordufan and Darfur, and the extensive clays of the plains of the Sudan. These latest formations will be discussed in the soil section (2.4).

2.4 Drainage System

2.4.1 The Nile

The drainage system in the Sudan is dominated by the Nile and its branches draining the Equatorial East African and Ethiopian plateaux. A characteristic seasonal rhythm is evident in the behaviour of the Nile and its tributaries, namely the low and flood seasons. They are coincident with the seasonal pattern of the rainfall in the areas of origin.

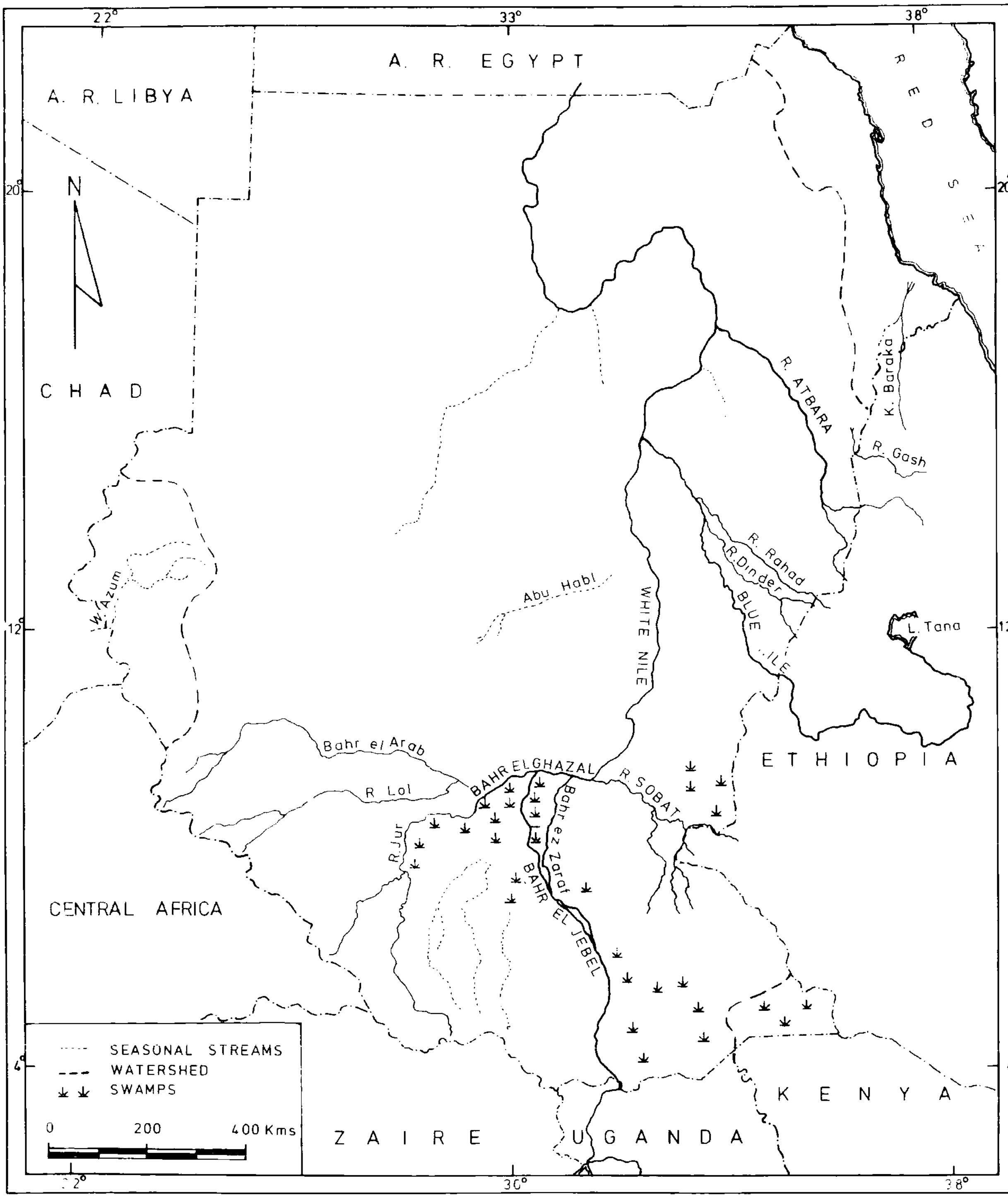
The main Nile originates in Lake Victoria and obtains more water from the neighbouring lakes of East Africa. As the Nile enters the southern Sudan it enters the plain and an almost flat region where it flows sluggishly and overfloods its banks into an extensive area resulting in a large swampy landscape (Sudd) between latitudes 5^{o}N and 10^{o}N. In this way a considerable amount of water is wasted and prevented from contributing to the Nile water. Some of the water is lost through evaporation and percolation and some of it fails to find its way to the river course for the lack of considerable gradient. Just before Malakal the river regains a well defined channel and is named the White Nile. It is at this stage that it obtains more water from the branches draining the Congo-Nile watershed in the south west. These branches, of which Bahr el Ghazal is the main one, contribute only small amounts of water to the Nile as much of their waters are wasted in the swampy area before they join the main Nile.

The main contributors to the Nile water are those branches draining the Ethiopian plateau. They are characterized by their strong currents due to the steep catchment areas and the relatively short distances before they reach the main Nile. They hence carry considerable amounts of silt and sediments from the plateau and deposit them on different parts between the land of origin and the Mediterranean Sea. The largest amounts of water carried by those rivers take place in the rainy summer season. In January, except for the Blue Nile, all the Nile tributaries which depend on the seasonal rainfall over the Ethiopian plateau lose their waters and convert into patchy swamps along the dry courses. This situation continues until about the beginning of July when the new effective flood season commences.

Taking those tributaries which originate in Ethiopia, (see Fig. 2.3) it can be seen that the Sobat is the main tributary of the Nile in its southern part. The Sobat collects considerable amounts of water from its tributaries such as the Baro before it joins the Nile just before Malakal. The Nile after travelling 12^{o} of latitude since its entry to the Sudan is joined by its main tributary, the Blue Nile, at Khartoum. This river flows from Lake Tana on the Ethiopian plateau, and although it is similar to other tributaries in its dramatic seasonal flowing changes, it differs from them by being perennial. The Blue Nile also has some seasonal tributaries of which the most important are the Dinder and the Rahad. Between Khartoum and the Mediterranean Sea, the River Atbara is the only tributary of the Nile and it also drains the Ethiopian plateau. This river is seasonal, yet it contributes a considerable amount of water to the Nile.

The mean total discharge of the Nile below Khartoum in the low season (January to June) is 13.8 milliard m^3.

Fig.2.3 DRAINAGE SYSTEM



Source : Sudan Surveys(Top. no. S., 625.40) and Barbour (1961)

Of this amount the White Nile contributes 10 milliard and the Blue Nile 3.8 milliard. In the flood season (July to December) the discharge is 76 milliard m^3 shared as follows : the Blue Nile 48, the White Nile 16 and the River Atbara 12 milliard m^3. The peak of the floods is reached in August when the discharge, measured below Khartoum, becomes 15 times that of April. When the peak is passed the floods fall rapidly until the end of October and then change to a gradual fall (Allan, 1948). The Blue Nile, in spite of its small contribution in the low season, in aggregate is the main contributor to the Nile water.

2.4.2 Other Systems

Apart from the Nile, the most important streams in the Sudan are the seasonal streams of Gash and Baraka (see Fig. 2.3). Both streams drain the Eritrean highlands and are characterized by their torrential flows. Both the rivers run parallel to the eastern boundaries of the Sudan and end in inland deltas, the Gash near Kassala and the Baraka near Tokar. These two rivers have an established agricultural significance, though many problems arise from the control of their waters. This is particularly so for the Khor Baraka. In the western Sudan streams draining the Nuba or Marra mountains rarely reach the Nile, but some of them are also important from an agricultural point of view. Besides these some water-courses running towards the Nile in the north west are important for their help to nomadic life in terms of water supply and grazing.

From all this it becomes clear that all the waters in the Nile Basin system are mainly provided from outside the

Sudan. This fact is related to the unreliable and erratic nature of the rainfall in most of the Sudan which does not result in perennial watercourses. Instead the result is small seasonal water courses which scarcely reach the Nile.

2.5 Soils

The study of soils is important in the context of their role in climatic and agricultural questions as well as in many other physical and cultural aspects of the region. Soils themselves are a result of processes related to the physical features, the geology and the climate of a country (Greene, 1948). The characteristics of soil, their mineral content and their structural qualities have direct and conspicuous (positive or negative) influences on agriculture. There is an interaction between climate and soil and they affect the hydrological cycle in the region. It is therefore important to consider the soils of the Sudan in this study for it helps the understanding of some of the reasons which led to the present pattern of agricultural activities, and contributes together with climate to a better understanding of the physical factors affecting agriculture in the Sudan.

There is a wide variety of soils in the Sudan, and there are none of homogeneous types which can easily be demarcated (Colvin, 1939; Barbour, 1961). Although no network of satisfactory empirical soil investigations exists in the Sudan, except for the Gezira (Greene, 1948) and the newly developed agricultural schemes, a general description of soils in the Sudan can be given.

According to Andrew (1948) the soils of the Sudan can be classified according to age, which has the advantage of hinting at the climatic conditions during which soil development took place, The soils fall generally under 3 main groups of which details can be seen in reference to Figure 2.4.

1. Tertiary sediments, sub-ironstone clays where exposed, and ironstone in west Equatoria in south western Sudan.

2. Pleistocene sediments with the following sub-divisions:

   i) Umm Ruwaba series (rarely exposed);

   ii) Sands and gravels underlying the clay plains (rarely exposed);

   iii) Kordofan fixed sand dunes and the clay of the plains (mostly alluvial but some in situ);

   iv) Red loams and unconsolidated ferrugineous clays of West Equatoria in the same region as category 1.

3, Recent deposits, valley alluvium, modern dune sands and modern soils overlying parent rocks in situ.

Greene (1948) suggested some catena characteristics for some of the soils divided as follows:

1. Toich catena; flood plains and sheet eroded upland west of the White Nile.

2, Alkaline catena; semi-arid grass plains east and west of the White Nile.

Fig. 2.4 SOILS (after Barbour, 1961)

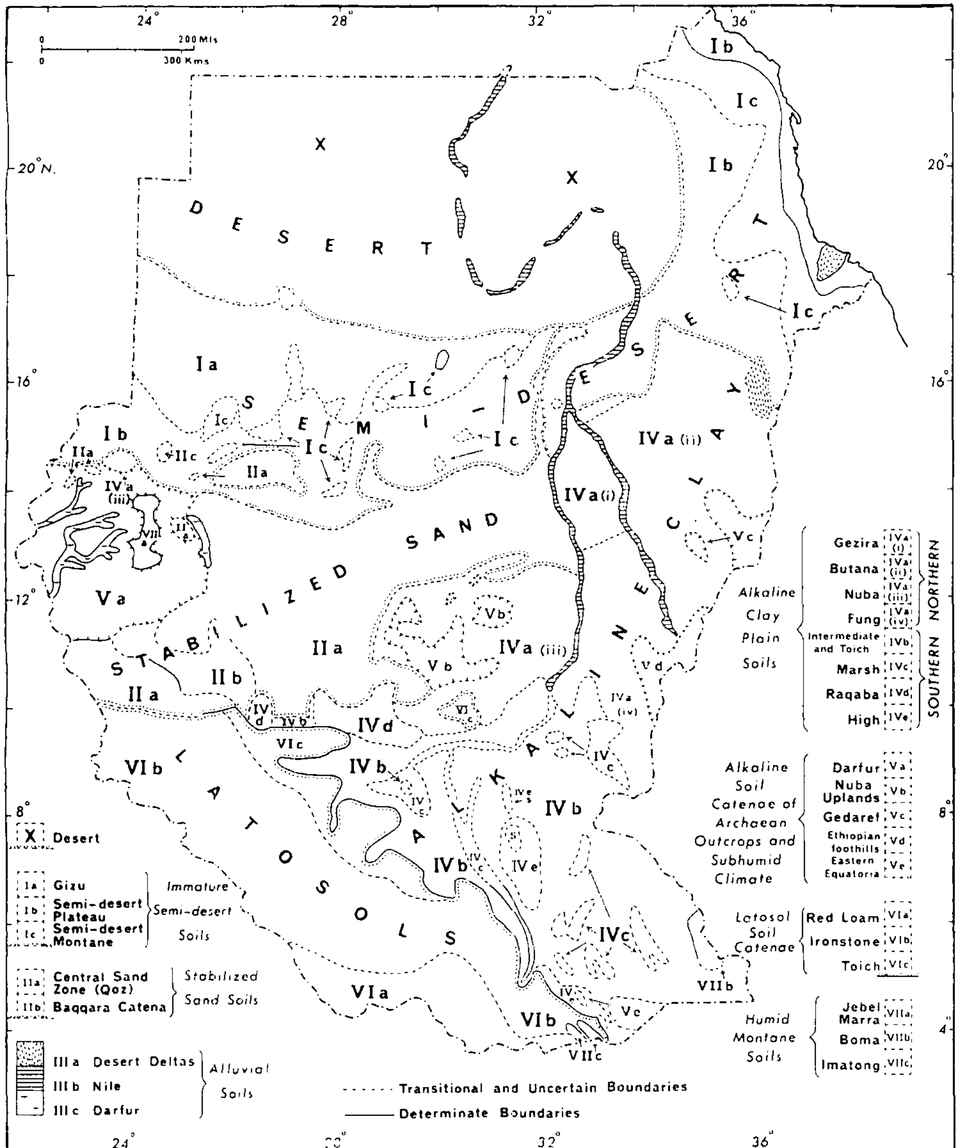
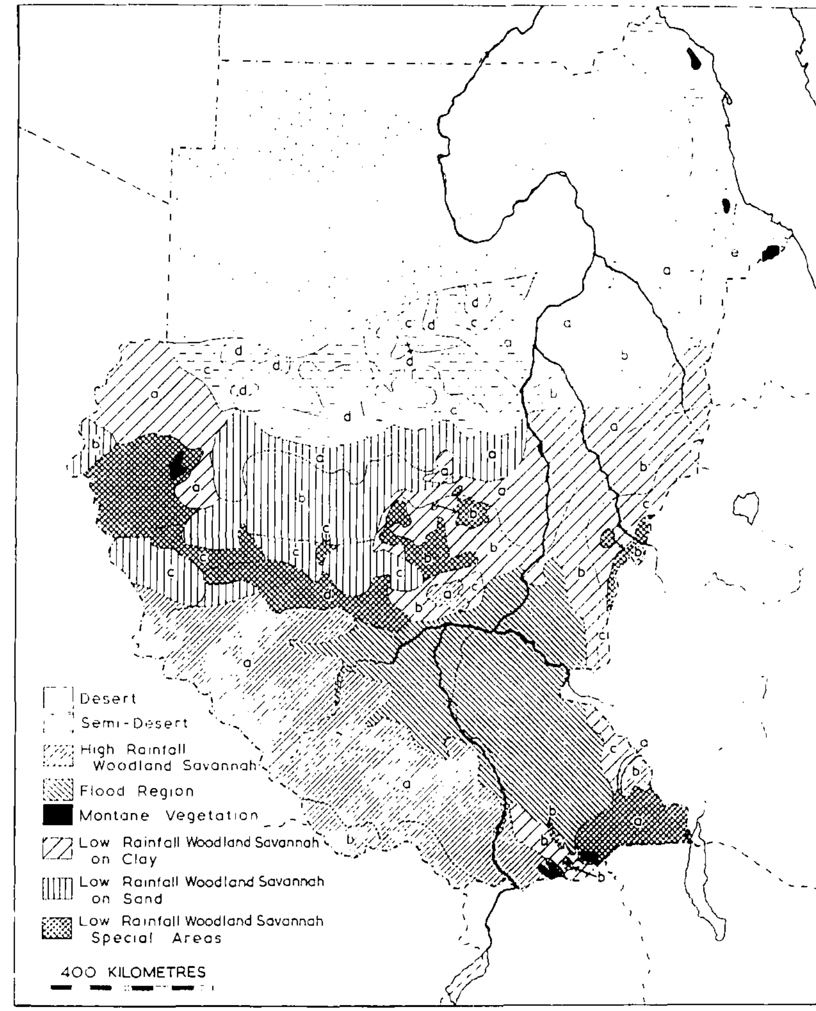


Fig. 2.5 VEGETATION (after Barbour, 1961)



3. Red loam catena, humid hilly country, near the borders of Uganda and Congo.

4. Ironstone catena; humid ironstone plateau along the Nile-Congo watershed.

Andrew (1948) stated that the catena characteristics do not have any geological significance in relation to soils of the Sudan. Tothill (1948), although not diagreeing with Andrew, advocates that the catena here is not meant to apply to the fully geological qualities of the catena but only to describe a hill to valley sequence of the soil. Greene stressed a 'soil rhythm' because of the seasonal changes due to a clear long dry season followed by a short wet season. Different factors seem to support that rhythm besides the climatic ones. The pre-yield crops and the after-yield crops in agriculture reflect this rhythm on soil condition.

Because of recent agricultural development schemes and projects more and more soil investigations have taken place to obtain a comprehensive view of the soils of the Sudan. In the soil laboratories studies are undertaken for the purposes of conserving and improving the soils of which the most well established ones are those of the Gezira scheme. The researches are mainly made to meet agricultural development needs, and generally examine the following soil qualities :

(1) properties of the soil;

(2) penetration and availability of water in the soil;

(3) water soluble salts in the soil;

(4) nitrogen supply for crops in the soil; and

(5) possibility of soil improvement.

By and large a long time is expected to elapse before a comprehensive accurate map of soil classification and detailed studies of the soils of different areas in the Sudan are completed.

2.6 Vegetation

The fact that rainfall in the Sudan varies from about zero in the extreme north to about 1500 mm per annum with a long rainy season in the extreme south is reflected in the type of vegetation. There is a general gradation from a true desert in the north to closed tall forests in the south. Soils also influence those types but relief has only a limited influence. From Figure 2.5 five principal latitudinal vegetation regions added to the montane type are generally recognized. They are :

1. Desert

This region which covers the area north of Latitude 17°N with the exclusion of the Red Sea hills is characterized by having rainfall less than 50 mm per annum. Trees and relatively tall grasses mainly grow in close relation to the water courses, while away from them short grasses are scattered over the desert. The Gezzu grazing area of the north western Sudan is an example of this latter type.

2. Semi-desert

The semi-desert region extends south to about latitude 14°N together with the region of the Red Sea hills. The rainfall here ranges between 500 mm and 200 mm per annum. Because rainfall is highly variable and unreliable the resultant vegetation is a mixture of grass with or without woody vegetation, or more usually with a variable scatter of scrub bushes with heights up to 2 metres.

3. Low Woodland Savanna

This region extends southwards to latitude 10°N including 2 main divisions :

i) Woodland Savanna on clay with rainfall between 400 mm and 570 mm p.a. This type mainly includes the Acacia Mellifra thornland which merges into Acacia Sayal-Balenites Savanna characterized by short grasses.

ii) Woodland Savanna on sand. This region includes such types as the Acacia senegal (gum arabic source) trees in areas of rainfall between 280 mm. and 450 mm p.a. and non-thorny trees where rainfall exceeds 800 mm p.a. Included in this region is the south eastern corner of the Sudan (Smith, 1948) although this and other areas have their own climatic characteristics. Such characteristics, as rainfall and temperature in terms of values and seasonal changes resulted in some differences in vegetation types.

4. Deciduous High Woodland Savanna and Swamp Grass

This region extends deep into the south to latitude 5°N and as it has more rainfall than the preceding region (750 - 1250 mm p.a.) its vegetation species are characterized by large trees (up to approximately 30 m high) and taller grasses such as those of the Sudd region between Juba and Malakal (Andrews, 1948).

5. Modified Tropical Rain forest

The rainforest region is confined to southwestern Equatoria in the extreme south. Rainfall is more than 1252 mm. Vegetation is a woodland in which patches of regeneration forest in various stages of regrowth alternate with areas of recent cultivation (Lebon, 1965).

6. Montane Vegetation

These types here have little in common other than their being different from their surroundings (Harrison and Jackson, 1958). The main areas of the montane types are the Imatong and Dongotona of the south, the Red Sea hills of the north east and Marra mountains of the west.

Finally, the account given in this chapter is an important background for the present study which considers the climate and agriculture phenomena in the Sudan. Reference will be given to local difference in climate and agriculture and the role of the physical factors in their performance. In general, the vast extension of the country across a range of latitudes, lack of a large relief contrast, difference in soils and drainage system pattern all have an important influence on the pattern of both climate and agriculture, and these will be explained in the succeeding chapters.

CHAPTER THREE

CLIMATE OF THE SUDAN : GENERAL SURVEY

3.1 General

The aim of the study in this chapter is to make a general survey of various climatic elements in relation to factors affecting them, their distribution over the Sudan and their seasonal and diurnal variations. Such knowledge is important for different fields of research or study, particularly those closely related to climate. This general survey is of special importance in this study where special interest is directed to the relationship between climate and agriculture. It stands as an essential background if any such relationship is hoped to be better understood. Generally 61 meteorological stations in the Sudan were selected for this study (Fig 1.1) but the number of stations used in the discussion of different elements of climate is affected by the age and status of those stations. Rainfall, for example, is well covered due to its widely used and simply operated instruments, temperature is fairly covered and elements like radiation are poorly covered.

As mentioned in Chapter 2, the Sudan lies within the tropics between latitudes 3^{o} and 23^{o}N. It lies in the interior of Africa and contacts the Red Sea only for a short coastline at its extreme north eastern boundaries. Because of this and because of the Red Sea being a narrow water surface and the Red Sea hills running parallel and close to it, the direct maritime influence on the Sudan climate is restricted to the coastal area. The climate of the Sudan is largely affected by tropicality and continentality. Added to that the Sudan is a vast plain with only small areas of high altitudes such as the Marra Mountains of Darfur and Nuba Mountains of Kordofan mentioned in Chapter 2.

From the previous generalization a detailed look at the climatic elements and factors affecting them is considered here. The climatic elements and aspects studied here are considered in the following sequence : radiation, temperature, pressure and wind systems, cloud cover and sunshine, relative humidity, rainfall and evaporation. They are generally discussed in the sequence of energy, dynamic and moisture associates. Understanding the nature and the relationships of these elements is of particular importance in understanding their relationships with crop yields in the Sudan. Several maps and block diagrams are compiled for this study from the period 1941-1970 for as many as possible of the selected 61 stations.

3.2 Radiation

3.2.1 General

The data on total solar radiation in the Sudan are very few because of the small number of high status meteorological stations measuring this phenomenon. There are only 9 stations with reasonably consistent data covering the period 1960-1978. The records hardly go back beyond 1960. However, average radiation is not as varied from year to year as other elements like rainfall, so those stations measuring radiation can yet give a reasonably accurate picture of radiation distribution in the Sudan. The spacing of those stations is also considered reasonable for it generally preserves a regional representation. The total solar radiation data used in this study were measured in calories per square centimetre per day.

The main factors affecting radiation are the angle at which the sun's rays strike the surface and the length of the time of exposure. Both of these are varied by latitude and by seasonal changes in the path of the sun in the sky (Strahler 1969). Sudan, being a tropical country with a long marked dry season on most of its lands with long periods of clear skies, receives great amounts of insolation.

3.2.2 Distribution of radiation

From Figures 3.1, 3.2 and 3.3 and Table 3.1 two patterns can be observed in the distribution of radiation over the country. First, in annual averages and averages of March - October inclusive the highest values are recorded in the north, decreasing southwards, and in the east towards the Red Sea. The second pattern which is noticed is for the winter season, November - February inclusive, when the centre of highest radiation shifts southwards to central Sudan while radiation values decrease both to the north and south of it. The Red Sea coast in this season recorded the smallest values as Port Sudan's record is only 342 cal/cm^2 in December.

The average annual radiation ranges between 581 cal/cm^2 recorded at Dongola in the north, and 467 cal/cm^2 at Juba in the south. April and May are the months when the Sudan witnesses its greatest amount of radiation. Within these two months the concentration of highest radiation is during April in the central areas and during May in the extreme

Fig.3.1 MEAN DAILY RADIATION (CAL./CM^2)

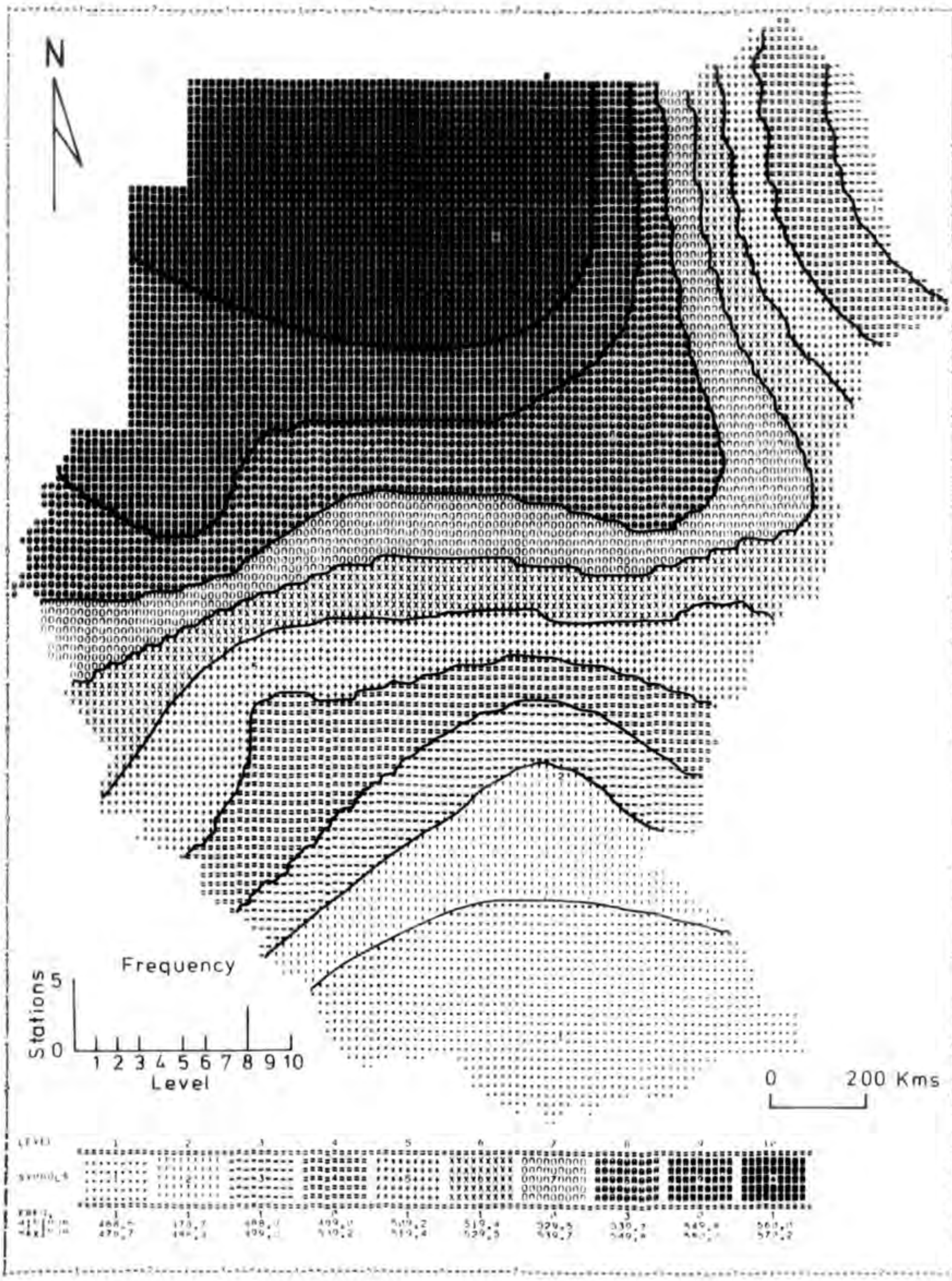


Fig. 3.2 RADIATION FOR 4 MONTHS (CAL./CM²)

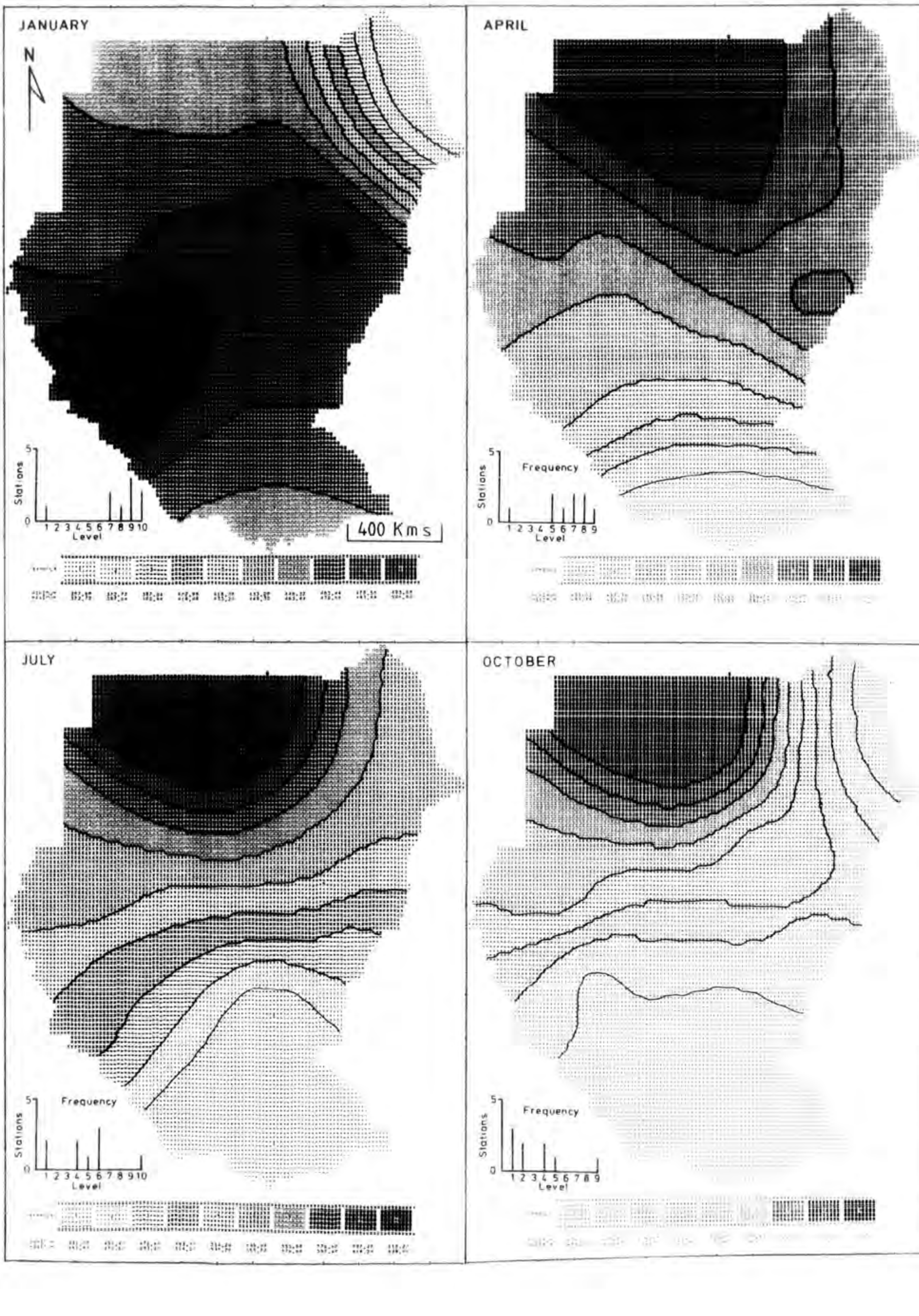
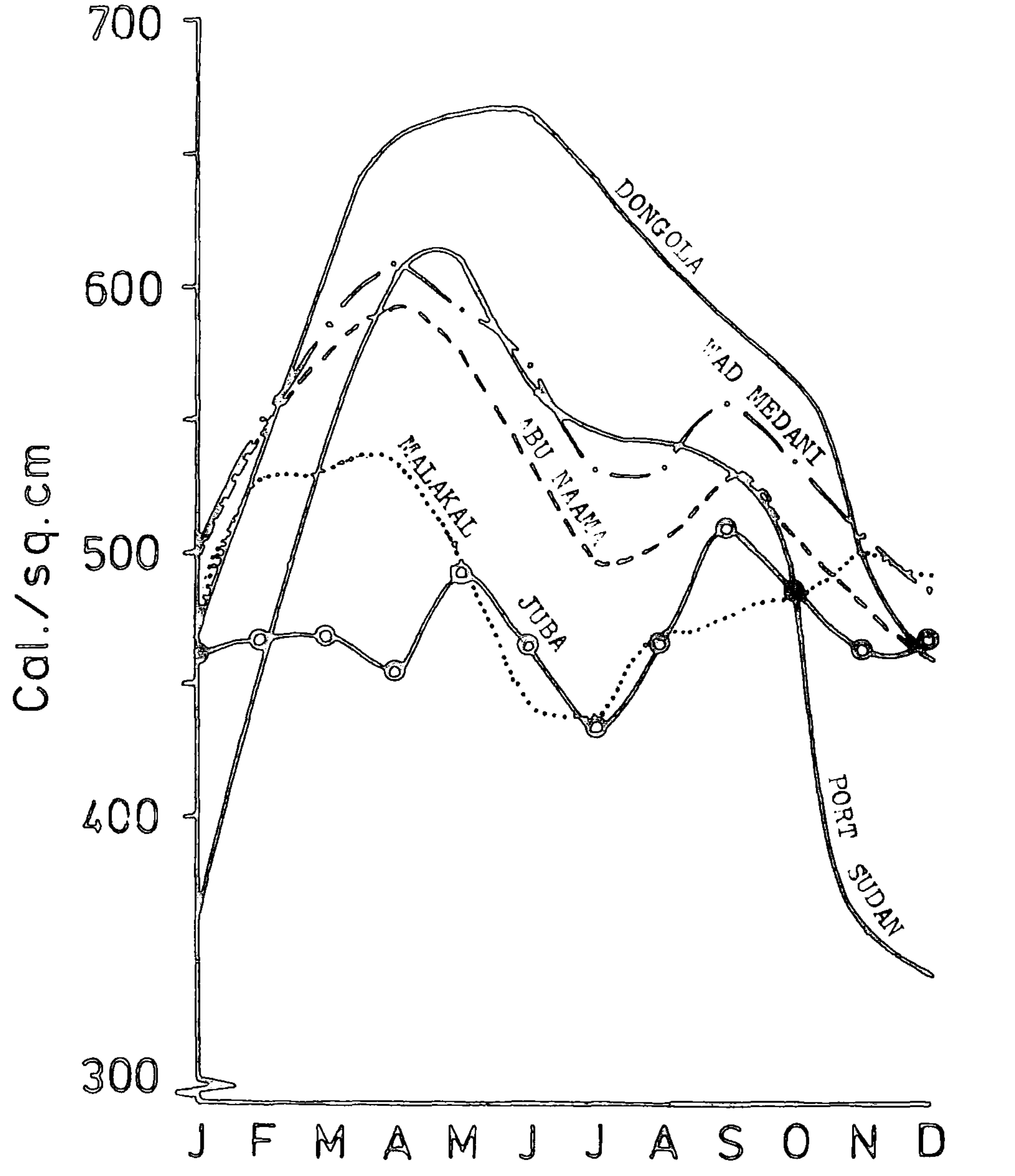


Fig.3.3 RADIATION DISTRIBUTION AT 6 STATIONS



north and north east. The extreme south has its highest record during September recorded at Juba (508 cal/cm^2).

The range of radiation through the year is more remarkable in the north because of the relatively large magnitude of the seasonal change of the angle and duration of the sun's rays striking the surface. The highest range is in northern Sudan, at Dongola with a range of 204 cal/cm^2 (see Table 3.1). The range in the south, on the other hand, is kept small because of the longer duration of the rainy season with high cloud cover, together with the sun always being near to overhead. The Red Sea coast represented by Port Sudan showed the largest range of radiation, 267 cal./cm^2, with a single maximum in May. In this area the overhead sun in summer and the relatively dry offshore winds resulted in high radiation. During winter, because the sun is far in the southern hemisphere and the on-shore winds bringing considerable amounts of cloud and fog to the sky of Red Sea coast, a large reduction in the amount of radiation and hence a large range is shown.

The maximum radiation is shown as a single maximum in the extreme north and north east, while it is split into two maxima by a minimum during July and August. These two months are known to be the core of the rainy season, except in the northern areas where no effective rain occurs, and the considerable amount of clouds results in a comparative reduction of radiation.

Solar radiation provides the energy input to the climate system of which temperature is one part. The study of the characteristics and the different aspects of temperature in the Sudan will be discussed in the following section.

Table 3.1 Average Radiation at 9 Selected Stations (cal/cm^2)

Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	year	Location	Range		
															West	Centre	East
Port Sudan	358	451	543	604	609	567	545	539	533	485	386	342	497	N			267
Dongola	461	546	617	656	663	665	639	611	585	566	498	459	581			204	
Shambat	486	548	590	623	589	561	551	547	552	518	498	470	553			153	
Wad Medani	494	548	585	607	586	568	529	530	553	532	505	483	543			124	
El Fasher	476	547	590	618	602	575	543	542	555	547	516	487	550		142		
Abu Naama	489	544	573	592	575	534	494	502	527	504	489	459	524			133	
Ghazala Gzt	509	536	564	569	549	525	505	539	550	523	512	491	531		78		
Malakal	481	527	530	534	497	442	437	468	475	482	497	490	488			93	
Juba	461	466	462	454	492	464	432	463	508	484	462	464	467	S		76	

Highest values are underlined

Source : Sudan Meteorological Department (1960-1978) Monthly Climatological Reports.

3.3 Temperature

Temperature is measured in the 61 stations selected for the study. The length of these stations records varies within the period of the study (1941-1970). While at some stations, temperature is covered through the whole period, at some other stations there might be records for fewer than 10 years.

The Sudan, being a tropical and an almost landlocked country, always experiences high temperatures. Figures 3.4 and 3.5 and Table 3.3 show that except over the Imatong Mountains in the extreme south east, and the northern Marra Mountains (Fig. 2.1) with temperatures of 18°C and 23°C respectively, average annual temperatures nowhere in the Sudan drop below 24°C. The average may rise to 30°C or more at the hottest part of the country. Average annual temperatures generally increase from south to north but in a gradual way to reach their highest values at the north eastern part of the country with its core on latitude 18°N.

From Table 3.2 it can be observed that average annual temperature and latitude do not match neatly ($r = 0.39$). However, the latitudinal order of temperature is more clearly observed, in the seasons. In winter a fairly strong negative correlation ($r = 0.77$) between January maximum temperature and latitude, while a very strong positive correlation ($r = 0.9$) between July maximum temperature and latitude occurred.

Longitude shows positive correlation with average annual temperature ($r = 0.67$) and that suggests concentration of high temperatures in the eastern parts of the Sudan in comparison

Fig 3.4   MEAN ANNUAL TEMPERATURE (°C)

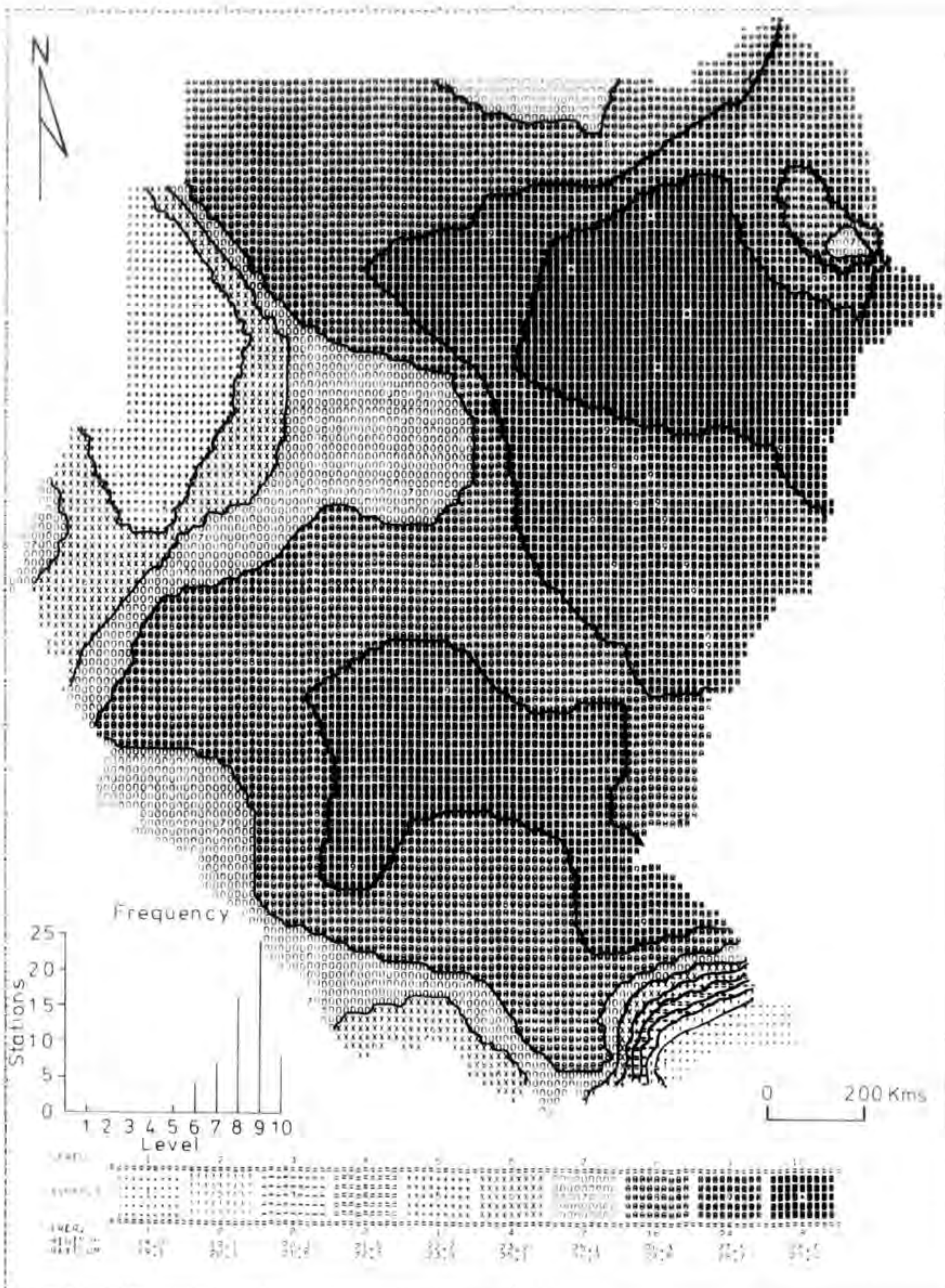


Fig.3.5 AVERAGE ANNUAL, ANNUAL MAXIMUM AND ANNUL MINIMUM TEMPERATURES (°C)

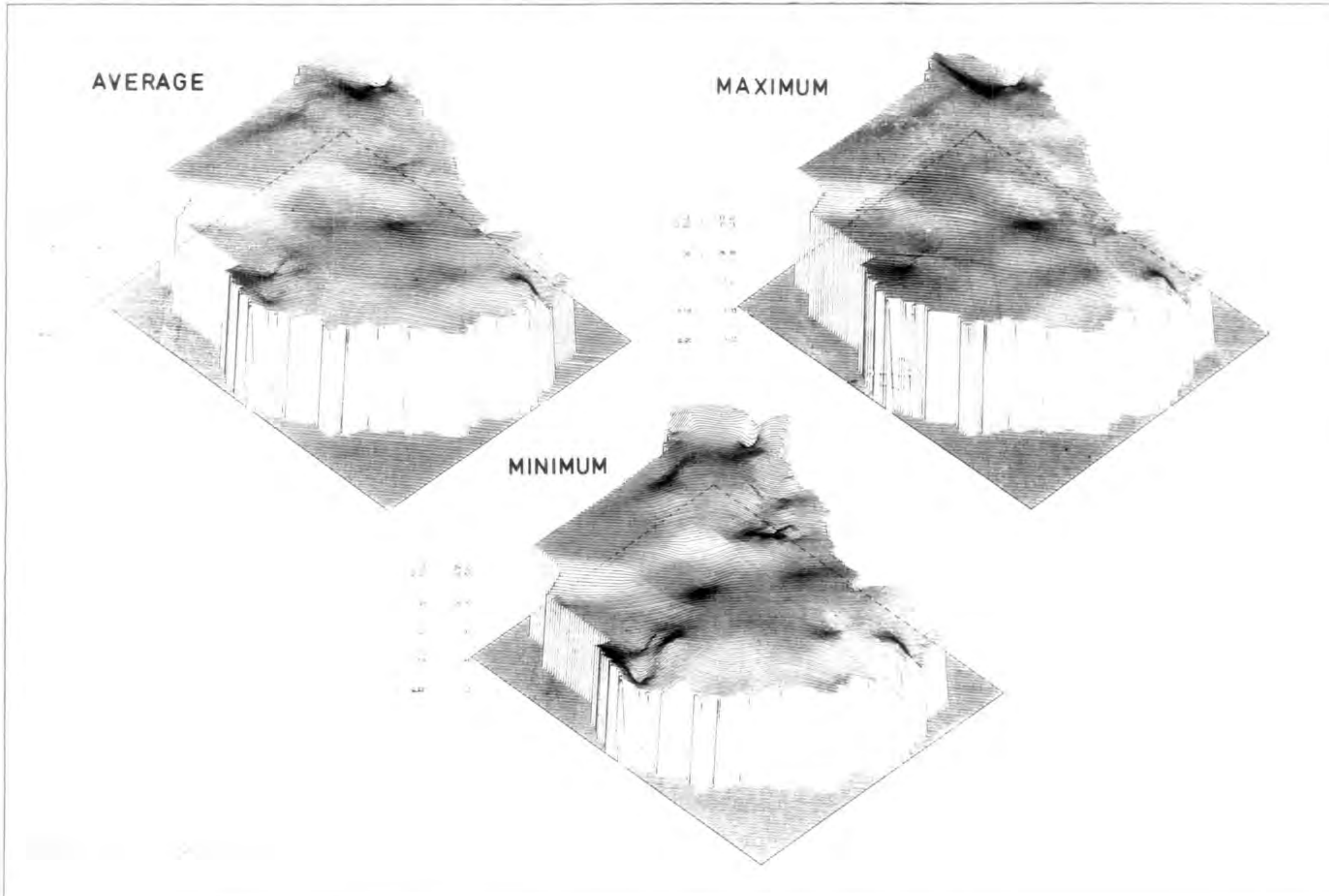


Table 3.2 Correlation Coefficients of Some Climatic and Location Variables at the 61 Stations of the Study

	Annual T	Jan. T	Jan MX	Jan MI	Jul. T	Jul.MX	Jul. MI	Jan-Jul RT	Ann.Rf	Jan.Rf	Jul.Rf	Ann.Rnd days
Annual T												
Jan. T	0.26											
Jan. MX.T.	0.09	0.81										
Jan. MI.T	0.34	0.81	0.51									
Jul. T.	0.60	-0.52	-0.69	-0.29								
Jul. MX.T.	0.52	-0.58	-0.73	-0.38	0.99							
Jul. MI.T	0.67	-0.40	-0.63	-0.14	0.97	0.93						
Jan-Jul.RT	0.14	-0.80	-0.86	-0.53	0.84	0.88	0.75					
Annual Rf	-0.46	0.64	-0.71	0.48	-0.90	-0.91	-0.86	-0.79				
Jan. Rf	-0.13	0.22	-0.05	0.45	-0.05	-0.07	-0.01	0.00	0.30			
Jul. Rf	-0.40	0.62	0.80	0.33	-0.92	-0.92	-0.88	-0.88	0.89	0.02		
Annual Rnd	-0.47	0.63	0.72	0.45	-0.91	-0.92	-0.86	-0.79	0.98	0.29	0.88	
Latitude	0.39	-0.66	-0.77	-0.50	0.89	0.91	0.83	0.81	-0.94	-0.23	-0.87	-0.27
Longitude	0.67	0.20	-0.07	0.40	0.48	0.45	0.51	0.20	-0.37	0.15	-0.45	0.07
Altitude	-0.75	-0.07	0.11	-0.25	-0.61	-0.56	-0.65	-0.29	0.37	-0.18	0.44	-0.14

T = Temperature ($^{\circ}C$)
MX = Maximum T. ($^{\circ}C$)
MI = Minimum T. ($^{\circ}C$)
RT = Range of T. ($^{\circ}C$)
Rf = Rainfall (mm)
Rnd = Raindays

N = 61

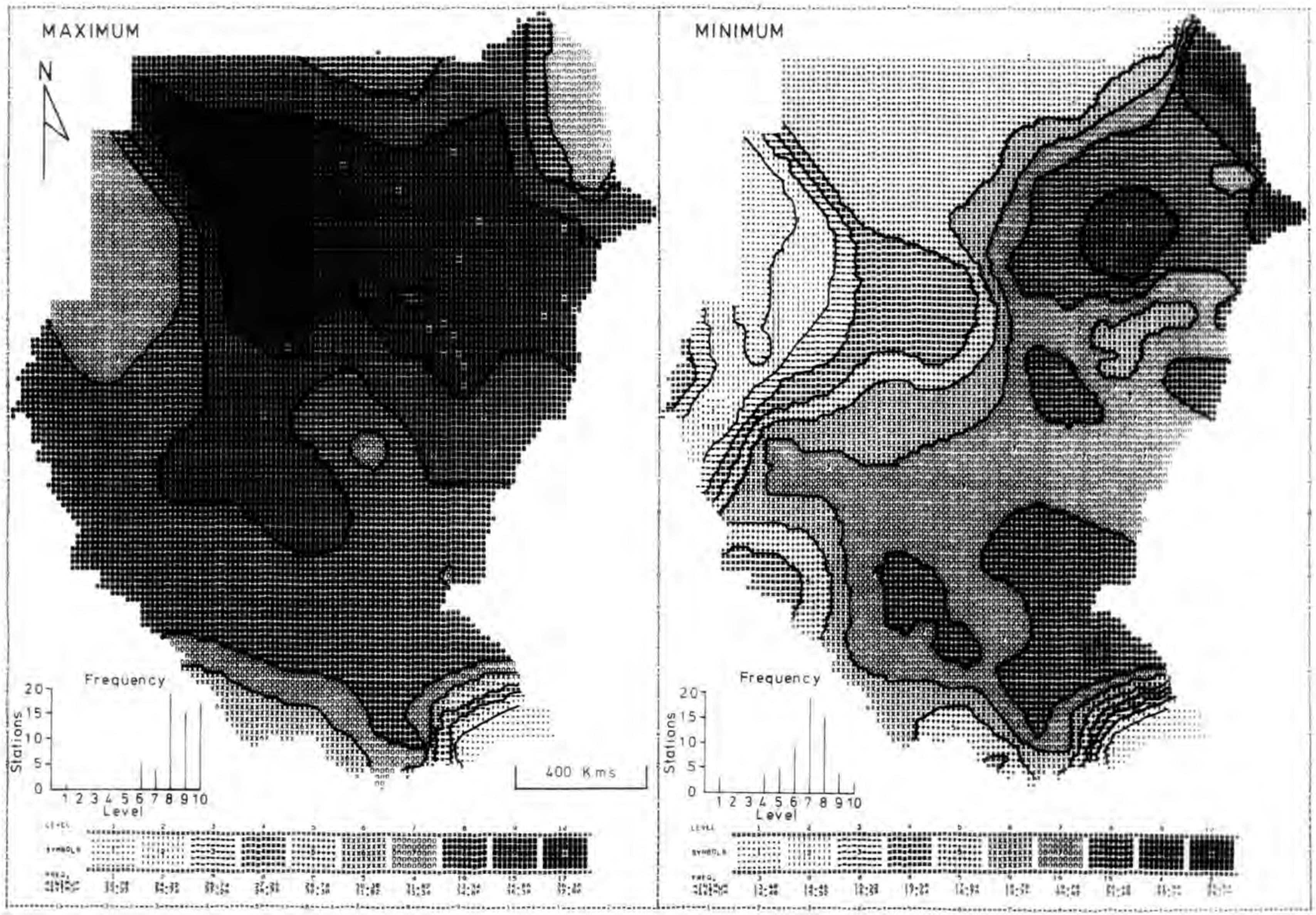
0.44 is significant at α = 0.001

with the western parts. This correlation is stronger than that obtained from latitude-average annual temperature relationships. This tendency can easily be picked out by eye when drawing a line to divide the country longitudinally into two parts. The stations in the western half have relatively lower temperatures than those of their same latitudes in the eastern half. However, the seasonal temperatures as exemplified by January and July show weaker relationships with longitude than they do with latitude.

Relief is another important factor affecting temperature. For the 61 stations considered in this study a fairly strong negative correlation (r = -0.75) exists between relief and average annual temperature. This relationship, though high, is kept down because of insignificant differences in relief at many of the stations. Stronger negative correlations are expected when comparing localities of significant relief differences. An example of this is found in Table A.2 (Appendix) where the highest station in each region has the lowest temperature amongst its neighbours. In general, the highest places in the Sudan, Nagishot, Kutum and Zalingei have the lowest temperature values.

Related to the average annual temperature are the average maximum and minimum temperatures shown in Figures 3.5 and 3.6. It is noted that, except at Nagishot in the extreme south east which has a maximum temperature value of 22.7 °C, the average maxima are everywhere above 31°C. The highest values were recorded in the north and the north east rising above 37 °C, the highest being at Halfa el Gedida

Fig. 3.6 ANNUAL MAXIMUM AND ANNUAL MINIMUM TEMPERATURES (°C)



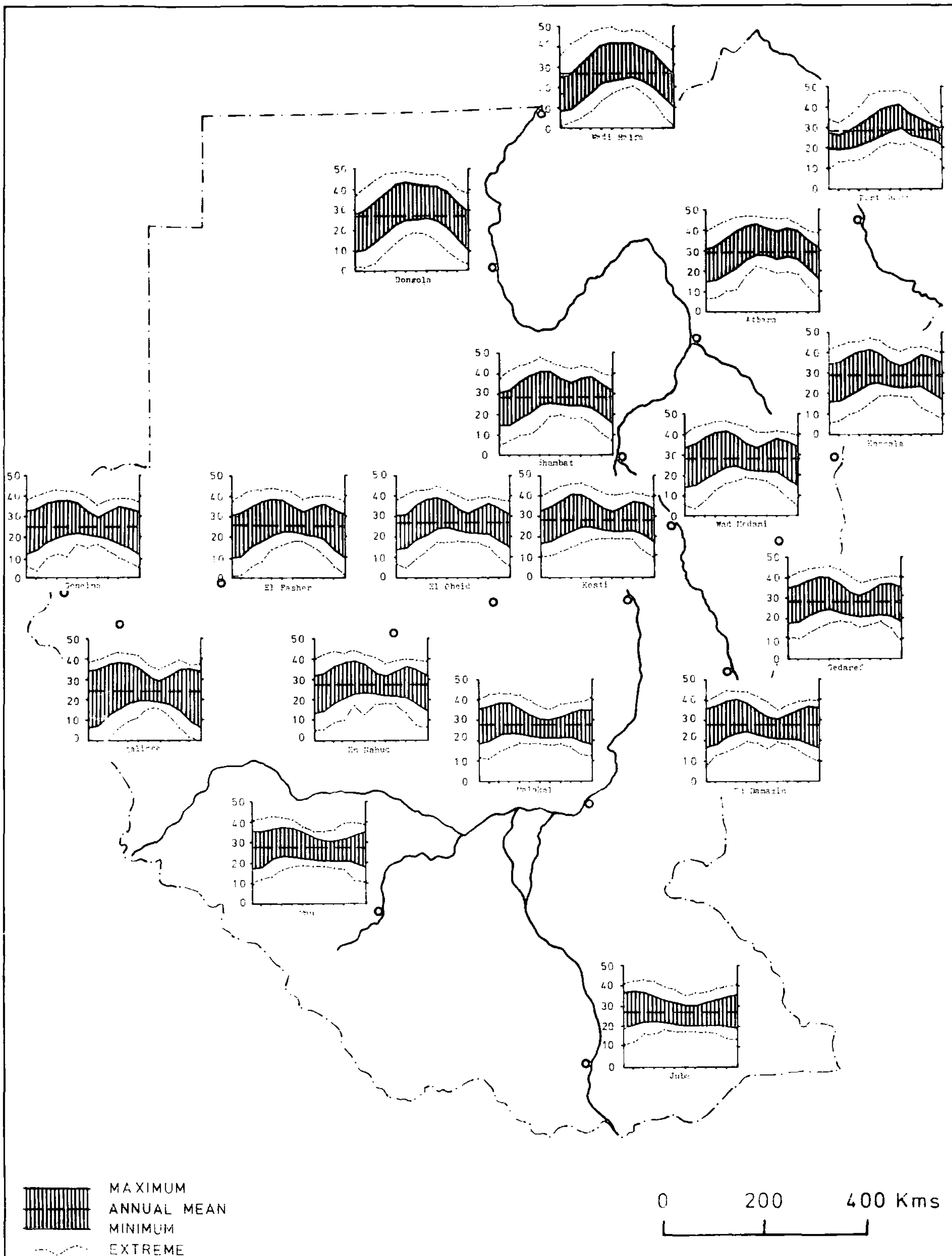
with 37.9°C. The highest values of the average minimum temperature are recorded at the Red Sea coast; highest at Tokar with a value of 24°C, and the lowest value is at Nagishot (13.4°C).

3.3.2 Monthly temperatures

The map in Figure 3.7 shows the average maximum, mean and minimum monthly temperatures at 18 selected stations. It can be observed that in the extreme north a single maximum and a single minimum are shown representing summer and winter temperatures respectively. The absence of effective rainfall in lowering summer temperature result in the observed pattern. Moving southward, clouds and rainfall are concentrated during the summer period, particularly during July and August. Temperatures rise sharply during the spring months but this rise abruptly ends with the advance of the rainy season. A secondary rise in temperature follows the termination of the rainy season resulting in a second maximum. This double maxima and minima is a feature described by Riehl (1979) as widely prominent in the monsoon regime. In the south at Juba the previously described pattern is not fulfilled and instead a dry season maximum and a rainy season minimum is observed.

Both maximum and minimum temperature ranges decrease southward. Maximum temperature range is 16.9°C and the minimum temperature range is 17.1°C at Wadi Halfa, 7.8°C and 10.3°C at Wad Medani and 6.8°and 3.5° at Juba (see Fig. 3.7). In central Sudan the relatively higher ranges of minimum temperatures to the west is at El Fasher, Geneina

Fig. 3.7 MEAN DAILY AND EXTREME TEMPERATURES (°C)

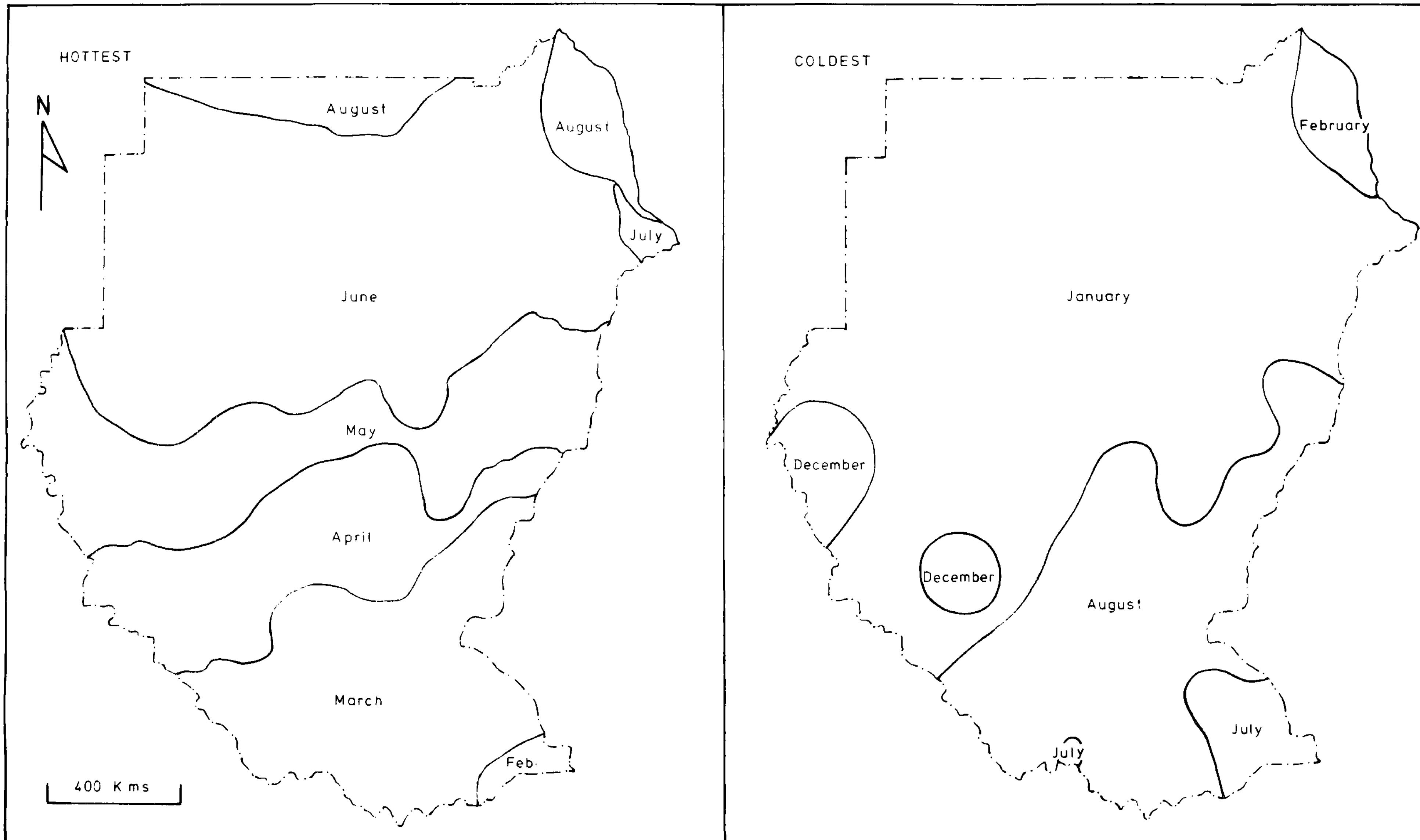


and Zalingei (above $10^{\circ}C$) are mainly a reflection of the relatively cooler winter nights compared with areas to the east. The higher ranges of maximum temperature (above $9^{\circ}C$) to the east in this central region as noticed at Gedaref and Ed Damazin may, on the other hand, be related to the more pronounced summer rain of those areas compared with the west.

Hottest and coldest month maps shown in Figure 3.8 present simple patterns over the Sudan. The hottest month's pattern can simply be related to the northward apparent movement of the sun, reflecting the position of the thermal low and backed by the Inter Tropical Convergence Zone. Lines demarcating the hottest months are observed to be situated further north by about 3° of latitude in the eastern than in the western parts of the country. February is the hottest month near the extreme south eastern border followed by March which is observed to be the hottest in areas up to latitude $11^{\circ}N$, in the east April is the hottest up to latitude $12^{\circ}N$, May up to $16^{\circ}N$ and June in areas north of that latitude. Near the northern borders, August appears as the hottest month and that seems to be because of the almost complete absence of rainfall. The Red Sea coast shows July and August as the hottest months.

The coldest months show a simpler pattern than the hottest months, and the Sudan can be divided into the north which is cooler in winter and the south which is cooler in summer. On the map a line running diagonally from latitude $15^{\circ}N$ in the east to latitude $7^{\circ}N$ in the west generally demarcates these two areas. January is the coldest month in the north, while August is the coldest in the south. In the northern region February is shown as the coldest over the northern Red

Fig. 3.8 HOTTEST AND COLDEST MONTHS OF THE YEAR



Sea coast while December is the coldest in small localities in the west. In the southern region, July appeared as the coldest month in the south eastern corner. The difference between the northern and southern regions is that the former is more susceptible to the cooler north easterly wind and cold fronts from the north in winter. As those winds and fronts penetrate deeper into the country they lose their cooling properties, depriving the south of having similar cool winters. Summer rain, heaviest in August, is the main cooling factor in the south.

For the study of temperature distribution in different seasons in the Sudan, 4 representative months are selected. These months are January, April, July and October and their temperature values and spatial distribution over the Sudan are shown in Table 3.3 and Figure 3.9. The distribution of average temperatures during the remaining months is found in Figure A.1. January's distribution of temperature generally follows a northeast southwest order with the lowest values recorded in the extreme north at Wadi Halfa with 16.5^{o} C. The highest value (above 28^{o}C) was recorded in the south east of the country. The reason for this pattern has been discussed in the previous paragraph. Generally, except in the north west and at Nagishot the average January temperature is always above 20^{o}C anywhere in the Sudan.

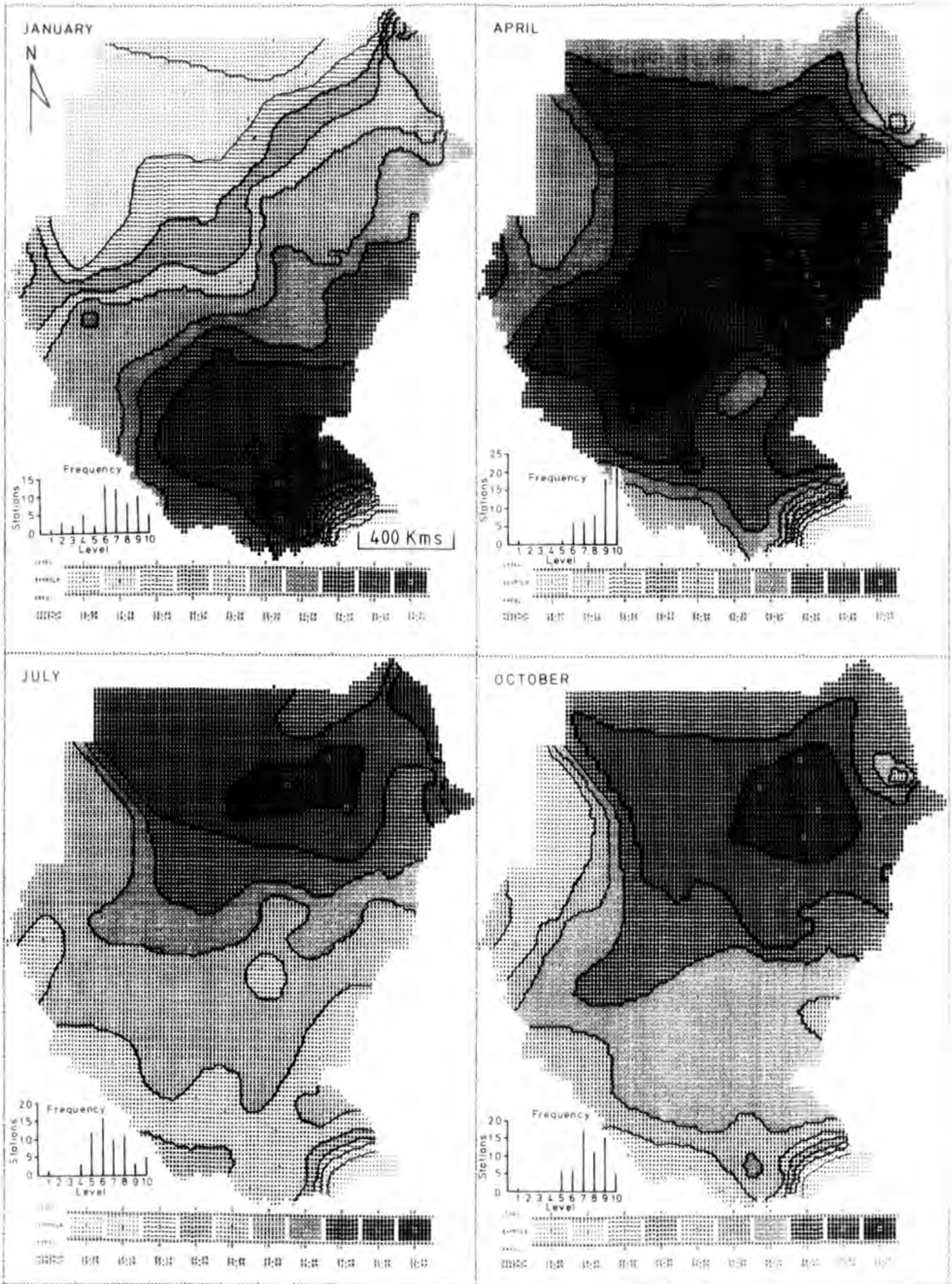
During April, the Inter Tropical Convergence Zone (I.T.C.Z.) lies south of latitude 11^{o}N marking the southern edge of the thermal low over northern Africa. Because of this and because of the dry conditions predominant over most of the Sudan, temperatures are observed to be always high (above

TABLE 3.3 ANNUAL AND SELECTED MONTHS' AVERAGE TEMPERATURES(°C)

		ANN	MAX	MIN	JAN	APR	JUL	OCT	RANGE JAN	RANGE JUL
1	WADI HALFA	26.2	34.6	17.7	16.5	27.0	32.9	28.7	16.6	17.1
2	STATION 6	26.4	34.9	18.1	18.0	27.0	29.9	28.8	15.6	15.2
3	PORT SUDAN	28.4	33.2	23.5	23.5	26.0	34.3	29.4	7.4	12.7
4	ABU HAMAD	29.3	37.1	21.4	21.0	29.5	34.4	31.5	15.7	14.6
5	DONGOLA	27.6	36.7	18.5	18.6	28.3	33.7	29.9	18.5	15.1
6	GEREIT	25.3	31.7	19.4	19.6	24.7	30.9	25.8	9.0	12.1
7	KARIMA	29.1	36.9	21.2	20.7	29.7	34.2	31.5	16.2	14.5
8	TOKAR	29.9	35.7	24.0	24.4	28.0	35.7	31.0	8.3	11.8
9	HAIYA	28.3	35.6	21.0	22.9	29.1	31.2	29.3	13.9	12.8
10	ATBARA	29.8	37.4	22.2	22.6	30.6	33.8	32.5	15.8	13.2
11	DERUDEIB	29.3	36.9	21.9	24.5	30.8	31.2	30.7	16.4	12.3
12	SHENDI	29.7	37.0	22.2	22.9	31.0	33.1	32.0	16.0	12.5
13	AROMA	29.0	37.5	20.4	24.1	31.0	30.1	30.9	19.6	12.5
14	SHAMBAT	28.6	36.3	20.9	22.7	30.0	31.4	30.9	16.1	12.5
15	KASSALA	29.2	37.3	21.1	25.2	31.4	29.5	31.1	18.3	12.2
16	HALFA EL GEDIDA	28.7	37.9	19.5	23.7	31.0	29.9	30.3	19.2	13.9
17	ET TURABI	28.4	36.8	19.8	22.8	30.0	30.4	30.1	19.7	13.2
18	ABU QUTA	28.4	36.8	19.9	23.0	31.0	30.4	30.1	19.0	12.6
19	QURASHI	28.3	36.9	19.6	23.3	30.4	30.2	30.1	20.1	13.0
20	SODIRI	26.0	36.5	17.3	20.2	29.3	30.5	29.6	18.3	11.2
21	WAD MEDANI	28.3	36.8	19.8	23.8	31.1	29.3	29.7	19.6	13.0
22	EL MANAQIL	28.3	36.5	20.0	23.1	31.4	29.3	29.9	18.8	12.7
23	KUTUM	23.3	32.2	14.4	18.0	26.0	26.5	24.5	21.4	12.8
24	GEDAREF	28.5	36.0	21.0	26.1	31.9	27.2	29.1	17.6	11.3
25	DUEIM	28.7	36.3	21.2	24.3	31.1	26.2	30.5	15.2	12.9
26	HAGABDALLA	27.8	36.6	18.9	23.4	30.3	28.8	29.2	21.7	12.8
27	EL FASHER	25.7	34.5	16.9	20.1	27.8	28.6	27.2	21.1	12.4
28	SENNAR	28.4	36.6	20.2	24.8	31.4	28.4	29.8	19.1	12.3
29	GENEINA	25.7	34.1	17.2	22.0	28.8	26.4	25.9	20.5	11.2
30	EL OBEID	27.0	34.3	19.6	22.1	29.7	28.2	28.8	17.1	10.5
31	KOSTI	28.7	36.0	21.4	24.8	31.5	29.0	30.1	16.2	11.3
32	SINGA	28.5	36.1	20.8	25.5	31.7	28.0	29.2	17.5	11.1
33	ZALINGEI	24.0	34.2	13.7	20.2	26.7	25.1	24.3	27.7	11.6
34	ABU NAAMA	28.1	36.3	19.9	25.2	31.8	27.1	28.2	20.0	10.8
35	EN NAHUD	27.2	34.9	19.5	22.7	29.9	28.0	28.7	19.3	10.4
36	NYALA	27.1	34.1	20.0	23.8	29.9	26.8	28.0	16.0	10.7
37	RASHAD	26.5	32.9	20.2	24.1	29.6	25.0	26.8	14.4	10.1
38	ROSEIRES	28.1	35.8	20.3	26.1	31.8	26.3	28.0	19.8	9.5
39	ED DAMAZIN	28.1	35.6	20.6	26.1	31.9	26.6	27.7	18.0	10.2
40	ER RENK	27.5	35.0	19.9	24.4	31.1	27.3	27.4	19.2	10.7
41	GHAZALA GZT.	27.5	35.1	19.8	23.3	30.6	27.5	28.3	18.3	10.0
42	KADUGLI	28.1	35.7	20.3	26.1	31.2	26.8	27.5	18.9	10.9
43	KURMUK	27.3	34.3	20.5	25.1	30.5	24.9	26.1	15.4	9.4
44	MALAKAL	27.9	34.5	21.2	26.9	27.4	26.2	27.6	17.0	9.1
45	AWEIL	27.5	34.1	20.8	26.0	30.8	26.3	27.1	17.9	9.6
46	NASIR	27.3	33.3	21.3	27.0	29.6	25.7	27.5	15.4	8.6
47	RAGA	25.8	33.7	17.7	23.2	28.4	25.4	26.2	23.3	10.2
48	AKOBO	28.1	34.5	21.7	28.5	30.1	25.9	27.6	16.7	9.8
49	WAU	27.7	34.4	20.9	26.8	30.3	26.2	27.4	18.0	9.5
50	TONJ	27.4	34.0	20.8	26.7	29.3	25.6	27.2	17.5	10.6
51	SHAMBE	26.8	33.4	20.2	26.0	28.2	26.0	26.8	15.6	11.5
52	PIBOR	27.9	34.1	22.0	28.5	29.6	26.2	27.0	16.3	9.9
53	ROMBEK	27.5	34.0	21.1	26.7	29.5	25.9	27.2	17.2	10.1
54	BOR	27.4	33.8	21.6	28.0	28.8	25.7	26.5	15.3	9.9
55	LI YUBU	25.3	31.1	19.4	24.7	26.0	23.8	24.7	14.0	9.1
56	MARIDI	24.7	31.3	18.1	25.1	25.5	23.2	24.2	18.2	11.4
57	JUBA	27.5	33.9	21.1	23.5	29.0	25.6	27.0	17.0	9.7
58	YAMBIO	25.0	31.3	18.7	25.7	26.9	23.9	24.7	16.8	10.2
59	TORIT	26.6	33.6	19.6	28.0	27.5	24.9	26.3	18.1	11.1
60	NAGISHOT	18.9	22.7	13.4	19.3	18.8	16.2	18.0	10.3	6.5
61	YEI	24.6	31.0	17.2	24.9	25.9	25.9	23.9	18.6	10.7

SOURCE: METEOROLOGICAL NORMALS AND ANNUAL REPORTS 1941-1970, SUDAN METEOROLOGICAL DEPARTMENT

Fig. 3.9 AVERAGE TEMPERATURE FOR 4 MONTHS (°C)



$28^{o}C$). The centre of the highest temperature during this month lies between latitude $11^{o}N$ and $14^{o}N$ with its core around Gedaref and Ed Damazin, both having values of $31.9^{o}C$. From that area temperature decreases outwards in all directions toward the boundaries. Another small area edged by Kadugli; Ghazala Gzt and Aweil, with values around $30^{o}C$, can be distinguished from areas with relatively lower temperatures around it. The higher places, previously mentioned, always reflected relatively lower temperatures and the lowest value ($18.8^{o}C$) is at Nagishot.

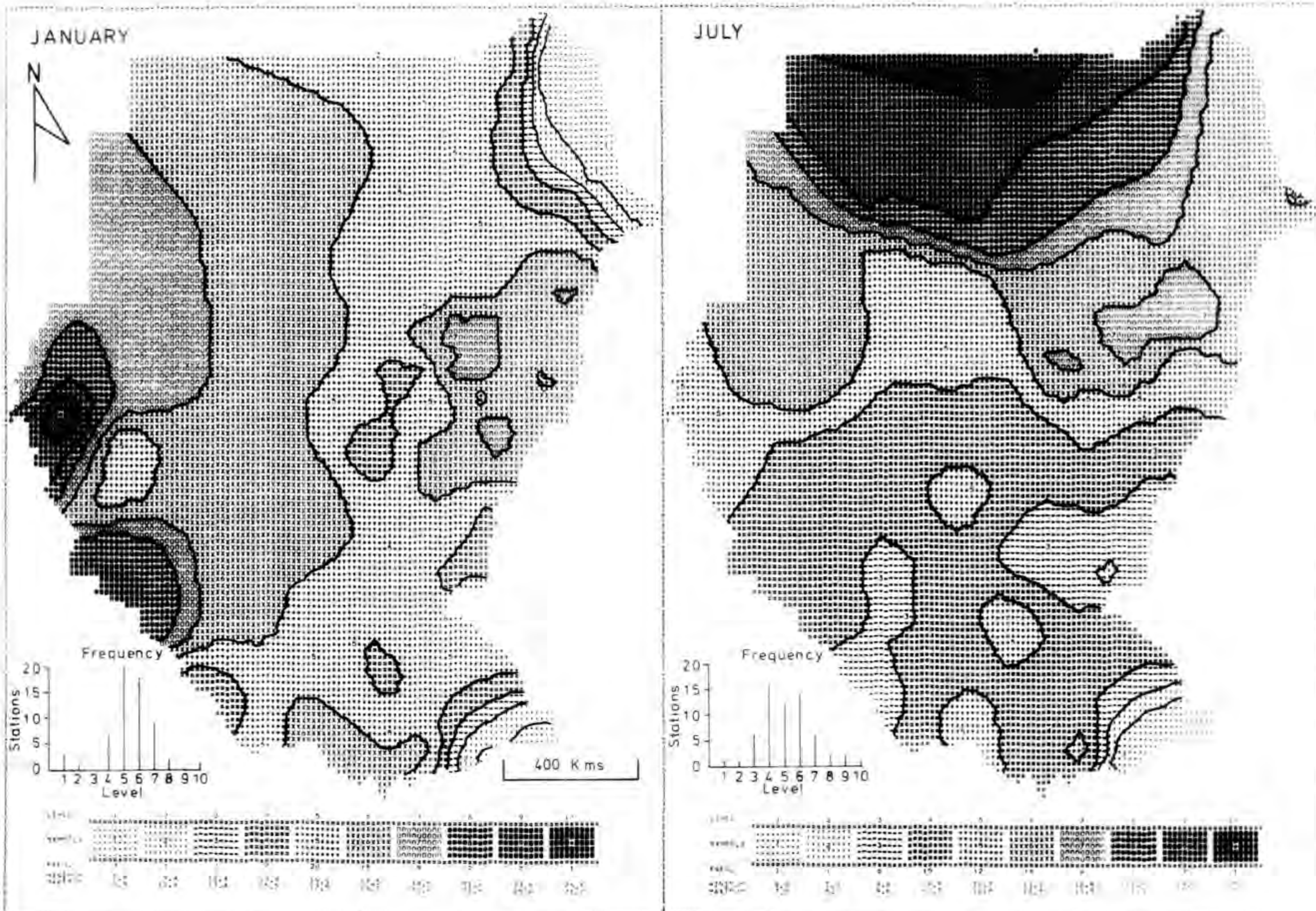
During July the solar equator is over the northern Sudan, associated with the advance of the moist and relatively cooler south westerly winds deep into the Sudan. The northern part of the country is still dominated by the dry northeasterly winds with the highest temperatures. This fact is reflected in a very strong negative relationship between temperature and rainfall in July with a correlation coefficient of -0.92. The drop in temperature in the rainy season, represented by July, as stated by Riehl (1979), ".. is not only because of heavy cloudiness and attendant high cloud albedo, but also and more important, because the solar energy absorbed in the ground is returned to the atmosphere through the powerful evaporation mechanism." The highest temperatures are recorded over the Red Sea coast, highest at Tokar with $35.7^{o}C$, followed by an area on the Nile in the north with Abu Hamad, Karima and Atbara having temperatures around $34^{o}C$. The lowest temperature is at Nagishot, $16.2^{o}C$. Apart from the latter area, temperatures over the country are above $23^{o}C$, and are above $28^{o}C$ north of latitude $15^{o}N$.

October shows the centre of highest temperature (around 32°C) in the same northern area of the Nile. Although the highest temperature at this place is not as high as in July, there is a general rise in temperature in the rest of the country. The area of temperatures above 28°C expands as far south as latitude 12°N, and, except at the Imatong mountains with 18°C, it is everywhere above 24.2°C. (see Fig. 3.9). The rise of temperature in this month is strongly related to the recession of moist conditions.

3.3.3 Diurnal and extreme ranges of temperature

The diurnal range of temperature during January is largest in the west, and decreases with increasing longitude in the Sudan. The difference between the average maximum and minimum is highest at Zalingei and lowest at Port Sudan, with ranges of 27.7°C and 7.4°C, respectively. In central Sudan the ranges decrease from west to east to about longitude 30°E and then increase. The contrast of diurnal range of temperature is not great between north and south in January. Wadi Halfa in the north and Juba in the south have ranges of 16.6° and 17.0° respectively. From this it can be seen that January is generally a month of hot days and cool nights in the Sudan. During July (Fig. 3.10), the highest difference between maximum and minimum temperature occurs in the extreme north where Wadi Halfa has a record of 17°C. The range decreases southward till at Juba it drops to only 9.7°C. The reasons for the low July temperatures described earlier in this chapter apply more significantly to maximum temperatures (see Fig. 3.7). In general, the low ranges

Fig. 3.10 DAILY RANGES OF TEMPERATURE IN JANUARY AND JULY



of this month indicate that July is a month of hot days and nights.

The highest ever recorded temperature during the period 1941-1970 at 18 selected stations are also shown in Figure 3.7. In many stations these records frequently rise above 40°C and reached 48.7°C during June 1963 at Dongola. The lowest temperatures recorded were in the extreme north and west during January; Wadi Halfa, Dongola and El Fasher approached 0°C. Zalingei is the only station where temperature falls to -1°C.

3.4 Pressure and wind systems

3.4.1 Characteristics

January and July are selected here to show the general pressure and wind systems in the dry winter and the wet summer seasons. Between these two seasons lie the transitional seasons associated with the advance and retreat of south westerly winds. Figures 3.11 and 3.12 show the general distribution of pressure and wind at the surface and the 300 mb levels during winter and summer, while Figure 3.13 shows wind direction during 4 seasons.

During winter the atmospheric circulations over the Sudan are characterised by the dominance of the Saharan High, which is an extension of the Azores anticyclone, together with the strengthening of the Arabian High. As those highs converge toward each other over the Red Sea area a trough is formed which is liable to displacement to the east or west according to intensification of either of the highs

Fig. 3.11 PRESSURE AND WINDS (after Bhalotra,1963)

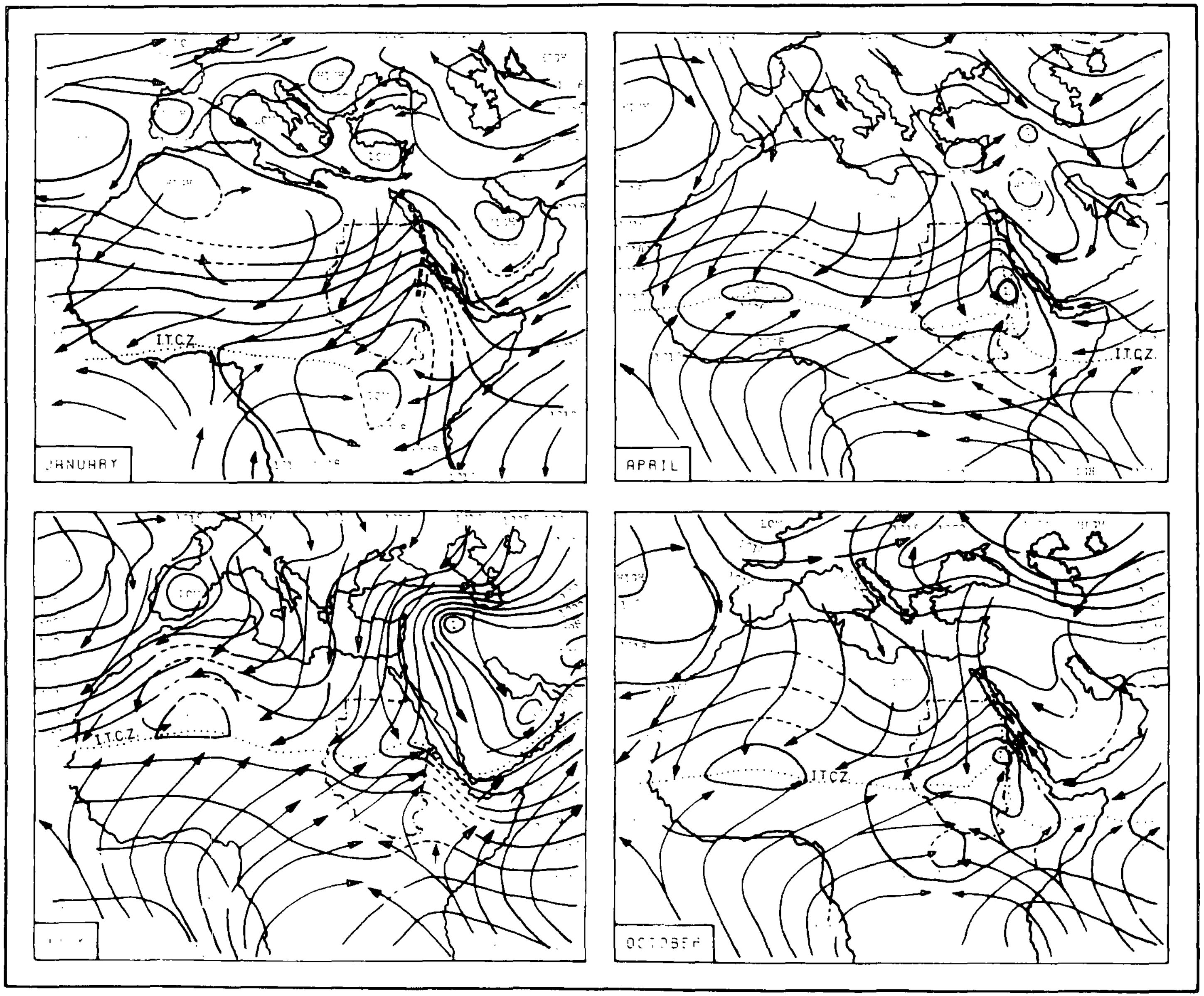


Fig.3.12 PRESSURE AND WINDS AT 300MB IN JANUARY AND JULY (after Thompson,1965)

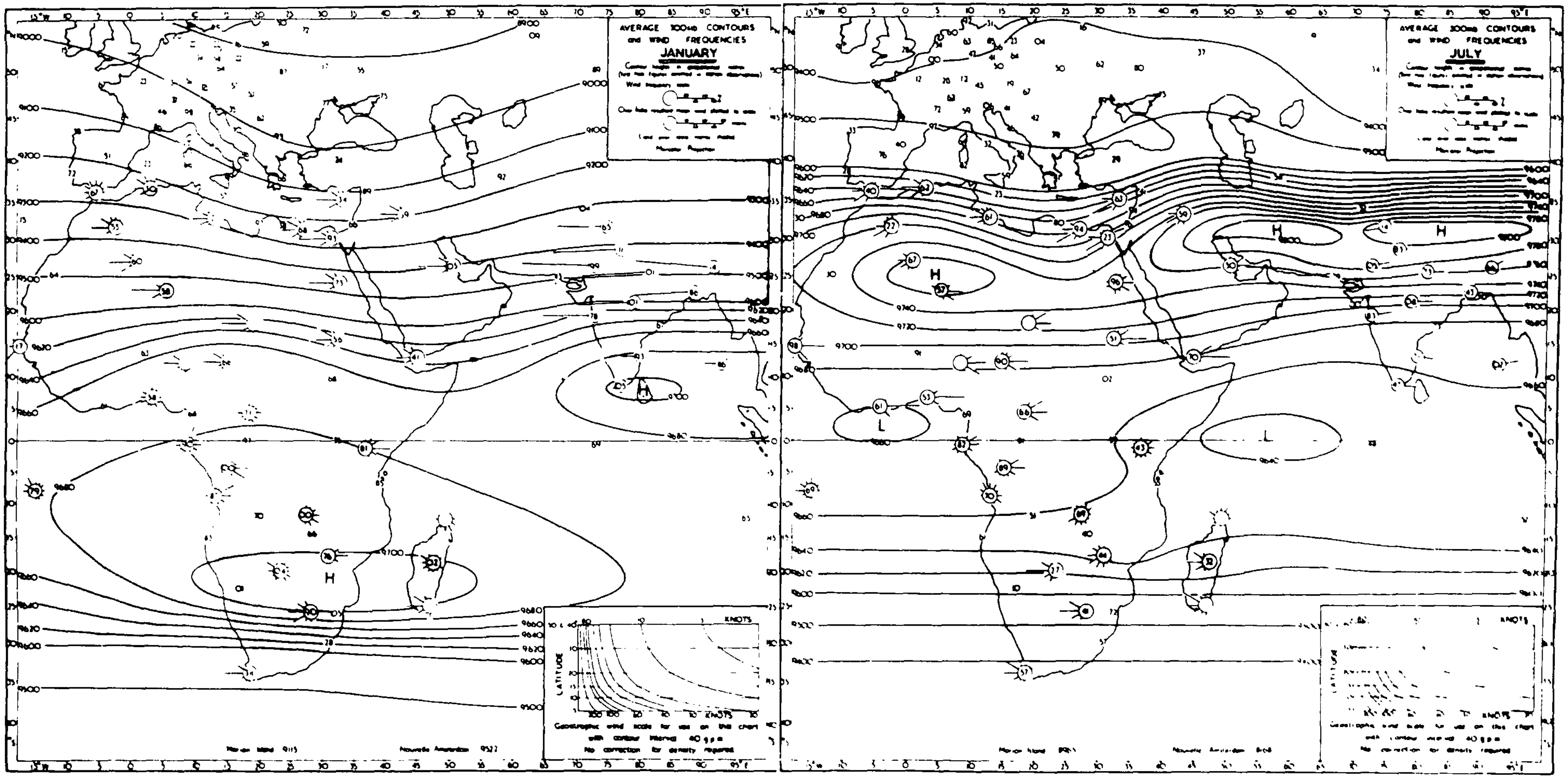
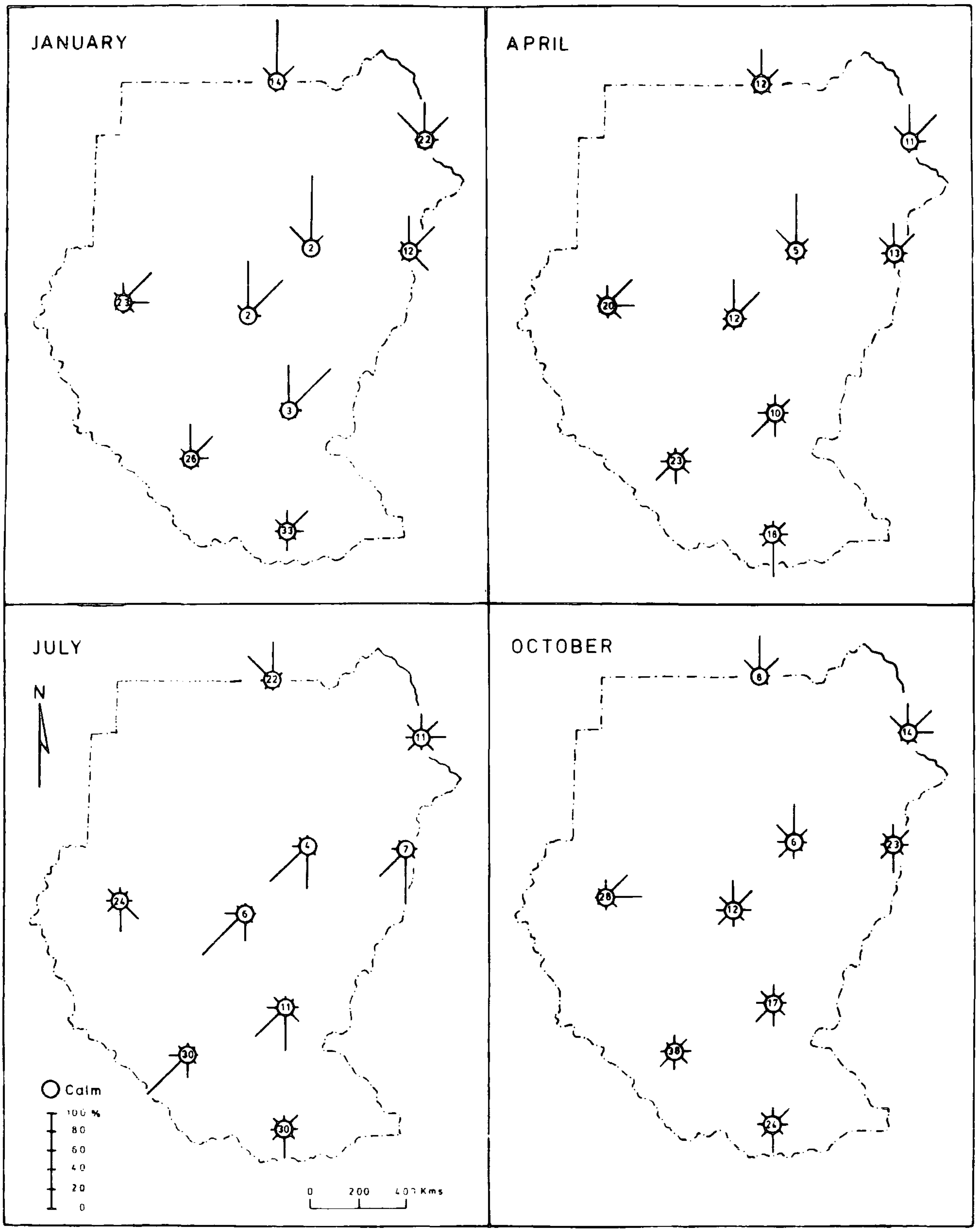


Fig. 3.13 THE FREQUENCY OF WINDS AT NINE STATIONS



(Kendrew, 1953; Bhalotra, 1963). The high pressure which forms over central Asia extends when intensified to include the Balkan area. It is noted that during this season two low pressure zones exist, one is over the Mediterranean Sea and the other, which is very weak, over Central Africa. The anticyclone that is associated with the Sahara High controls the circulations over north and north eastern Sudan. Because of the subsiding nature of the air it gets warmer and very dry and results in clear skies. The occasional intensification of pressure over Central Asia and the Balkans results in cold air invading north Sudan, while the frontal activity over the Mediterranean depression causes very cold air to flow from Eurasia over north Africa and the Sudan. The average wind directions over the Sudan during January are mainly from the north at the surface level, and from the west at the 300 mb level.

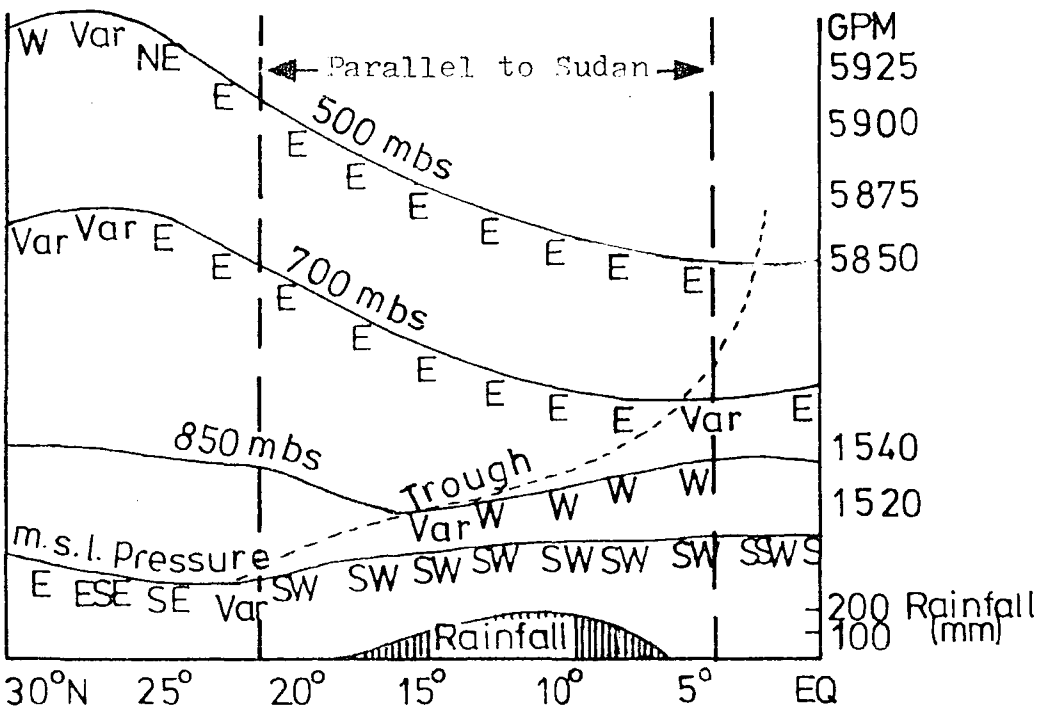
The picture gradually changes with the advance of the seasons. The Saharan high shrinks to a cell to its north west and the Arabian High becomes weaker, until in summer the sea level pressure characteristics are totally reversed to those of winter. In July a deep low prevails over Iraq and Arabia and extends over north west India and originates winds that affect east Egypt and north east Sudan. A shallow thermal low is positioned over the southern Sahara, but is replaced by the deep Saharan anticyclone at a height of 3 km. The latter continues to be effective over northwestern Sudan and west Egypt (Bhalotra, 1963). In this season an equatorial trough, which in fact deviates from the equator according to season, extends in the northern hemisphere, tilting southward with height (Kenworthy, 1975). This trough draws the south easterly trade winds from the southern hemisphere as they flow out from the two high pressure zones of the South Atlantic and south Indian Oceans to become south westerly winds. In July these winds are dominant in most of the Sudan except the extreme north and north east where the north easterlies still blow. The area of contact between those winds is known as the Inter Tropical Convergence Zone (I.T.C.Z.).

3.4.2 The Inter Tropical Convergence Zone

Within the northern hemisphere tropical area, the zone of meeting of two air masses marked by the surface south westerly winds and the north easterly trade winds has been recognized for a long time. The study of this phenomenon has undergone different stages of development through time. The pre-Second World War meteorologists came to believe in an equatorial or intertropical front. But since the frontal dynamics are not applicable (Palmer, 1951) because of little air mass contrast (Thompson, 1965; Barrett, 1974; Nieuwolt, 1977) the idea of the front gave way. A zone of convergence rather than frontal lines, named as the Inter Tropical Convergence Zone (I.T.C.Z.) has been adopted. However, although this terminology is broadly accepted, it is believed that such a description is not quite satisfactory. Riehl believes that there is a degree of inaccuracy when terming this phenomenon as a convergence zone because, he says, "convergence is only intermittent." Palmer (1951) taking the argument even further assumes that the I.T.C.Z. is only a statistical fact different from the day-to-day weather situation. Barrett (1974) opposed Palmer's idea and advocated that evidence from satellites was found. Barrett believes that the observed increased complexity of the I.T.C.Z. due to the satellite era necessitates new terms to differentiate its most meteorologically significant aspects. He listed the most acceptable new terms such as Inter Tropical Confluence (I.T.C.), the Inter Tropical Vorticity Zone (I.T.V.Z.), the Inter Tropical Cloud Band (I.T.C.B.) and what he suggested as the Equatorial Axis of Instability which is defined as the geometric centre of the I.T.C.B. However, in this study for practical purposes the general term I.T.C.Z. together with I.T.C.B. are used.

The atmospheric structure in relation to the I.T.C.Z. is believed to present the key to understanding the climatic characteristics of the southern Sahara and Sudan. The I.T.C.Z. as mentioned earlier marks the contact between the hot dry air from the north and the cooler, moist maritime air from the south. Because the northerly air is warmer and of less density than the southerly air, their meeting zone slopes upward and inclines sharply southward (Solot, 1950; Trewartha, 1962; Thompson, 1965). Figure 3.14 shows a cross-section in the lower atmosphere along the Greenwich Meridian between the equator and latitude 30°N during July. Thompson (1965) believes that this cross-section is reasonably representative of conditions over most of Africa. The boundary parallels of the Sudan are indicated by broken lines on the cross-section. It is stated by Thompson that the surface equatorial trough is near latitude 20°N and extends eastward to Arabia and India, near about latitude 15°N at 850 mb and between the equator and latitude 5°N at 700 mb and 500 mb. It can

Fig.3.14 A cross-section along the Greenwich meridian during July showing the relationship between the equatorial trough in the lower troposphere and the mean rainfall (after Thompson.1965)



also be observed from this Figure (3.14) as well as from Figure 3.12 that at the 300 mb level a complete reverse of winds from westerlies in January to easterlies in July takes place. The inclination southwards of the I.T.C.Z. with increase of height in the atmosphere has an important impact on weather in general, and on rainfall in particular. As Figure 3.14 shows, rainfall increases southward away from the surface position of the I.T.C.Z. This impact will be discussed later (see section 3.7.1).

The I.T.C.Z. advances in the Sudan from early March until it reaches its furthest northern position at latitude 20^{o}N on the eastern part of the country by August. It begins to retreat rapidly from September, to withdraw from the Sudan by the end of November. It is more clearly identified, and it occupies a more northerly position, in the eastern than in the western parts of the Sudan : in summer its average position is on latitude 18^{o}N in the east and latitude 15^{o}N in the west (Bhalotra, 1963).

3.4.3 Dust-storms

Dust-storms are a remarkable weather phenomenon in the Sudan. They are characterized by an increase of wind force to a degree that they can blow dust or sand and result in poor visibility. Dust-storms can generally be divided into 3 categories :

1. Haboobs,
2. Dust-storms of the monsoon winds, and
3. Dust-storms of the northerly winds.

Haboob

The word 'Haboob', an Arabic word means blowing of wind, is restricted in use by meteorologists to the summer dust-storms that are associated with thunderstorms or cumulonimbus clouds, to differentiate it from the general vague use of the word. In the first stage of the thunderstorm, or cumulus formation, ascending air, present throughout the cell, encounters descending air around the cell resulting in horizontal convergence at the surface. This upward current is diverted to a downward one and the rainfall begins to fall as the cell develops. In the mature stage the system witnesses two currents : an ascending one against a descending rainy current, each occupying a side of the cloud, and a divergence at the surface in the rain area is noticed. It is at the mature stage when the Haboob started to form. Here rain falls but evaporates before reaching the ground. At this stage the descending current, being cooled by the evaporating rain, reaches the ground and spreads outwards undercutting the dusty air ahead. Due to its passing over hot ground it becomes very unstable and results in more dust carried in rising currents, and the haboob sometimes appears as a wall of dust (Freeman,1952).

Haboobs, though intense, are of a localized nature with widths between 16 and 80 km. and of short duration. They are accompanied by low visibility and thunderstorms even if no rainfall occurs. The occurrence of the Haboob activities, as related to the advancing rainy season, has its main distribution between Kassala and Khartoum with a great concentration over the latter. However, the severity of the Haboob decreases later in the rainy season over central Sudan because of the grass cover and the soil being too compact to be easily blown off. The northern drier part still witnesses comparatively profound haboobs (Sutton, 1931; Farquharson, 1937; Ireland, 1948; Freeman, 1952).

Duststorms of the monsoon winds

These duststorms, like the Haboobs, are a summer type. Their occurrence is related to the rapid advance of the I.T.C.Z. northward and the steepening of the pressure gradient accentuating the southwesterly winds (monsoons) to blow sands and dust off the dry loose soil. These duststorms are widespread and of longer duration compared with the haboobs. They are severe in the north and especially on the desert, and their frequency decreases with the advance of the rainy season for the same reasons mentioned in the case of the Haboobs. The onset of the duststorm is fairly gradual with a maximum frequency in the early morning (El Fandy, 1949; Freeman, 1952).

Duststorms of the northerly winds

This type of duststorms, as described by Sutton (1931) and Freeman (1952), is related to the development of the Mediterranean depression during winter where its associated cold front results in a rapid spread of cold air southward over Egypt and Sudan. The steepening of the pressure gradient strengthens the speed of the wind and hence causes dust blowing. The duststorms of this type in the Sudan are conventionally believed to follow the rear of the front. However, Delsi (1967), although accepting that this theory works satisfactorily during the early part of the dry season (winter), argues that later in the season (April and May) duststorms may exist ahead of the cold front by 96 to 320 kms. as they exist to its rear. He relates these pre-frontal duststorms to the development of the "Sudan Thermal Low", which is the predominant feature at this time, and the Libyan high pressure. A steep pressure gradient occurs ahead of the front as the Libyan High moves eastward shortening the distance from the Thermal Low. Delsi suggests that the most reliable way to note the passage of the front is by observing a drop in temperature compared with temperature 24 hrs earlier at the same station than by duststorms. This type of duststorm generally carries extensive dusts and may reduce visibility to less than 3.2 kms. However, these duststorms rarely occur south of latitude 12^{o} because of vegetation cover and lack of loose dust.

3.5 Cloud cover and sunshine

3.5.1 Cloud cover

The cloudiest skies in Africa, north of the equator, are observed to the south of the I.T.C.Z. in the sector occupied by the moist southerly winds where convective activity is prevalent (Trewartha, 1962). This area, as mentioned before, is known as Inter Tropical Cloud Band (I.T.C.B.). Together with other factors, discussed later, atthe I.T.C.Z. any developing low clouds will be dessicated by the dry Saharan air (Trewartha, 1962).

Cloud cover in the Sudan is estimated in oktas of the sky shared by all types of clouds. Ten stations are selected here and the data related to them are shown in Table 3.4, out of which 6 stations are chosen for the graphical presentation in Figure 3.15. The average annual cloud cover shows small values in the north increasing southwards in the country where the amount at Juba is more than 5 times that over Dongola (5.8 compared with 1.0 oktas). The densities and the types of clouds are also spatially different and the rain producing types are generally more frequent to the south of the country due to the advance and the duration of the moist southwesterly winds in relation to the movement of the I.T.C.Z.

The monthly average cloudiness shows that everywhere, except at Port Sudan being cloudiest in winter, July and August are the cloudiest months of the year. At that time most of the Sudan lies within the reach of I.T.C.B. In these months the amounts of cloud cover increase southward from less than 2 oktas over Dongola in the north to 6.5 oktas over Malakal in the south and then slightly drop over Juba (6.3 oktas). During the dry season December marks the smallest amount of cloud cover in most of the stations. The value of cloud cover does not rise above 3.0 oktas except at the Red Sea and in the extreme south. December and January are the cloudiest months of the year at Port Sudan with average values of about 4.0 oktas. South of latitude 10^{o}N medium clouds may occasionally occur due to thundery activity over the Ethiopian plateau (Griffiths, 1972) or due to unusual penetration of the I.T.C.Z. (Bhalotra,1963).

Table 3.4 Amount of Cloud Cover (oktas) at 10 Stations at 2 p.m. Z

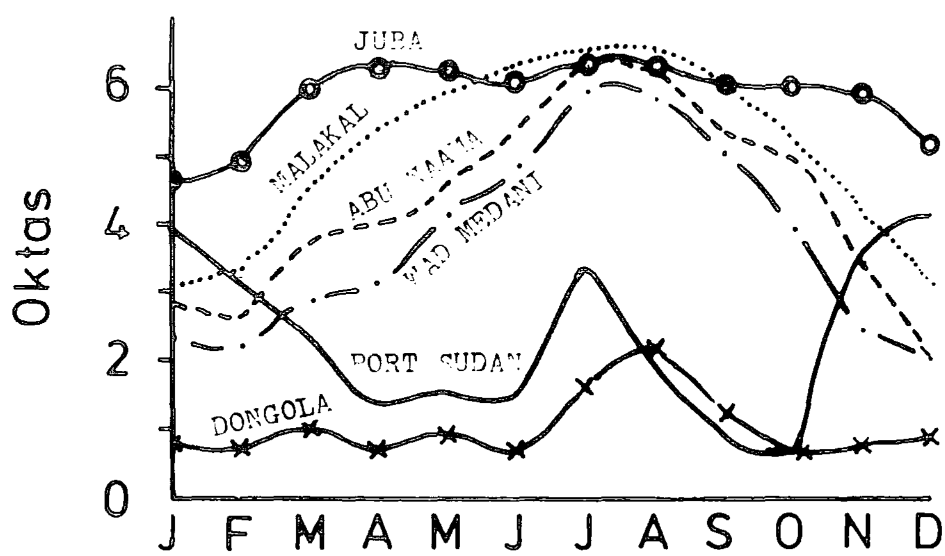
Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Location
Port Sudan	3.9	3.1	2.3	1.3	1.5	1.5	3.3	2.9	1.9	1.7	3.6	4.1	2.6	NE
Dongola	0.8	0.7	1.0	0.7	0.9	0.7	1.6	2.1	1.2	0.6	0.7	0.8	1.0	N
Shambat	2.2	1.5	2.1	1.8	2.0	2.9	4.5	4.4	3.8	2.7	1.7	1.6	2.6	
Kassala	2.3	1.8	2.3	2.4	3.0	3.8	5.4	5.3	4.0	3.0	2.1	1.9	3.3	
Wad Medani	2.3	2.0	2.9	3.1	4.1	4.8	5.9	5.8	5.0	3.9	2.4	2.1	3.7	
El Fasher	2.7	2.4	3.5	3.3	3.8	4.3	5.6	5.9	5.0	3.3	2.8	2.5	3.8	
Abu Naama	2.8	2.6	3.7	4.0	4.6	5.4	6.3	6.2	5.3	4.9	3.4	2.0	4.3	
Ghazala Gzt	4.0	3.6	4.1	4.7	4.6	5.1	5.6	5.7	5.1	4.3	3.3	2.9	4.4	
Malakal	3.1	3.3	4.5	5.4	4.9	6.3	6.5	6.5	6.0	5.2	4.1	3.1	5.0	
Juba	4.6	4.9	6.0	6.3	6.2	6.1	6.3	6.3	6.0	6.0	5.9	5.1	5.8	S

Z = GMT + 2 hrs.
highest values are underlined

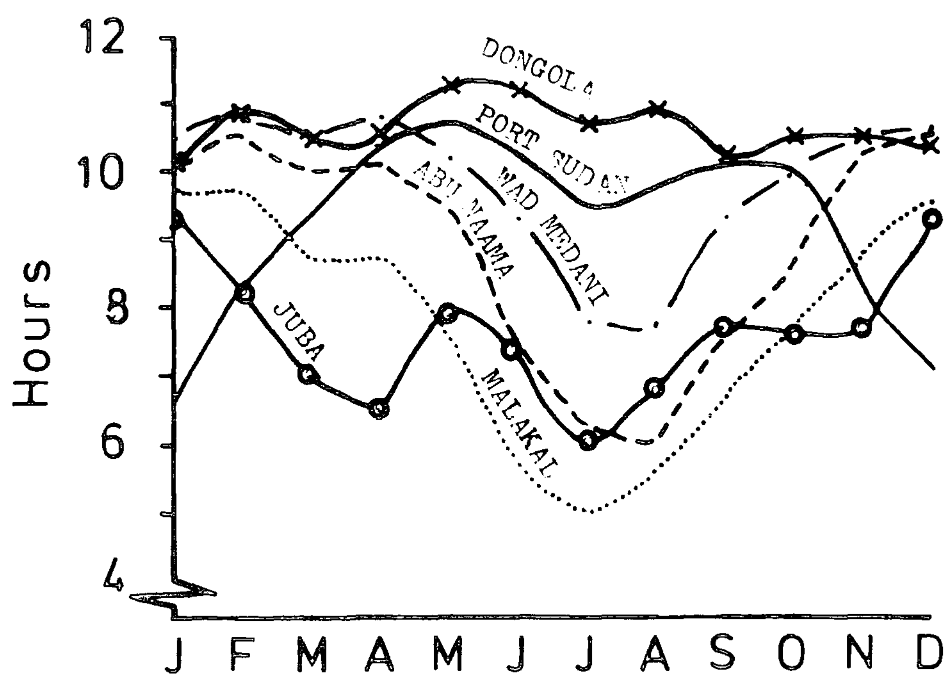
Source : 1941-1970 Climatic Normals, Meteorological Department, Sudan.

Fig.3.15 CLOUD COVER AND SUNSHINE AT 2p.m. Z FOR 6 STATIONS

CLOUD COVER



SUNSHINE



Z = G.M.T. + 2hrs

3.5.2 Sunshine

Sunshine is measured at a few stations in the Sudan by Campbell-Stokes recorders and readings are given as hours of bright sunshine. The data are also expressed as a percentage of possible sunshine of an assumed clear atmosphere. Table 3.5 shows the mean monthly and yearly sunshine at 10 stations in the country with varying lengths of records during the period 1950-1970. Sunshine percentages of possible for January, April, July and October are shown in Figure 3.16.

Sunshine hours, being at least 62% of the possible are very great over the Sudan, and a general negative relationship between sunshine and cloud cover can easily be observed from Figure 3.15. The average sunshine values are highest at Dongola in the north with 10.6 hrs. from where the values continuously decrease to reach the lowest level of bright sunshine (7.6 hrs.) in the south at Juba. The highest values occur during May in the extreme north and north east, during April in the north and during winter in the south. July and August show the shortest duration of daily sunshine. This can be related to the situation of cloud cover previously discussed. The hours of sunshine in August are 6.8 hrs. in the extreme south while they are 9.8 hrs. out of the cloud band in the north at Dongola.

Figure 3.16 shows the distribution of sunshine as a percent of the possible over 25 stations. It can generally be seen that the highest percentage of sunshine during the selected four months (January, April, July, October) is shown in the north. This zone extends over large areas in central

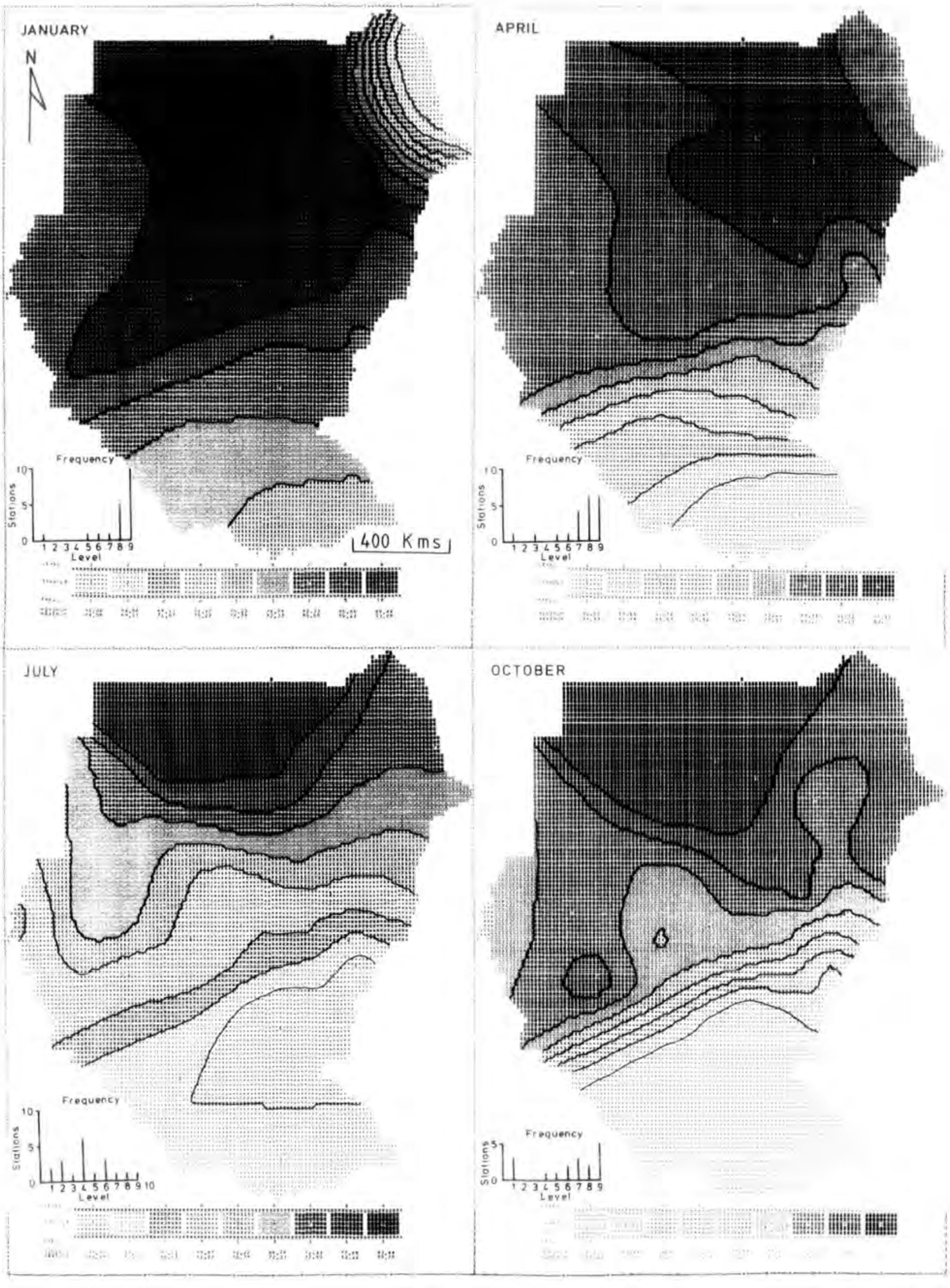
Table 3.5 Mean duration of bright sunshine in hrs ($\bar{x}$) and as percentage of possible

Station		Jan.	Feb.	Mar.	Apr.	May	June	Jul	Aug	Sep	Oct	No.	Dec.	Location	Year West	Year Centre	Year East
Port Sudan	$\bar{x}$	6.6	8.4	9.4	10.4	10.8	10.3	9.5	9.8	10.1	10.0	8.3	7.1	NE			9.2
	%	61	73	78	83	83	77	73	77	82	85	74	65				76
Dongola	$\bar{x}$	10.1	10.9	10.5	10.5	11.3	11.2	10.7	10.9	10.2	10.5	10.5	10.4	N		10.6	
	%	90	94	87	85	86	84	81	85	83	90	94	94			88	
Shambat	$\bar{x}$	10.5	10.7	10.4	10.7	10.1	9.9	8.7	8.7	9.3	10.2	10.7	10.5	↓		10.0	
	%	93	93	87	86	78	76	67	69	70	87	94	94			83	
Kassala	$\bar{x}$	10.0	10.5	10.3	10.7	10.6	10.0	8.4	8.3	9.9	10.3	10.1	9.9				9.9
	%	90	90	85	87	82	77	65	66	80	87	88	88				82
Wad Medani	$\bar{x}$	10.5	10.8	10.5	10.8	10.2	9.3	7.8	7.7	9.3	10.0	10.5	10.6			9.8	
	%	92	93	87	86	80	72	60	61	76	85	92	94			82	
El Fasher	$\bar{x}$	10.1	10.4	9.7	10.0	10.1	9.3	7.9	7.7	8.8	9.8	10.6	10.2		9.5		
	%	89	89	81	80	79	72	61	60	72	83	92	91		78		
Abu Naama	$\bar{x}$	10.1	10.5	10.0	10.1	9.4	7.5	6.3	6.1	7.6	8.7	10.2	10.5				
	%	89	88	83	83	74	57	49	49	62	73	88	90				
Ghazala Gzt	$\bar{x}$	10.3	10.6	9.8	9.9	9.9	9.1	7.4	6.2	8.5	10.1	10.5	10.6		9.2		
	%	91	91	81	80	78	70	58	50	70	85	92	94		78		
Malakal	$\bar{x}$	9.7	9.7	8.7	8.7	7.6	5.7	5.0	5.6	6.7	7.7	8.8	9.5			7.8	
	%	83	82	73	70	60	45	39	45	50	60	79	89			65	
Juba	$\bar{x}$	9.3	8.3	7.0	6.5	7.9	7.4	6.0	6.8	7.7	7.6	7.7	9.3	S		7.6	
	%	78	69	58	54	63	60	48	56	64	62	66	79			64	

Highest values are underlined

Source : 1941-1970 Climatic Normals, Meteorological Department, Sudan

Fig. 3.16   SUNSHINE FOR 4 MONTHS (% OF POSSIBLE)



Sudan during January, shrinks northward during April and July and enlarges again during October.

3.6 Relative Humidity

The relative humidity data used in this study are those calculated from the daily dry and wet-bulb temperature readings. At some stations prior to 1957 the relative humidity had been determined from mean monthly dry and wet-bulb temperatures.

Humidity in the Sudan grades generally from the south with the highest figures to the north and north west with the lowest, hence the south, can be described as relatively humid and the north as dry. There is also a relative concentration of higher humidity in a small area at the Red Sea (see Fig. 3.17 and Table 3.6). The morning humidity (8 a.m.Z = 6 G.M.T.) is highest at Pibor, Torit, Maridi and Yambio, with values ranging between 87% and 84%. The lowest morning value is at Abu Hamad (28%). The afternoon relative humidity, as expected, is always lower than that of the morning with the highest value dropping to 59% recorded at Port Sudan followed by Maridi and Yei with values of 56% and 54% respectively. The lowest afternoon relative humidity is at Abu Hamad and Karima recording values of 16% each. The evening situation of relative humidity is not considered here because it is not registered in most of the stations.

The afternoon relative humidity during the 4 representative months of the seasons is discussed here, and it can be seen from Figure 3.18 and Table 3.6 that January is a dry month, where relative humidity approaches 70% only at Port Sudan or the Red Sea coast. Nagishot has a value of 42%

Fig. 3.17 ANNUAL RELATIVE HUMIDITY

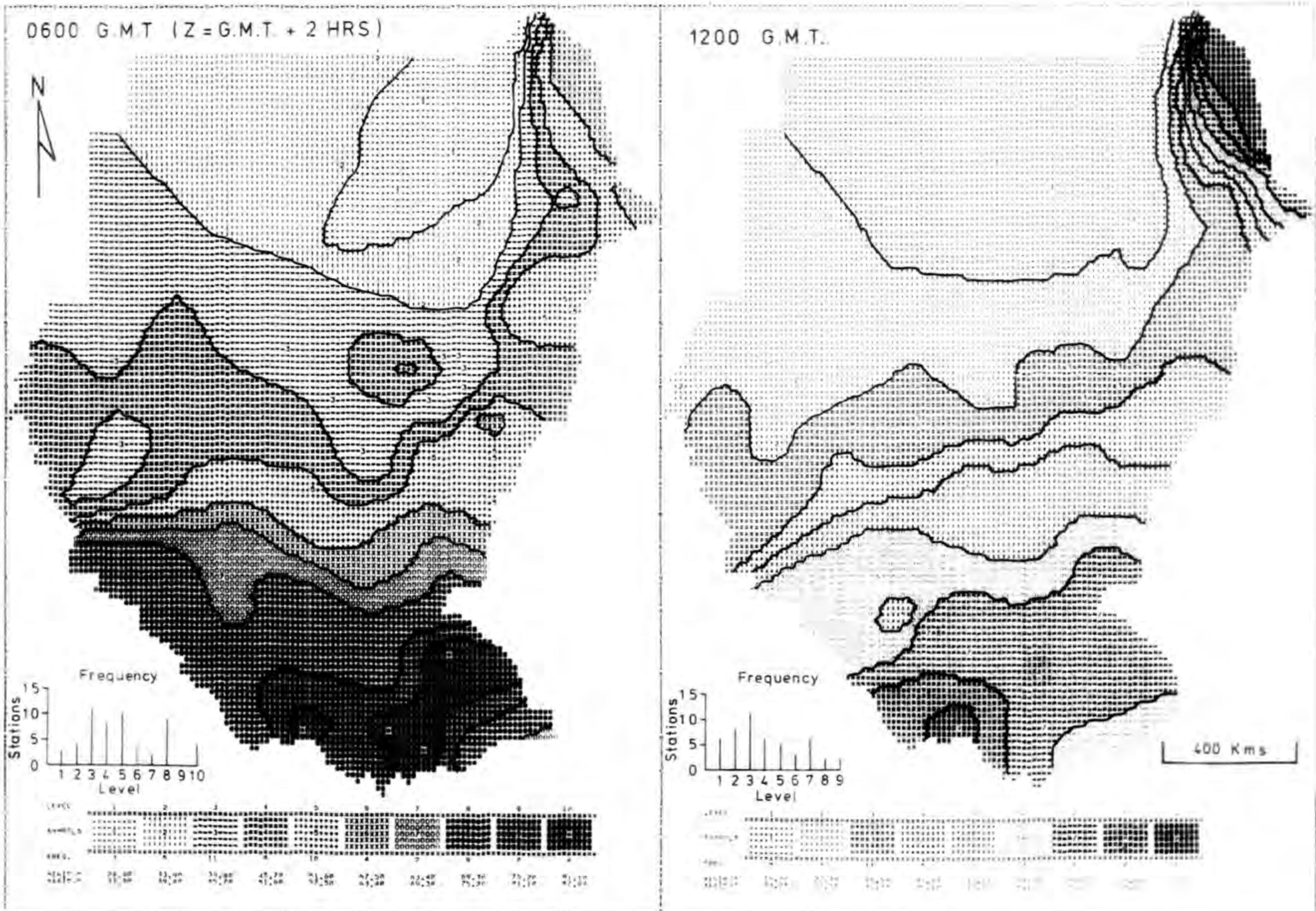
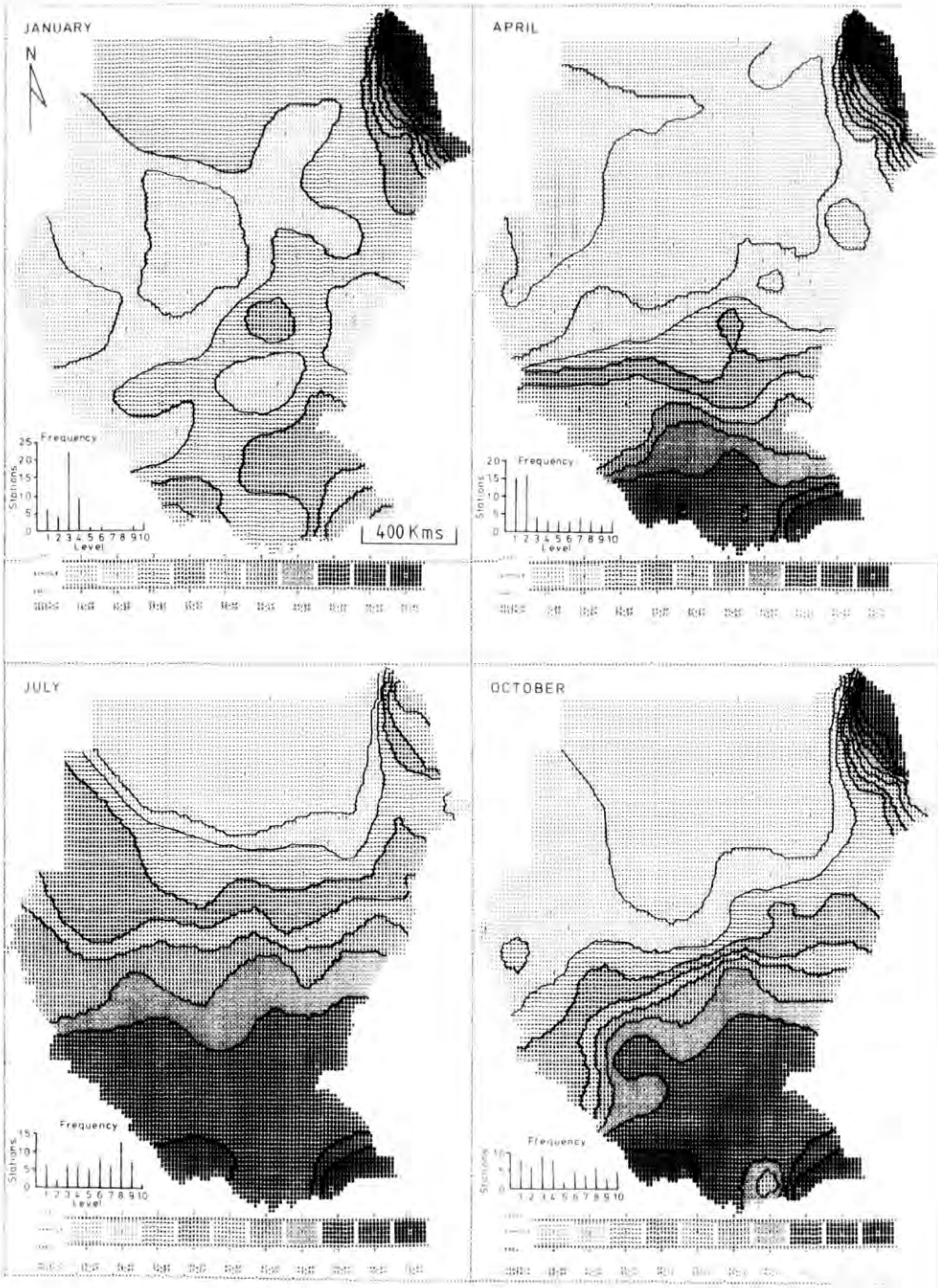


Fig. 3.18 RELATIVE HUMIDITY FOR 4 MONTHS



while the rest of the stations never show values above 34% in this month. The lowest records are kept at the west where Geneina, Nyala and Zalingei showed 11%, 13% and 14% relative humidity respectively.

April, as January, is generally a dry month and very dry north of latitude 11^{o}N. Wad Medani and Karima recorded 9% and 10% respectively. The humidity in the Red Sea in this month is as high as it is in January. The only marked difference occurs in the south where values rise to high percentages; highest over Nagishot with 62%. July represents the rainy season in the Sudan, except in the Red Sea area. It is hence the most humid among the 4 selected months. The south is the most humid, with the highest value of 79% at Nagishot. The values are higher than 47% up to latitude 13^{o}N and more than 34% up to latitude 15^{o}N. The lowest values in the north are not more than 15%. The Red Sea shows a drop in relative humidity to only 45%. October shows a similar pattern to the annual relative humidity with highest values in the south and lowest ones in the north. The intensification of humidity, 65%, over the Red Sea coast together with eastern areas receiving more moisture than their latitudes to the west causes the isolines of relative humidity to run in a north east - south west direction.

TABLE 3.6 ANNUAL AND SELECTED MONTHS' RELATIVE HUMIDITIES AT Z (%)☆

	ANN 8AM	ANN 2PM	JAN 2PM	APR 2PM	JUL 2PM	OCT 2PM
WADI HALFA	35	17	23	12	15	17
STATION 6	32	20	25	16	16	19
PORT SUDAN	59	59	67	60	45	65
ABU HAMAD	28	16	22	11	16	15
DONGOLA	35	19	25	14	18	19
GEREIT	54	41	57	37	31	40
KARIMA	30	16	20	10	17	16
TOKAR	60	47	63	52	27	48
HAIYA	45	28	32	20	28	27
ATBARA	35	18	23	11	21	17
DERUDEIB	47	26	30	17	34	26
SHENDI	37	21	24	12	27	19
AROMA	57	28	29	18	37	28
SHAMBAT	39	21	21	11	31	21
KASSALA	53	28	27	17	41	25
HALFA EL GEDIDA	57	27	25	23	34	29
SODIRI	42	20	15	11	34	18
WAD MEDANI	42	24	18	9	39	27
EL MANAQIL	45	28	25	15	39	34
KUTUM	44	24	19	17	35	22
GEDAREF	47	31	23	19	47	33
DUEIM	52	27	24	16	37	28
HAGABDALLA	45	30	24	18	44	30
EL FASHER	49	23	18	13	37	22
SENNAR	44	29	23	18	42	32
GENEINA	46	24	11	11	48	20
EL OBEID	45	25	16	12	47	23
KOSTI	42	29	23	13	46	31
SINGA	49	31	25	18	48	34
ZALINGEI	51	27	14	15	52	26
ABU NAAMA	59	31	17	15	54	37
EN NAHUD	50	26	15	13	48	25
NYALA	42	25	13	12	49	24
RASHAD	41	40	32	26	59	47
ROSEIRES	57	35	21	19	58	39
ED DAMAZIN	53	33	18	16	57	43
ER RENK	55	36	26	20	53	44
GHAZALA GZT.	51	31	18	18	55	33
KADUGLI	53	37	23	23	54	44
KURMUK	56	39	20	27	63	48
MALAKAL	59	39	18	26	63	53
AWEIL	68	43	24	32	65	53
NASIR	70	48	30	37	68	60
RAGA	74	41	22	32	64	32
AKOBO	70	46	28	37	62	55
WAU	69	38	17	33	67	48
TONJ	75	49	27	45	66	50
PIBOR	87	45	33	42	62	53
ROMBEK	73	46	26	43	63	54
BOR	73	50	32	49	69	57
MARIDI	84	56	28	57	69	63
JUBA	84	45	24	46	62	50
YAMBIO	84	54	34	56	68	63
TORIT	86	44	25	49	60	41
NAGISHOT	72	62	42	62	79	63
YEI	74	54	27	47	62	55

☆ Z = G.M.T. + 2 HOURS

SOURCE: SUDAN METEOROLOGICAL DEPARTMENT
(1973) CLIMATOLOGICAL NORMALS 1941-1970.
(1950-1975) ANNUAL METEOROLOGICAL REPORTS, KHARTOUM

3.7 Rainfall

3.7.1 Characteristics

Rainfall is recorded by raingauges which are mounted on iron supports so that their rims are one metre above ground. Rainfall is the best covered in the Sudan of all the climatic elements in terms of its network of coverage and length of record. Rainfall in the Sudan generally occurs in a few months, centring around July and August. The rest of the year is characterized by dry conditions. The nature, the mechanism and the distribution of rainfall over the Sudan are affected by the atmospheric circulations over Africa and Asia. As mentioned in section 3.4.2 the moist air originally invades the Sudan from the south (or south west). This fact, as can be seen from Table 3.2 is reflected in a very strong negative correlation between mean annual rainfall and latitude (r = -0.94).

It is the annual migration of the I.T.C.Z., as mentioned in section 3.4.2, which is the controlling climatic factor. Flohn (1960) and Solot (1950) described it as the 'principal rain producer'. It is believed that rainfall can occur only at distances far enough south of the surface I.T.C.Z., approximately 320 kms., where the layer of the moist and thermally unstable air is deep enough to allow the development of large rain producing clouds such as cumulonimbus (Trewartha,1962). From a study over the Atlantic Ocean Flohn (1960) brought evidence of a zone of highest rainfall from where the amounts decrease both north and south. This was found by Kruger (1962, noted in Bhalotra, 1963) and El Tom (1966) to be generally matching the summer situation in the Sudan despite its continentality. In the present study an argument for this can be found by comparing stations along longitudes 31^{o}E to 34^{o}E where a general concentration of heavier rainfall is found between latitudes 7^{o}30' N and 11 N (see Table A.3). This can also be observed by comparing Malakal with Kosti in the north and with Juba in the south (see Fig. 3.23). The southward reduction of rainfall shown also in Figure 3.14 is, in the opinion of Thompson (1965), due to the existence of temporary high pressure conditions and the subsequent subsident motion from the southern hemisphere anticyclones. However, further studies of upper air condition are needed to assess the credibility of this assumption (El Tom 1971).

Another important factor affecting rainfall over the Sudan is the existence, in summer, of a tropical easterly jet stream near latitude 15^{o}N within the upper easterlies. It is formed in the upper troposphere above 700 mb with its strongest gradient between 150 mb and 100 mb over China and travels through India, Arabia and at least over the Sudan in Africa. This jet stream which oscillates with the I.T.C.Z. at a distance of about 4.5^{o} of latitude to the south of it, has its northern flanks subsiding and its southern flank ascending. The result is an encouragement of convection and accentuation of rainfall at its southern side, but suppression of similar conditions at its northern side (Koteswaram, 1958; El Tantawy, 1963; Das, 1968).

The distribution of rainfall over the Sudan is also affected by line squall activity. Line squalls ordinarily develop during the afternoon as a series of cumulonimbus cells roughly formed into lines, because of topography, and move westward. According to Bhalotra (1963) they are generally formed in the Sudan in a zone 560 kms. wide with their northern edges about 240 kms. south of the I.T.C.Z. It is noted that the most favourable area for these line squalls is the Ethiopian foothills, and to a lesser degree the western slopes of the Marra Mountains and minor isolated line squalls around Khartoum. Bhalotra found that stations in southern and central Sudan witness two periods of line squall activities. These activities occur during the advance and retreat of the I.T.C.Z. However, although line squalls disintegrate after travelling short distances, the Ethiopian highlands line squalls may occasionally travel over 800 kms. This situation affects the distribution of rainfall as the line squall contribute more rainfall to areas nearer to their origin.

Finally, relief is observed to have little effect on rainfall distribution over the whole country. From Table 3.2 the correlation coefficients between relief and rainfall are only 0.37 in the annual, and 0.44 in the July averages. This situation is because the Sudan, as mentioned in section 2.2. in general is a vast plain and the orographic effect on the distribution of rainfall is localized mainly in the Marra, Nuba and the Red Sea high lands. In these areas higher rainfall values are seen on the windward side of the highlands compared with those on the leeward side. The Ethiopian highlands have a considerable effect on rainfall in eastern Sudan where considerable condensation occurs in relation to the southwesterly winds in their course of climbing the mountains and the resultant clouds are driven westward by the upper easterlies.

3.7.2 Distribution and Variability of annual rainfall

Distribution

From the previous discussion in this chapter and from Table 3.7 and Figures 3.19 and 3.20, it can be seen that mean annual rainfall over the Sudan varies from more than 1470 mm in the extreme southwest to only 3 mm near the border with Egypt, besides showing regional differences in the length and time of occurrence which can roughly be related to a north-south arrangement. The average rainfall between the southern boundaries and latitude 10^{o}N is more than 740 mm. and the isohyets of this region are observed to be tilted northward in the central part because of heavier rainfall on the Nuba Mountains compared with areas east and west of it. Latitude 14^{o}N marks the 445 mm isohyets at the centre while the line is pushed northward both in the east, as previously explained, and in the west. The westward increase of rainfall can be explained by the fact that the nearer the area to the western border the nearer it will be to the source of the moist south westerly wind and as these winds travel deeper in the country they gradually lose their moistures. This is added to orographic effect in increasing rainfall in the west as mentioned before. Areas north of latitude 16^{o}N generally have rainfall less than 150 mm. To these and other reasons El Tom (1974) relates the special dryness along the White Nile shown by southward tilting of the isohyets.

Fig.3.19 MEAN ANNUAL RAINFALL (MM)

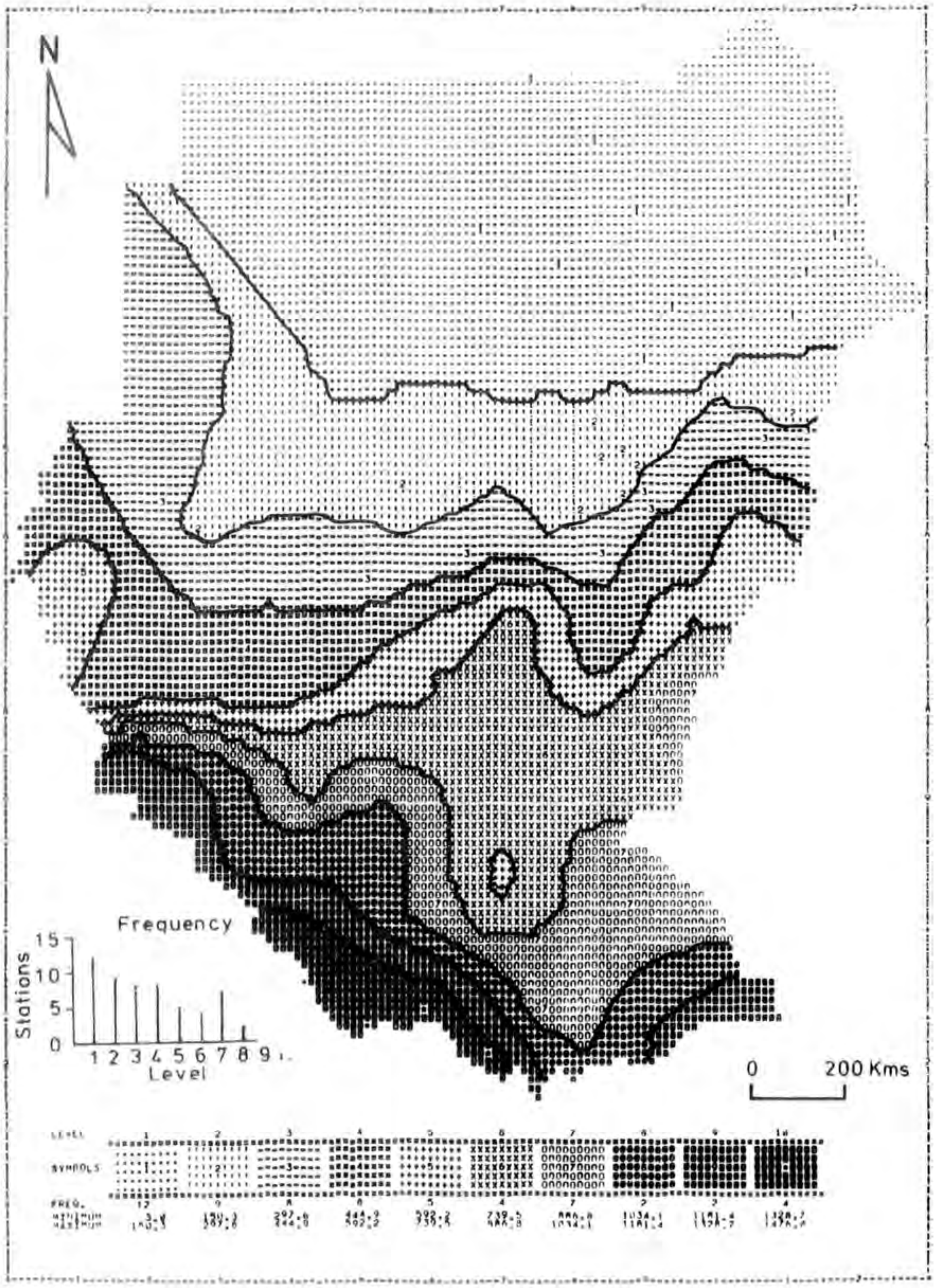


Fig.3.20 MEAN ANNUAL RAINFALL (MM)

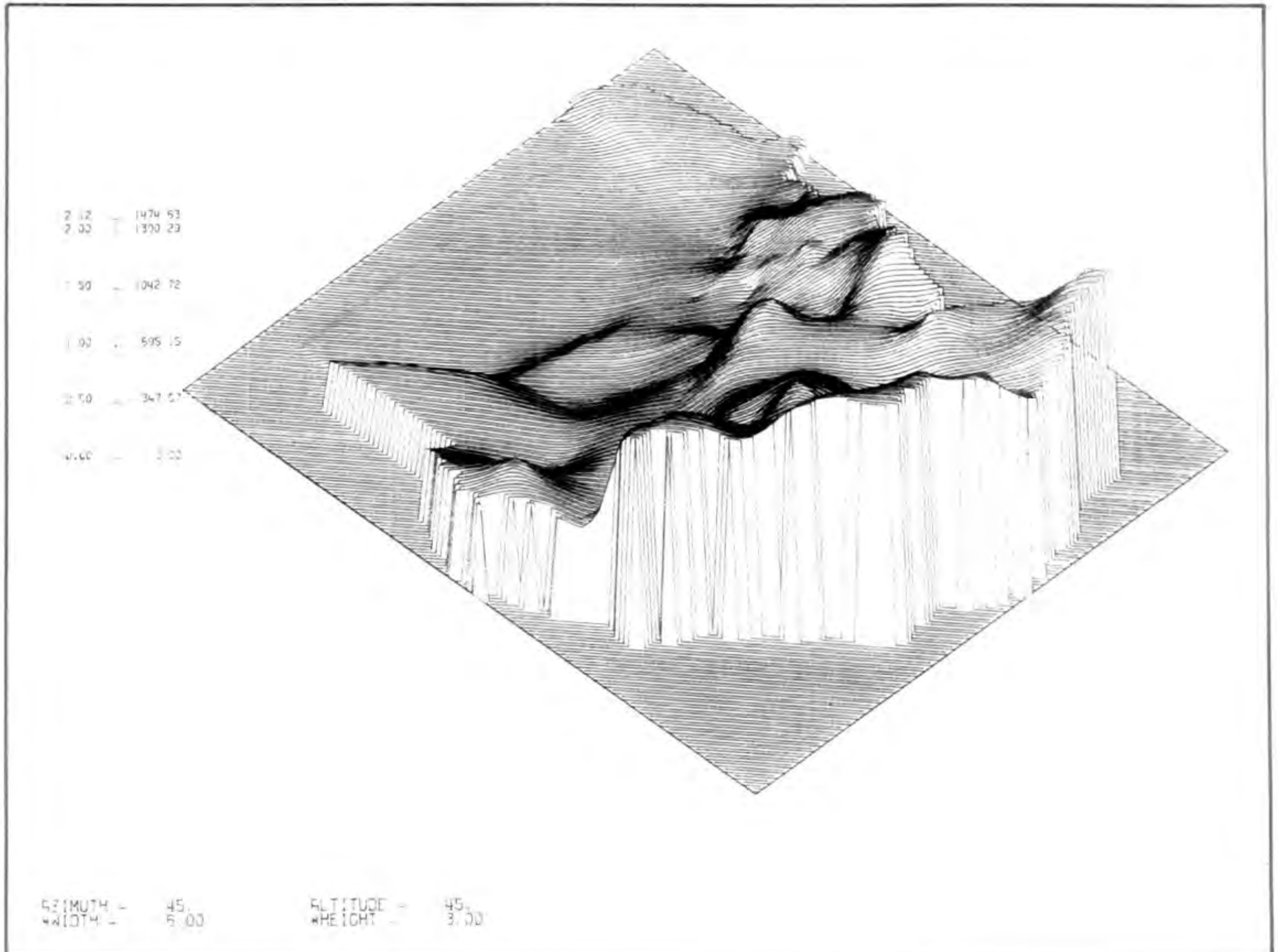


TABLE 3.7 ANNUAL AND SELECTED MONTHS' RAINFALLS (MM)

		ANN	JAN	APR	JUL	OCT	+1 MM DAYS	+10MM DAYS	%☆	S.D.☆	C.V.☆
1	WADI HALFA	3	0	0	1	1	1.0	0.1	1	7.8	257.2
2	STATION 6	7	0	0	3	0	0.5	0.5	1	9.8	171.9
3	PORT SUDAN	122	23	1	10	5	12.9	3.0	23	62.8	65.7
4	ABU HAMAD	15	0	0	6	0	2.8	0.4	14	29.1	183.4
5	DONGOLA	21	0	0	6	0	2.7	0.7	26	22.0	118.6
6	GEBEIT	122	2	3	37	8	11.9	4.8	40	72.3	67.1
7	KARIMA	41	0	0	13	1	4.9	1.2	24	45.6	113.5
8	TOKAR	87	18	1	9	4	11.5	2.6	23	60.6	76.0
9	HAIYA	87	0	3	23	4	11.7	3.6	28	67.0	78.4
10	ATBARA	69	0	0	27	1	8.5	2.0	27	41.3	61.8
11	DERUDEIB	115	0	1	33	5	11.7	3.9	33	95.9	78.3
12	SHENDI	117	0	1	37	1	10.4	3.8	37	76.3	66.6
13	AROMA	227	0	1	65	7	20.9	9.2	44	88.9	39.2
14	SHAMBAT	165	0	0	50	3	15.8	5.3	34	76.1	45.9
15	KASSALA	314	0	4	97	9	30.1	10.2	34	79.0	26.0
16	HALFA EL GEDIDA	358	0	1	118	9	25.7	11.9	46	94.0	30.1
17	ET TURABI	257	0	2	85	9	21.9	8.1	37	99.9	42.3
18	ABU QUTA	242	0	1	79	8	21.0	8.5	40	91.2	38.7
19	QURASHI	265	0	1	77	11	22.5	10.4	46	88.5	35.4
20	SODIRI	202	0	1	73	2	15.0	7.0	47	79.2	38.9
21	WAD MEDANI	362	0	1	116	19	37.2	11.6	31	88.4	25.0
22	EL MANAQIL	262	0	2	85	16	18.0	10.0	56	119.8	43.0
23	KUTUM	316	0	1	86	3	30.8	9.7	31	100.3	33.0
24	GEDAREF	579	0	4	154	24	48.2	19.7	41	81.4	13.9
25	DUEIM	276	0	4	75	10	20.2	9.7	48	84.2	32.7
26	HAGARDALLA	430	0	2	122	27	33.4	14.1	42	91.5	22.2
27	EL FASHER	286	0	1	86	6	32.4	9.8	30	127.3	44.2
28	SENNAR	472	0	4	138	31	38.1	16.3	43	96.3	20.7
29	GENEINA	559	0	3	168	10	53.9	19.7	37	137.7	26.0
30	EL OBEID	386	0	2	113	19	35.7	12.6	35	129.2	35.0
31	KOSTI	396	0	2	111	21	40.3	11.1	28	84.1	21.4
32	SINGA	582	0	3	161	24	43.0	19.0	44	86.2	15.0
33	ZALINGEI	665	0	5	189	19	62.1	23.4	38	145.2	22.3
34	ABU NAAMA	574	0	1	123	36	53.9	19.8	37	83.9	14.4
35	EN NAHUD	406	0	2	112	20	39.1	13.0	33	94.2	24.1
36	NYALA	470	0	3	138	18	42.6	16.4	38	88.6	19.2
37	RASHAD	781	0	10	159	94	63.0	27.0	43	106.7	14.3
38	ROSEIRES	732	0	11	152	41	64.8	26.5	41	104.2	14.3
39	ED DAMAZIN	730	0	19	181	41	67.4	24.1	36	71.0	19.7
40	ER RENK	519	0	3	117	50	42.3	17.8	42	117.7	23.4
41	GHAZALA GZT.	473	0	6	108	29	41.6	16.0	38	67.3	14.9
42	KADUGLI	735	0	14	139	79	60.3	24.5	41	138.1	19.4
43	KURMUK	982	0	33	165	100	73.1	32.9	45	165.6	17.1
44	MALAKAL	787	0	21	149	71	67.2	23.9	36	138.6	17.6
45	AWEIL	875	0	26	192	46	66.6	27.0	41	182.9	20.8
46	NASIR	791	0	34	151	59	59.4	25.7	43	167.5	21.6
47	RAGA	1188	0	55	210	97	85.5	39.5	30	140.1	11.8
48	AKOBO	997	3	56	198	81	71.5	30.9	43	168.7	16.9
49	WAU	1175	1	75	205	141	88.0	36.1	41	177.8	11.5
50	TONJ	1076	3	78	200	81	77.6	34.4	44	193.8	19.0
51	SHAMBE	729	1	53	153	56	45.4	19.9	44	174.0	26.5
52	PIBOR	953	9	64	179	100	59.0	28.0	47	229.2	22.3
53	RUMBEK	953	1	75	163	72	73.2	28.7	39	186.4	19.5
54	BOR	905	5	79	142	119	67.4	29.9	44	153.2	16.6
55	LI YUBU	1476	10	124	178	192	103.7	51.3	49	231.8	15.4
56	MARIDI	1411	11	140	194	149	109.6	52.4	48	189.1	13.5
57	JUBA	988	4	95	136	115	94.9	31.1	33	162.5	16.6
58	YAMBIO	1464	12	148	167	180	116.5	51.2	44	234.4	16.2
59	TORIT	1022	7	98	174	102	99.5	33.7	34	168.7	16.1
60	NAGISHOT	1184	15	116	231	56	98.9	45.3	46	200.9	16.9
61	YEI	1373	10	130	184	173	105.0	51.0	49	171.6	12.6

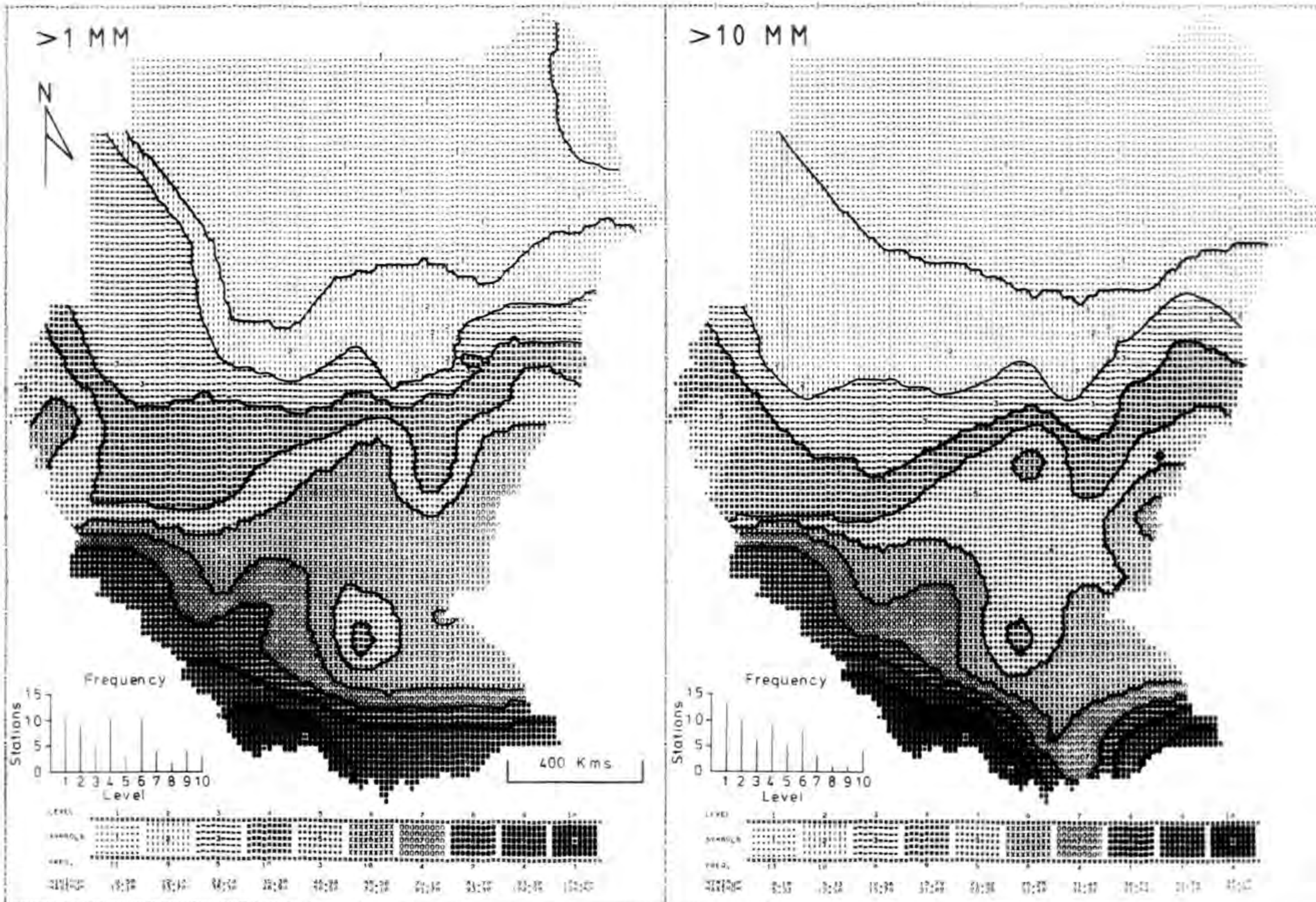
☆ S.D.= STANDARD DIVIATION
☆☆ C.V.= COEFFICIENT OF VARIATION
SOURCE: SUDAN METEOROLOGICAL DEPARTMENT (1973) RAINFALL AVERAGES 1941-1970, KHARTOUM, SUDAN.

Raindays

The average annual number of rain days with >1 mm and with >10 mm are investigated at 61 stations with different lengths of record within the study period (1941-1970). The spatial pattern of the number of rain days at both levels in Figure 3.21 quite resembles that of the annual rainfall. A very strong correlation (0.98) between the number of rain days (>1 mm) and the mean annual rainfall is produced (see Table 3.2).

The bulk of rainfall over the Sudan, as a part of the low latitude area, is of convective origin occurring in showers and thunderstorms (Riehl, 1979). It is noted that the character of individual storms and showers is much the same throughout the Sudan and the difference in total values is mainly due to the differences in the number of showers (Bhalotra, 1963). Considering the number of raindays with >10 mm as a percentage of those with >1 mm it can be observed that about half of the stations have 40% of their raindays with >10 mm. The majority of the stations south of latitude 17°N have over 30% of their raindays with >10 mm. The highest percentage is obtained over the wet south (approaching 50%) while lowest (<20%) occurs over the extreme north where rainfall is meagre (see Table 3.7). It can also be observed that the percentage of the number of days with >10 mm rainfall of those with >1 mm rainfall are relatively higher in the east if compared with western areas.

Fig. 3.21 MEAN ANNUAL NUMBER OF RAINDAYS



Variability of annual rainfall

The range of rainfall likely to occur in relation to the mean is important in understanding the climate of the Sudan. This kind of assessment about reliability of rainfall is particularly needed for marginal areas. The need can somewhat be met by calculating the standard deviation of rainfall for each station by:

$$\sigma = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}$$

where x_i = the value of rainfall, n = number of cases

From Table 3.7 the standard deviation is observed to be grading from the south as the highest to the extreme north as the lowest. The highest values of standard deviation coincided with the highest values of rainfall. Yambio and Li Yubu in the south have standard deviations with values of 234.4 and 231.8 respectively, and Wadi Halfa and Station 6 in the north have values of 7.8 and 9.8 respectively.

Although the standard deviation is quite useful in explaining the extent of rainfall variability, for the purposes of comparison, the coefficient of variation is used (Spiegel, 1972; Gregory, 1973), the formula for which is

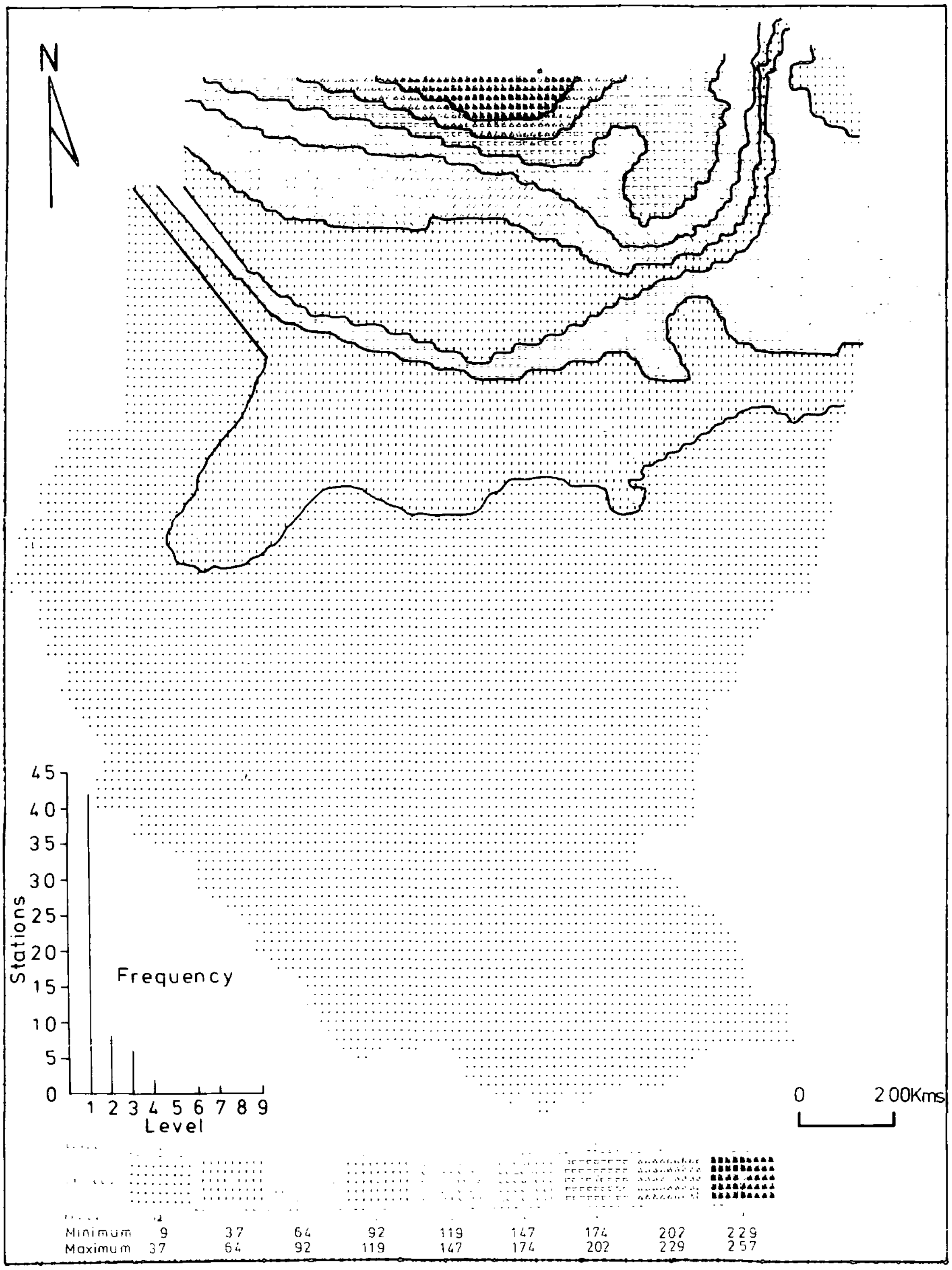
$$\frac{\sigma}{\bar{x}} \times 100 \ (\%)$$

The annual rainfall variability calculated according to this formulae is highest where rainfall is lowest and vice versa. This is partly caused by the effect of a small divisor ($\bar{x}$) which at 0.0 gives a coefficient of variation of infinity. This generalization can be observed from Figure 3.22 and Table 3.7. The highest value of the coefficient of variation is in the extreme north (257%), while central and southern Sudan have values less than 38%, and the southern and the south western parts of the country have the lowest values (< 16%). The coefficient of variation south of latitude 11°N is generally less than 20%. North of that latitude, apart from the eastern area and the Nuba Mountains, rainfall becomes more variable to a degree that it affects much of its reliability for agricultural purposes. To the north in the Sudan, variability is generally lower over the eastern than over the western areas, reflecting heavier and more reliable rainfall. In these areas, like the Gedaref area, chances for agriculture are always better than the places of the same latitude westward because of the more reliable rainfall.

3.7.3 Seasonal, monthly and diurnal rainfall

The rainy season needs to be defined for several different purposes, especially in agriculture. However, there is no general agreement about the criterion used to define a rainy month. One of the criteria is that erected by Cook (1946) which is reported by Gregory (1964) and applied to the Sudan by El Tom (1971). The basic idea is to define a month as being rainy if it has rainfall equal to or more than 10% of the total annual rainfall in the place under consideration. The month is considered as transitional if it has rainfall between 5% and 10%, and as dry if it has total rainfall less than 5% of the annual rainfall. From this identification an

Fig.3.22 COEFFICIENT OF VARIATION OF ANNUAL RAINFALL



idea about the rainy/dry season can be given. Figure 3.24 shows a map compiled for the Sudan according to this criterion. It can be observed that the rainy season extends from April to October in areas of the extreme south from where the period shrinks generally northward to be concentrated during July - September inclusive north of latitude 14^{o}N and only during July and August at latitude 20^{o}N. It can generally be said that except in the Red Sea area, July and August are the core of the rainy season in the Sudan. In the Red Sea area the rainy season is generally during November - January inclusive and the southern part of that area includes July also as a rainy month.

This criterion is not quite satisfactory for it only pays consideration to each place separately, in a way that it can be misleading. An example of that is the restriction of the rainy season to the period between April and October in the south while it can be seen from Figures 3.23, A.2 and Table 3.7 that rainfall occurs during every month of the year and the total rainfall of the dry months these are more than the mean annual rainfall in the Sudan north of latitude 16^{o}N. This can be shown in the case of Nagishot where September is excluded from the rainy season though it has an average of 97 mm rainfall. So, in general, this criterion should be taken in the context of the monthly distribution of rainfall of the country before a more logical criterion is developed. The shift of the rainy belt and the extent of the rainy season are related to the behaviour of the I.T.C.Z. Because of the slow northward and the rapid southward movement of I,T.C.Z., as previously explained, that the rain belt

Fig. 3.23 MEAN MONTHLY RAINFALL AT 18 STATIONS (MM)

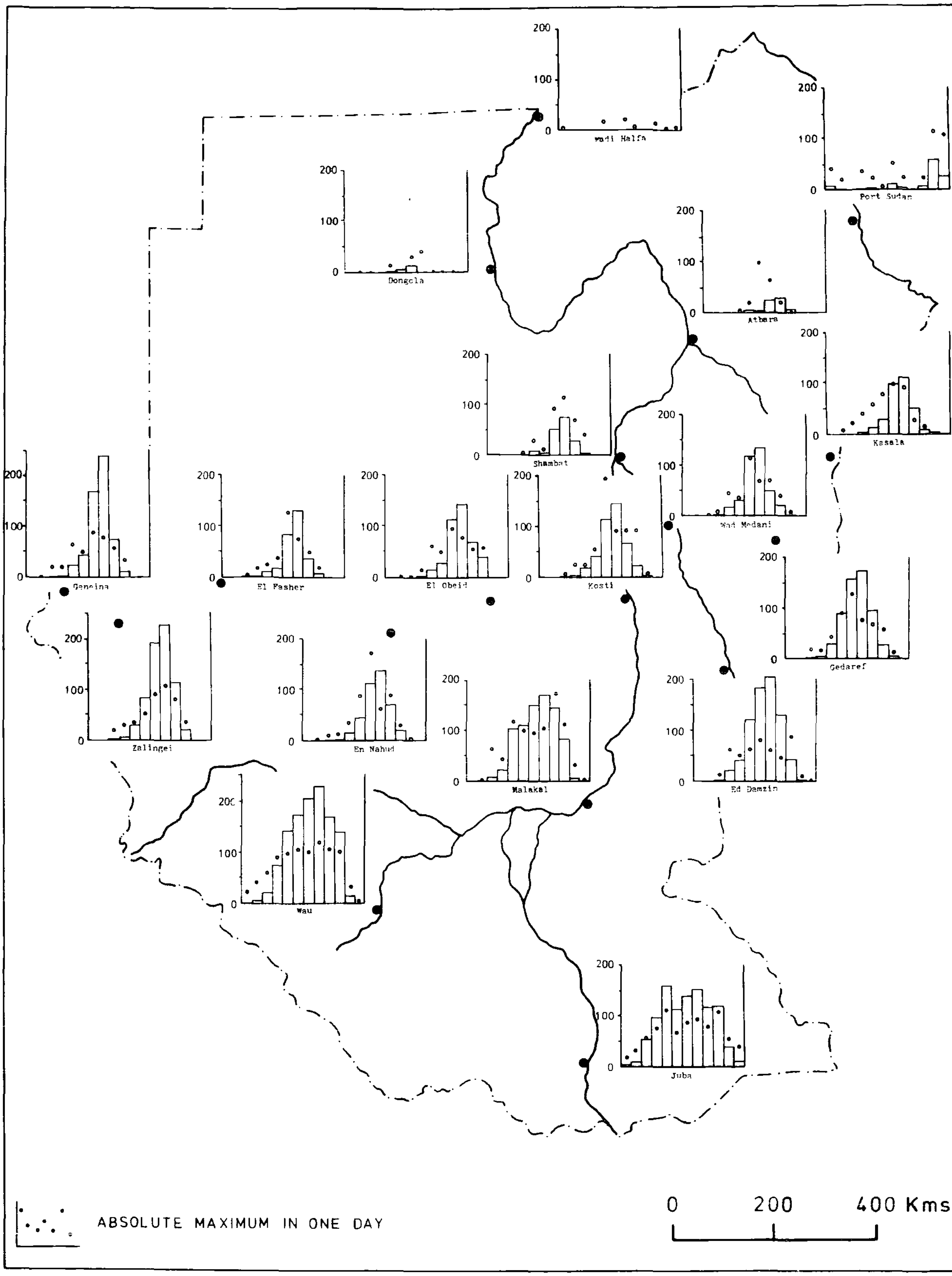
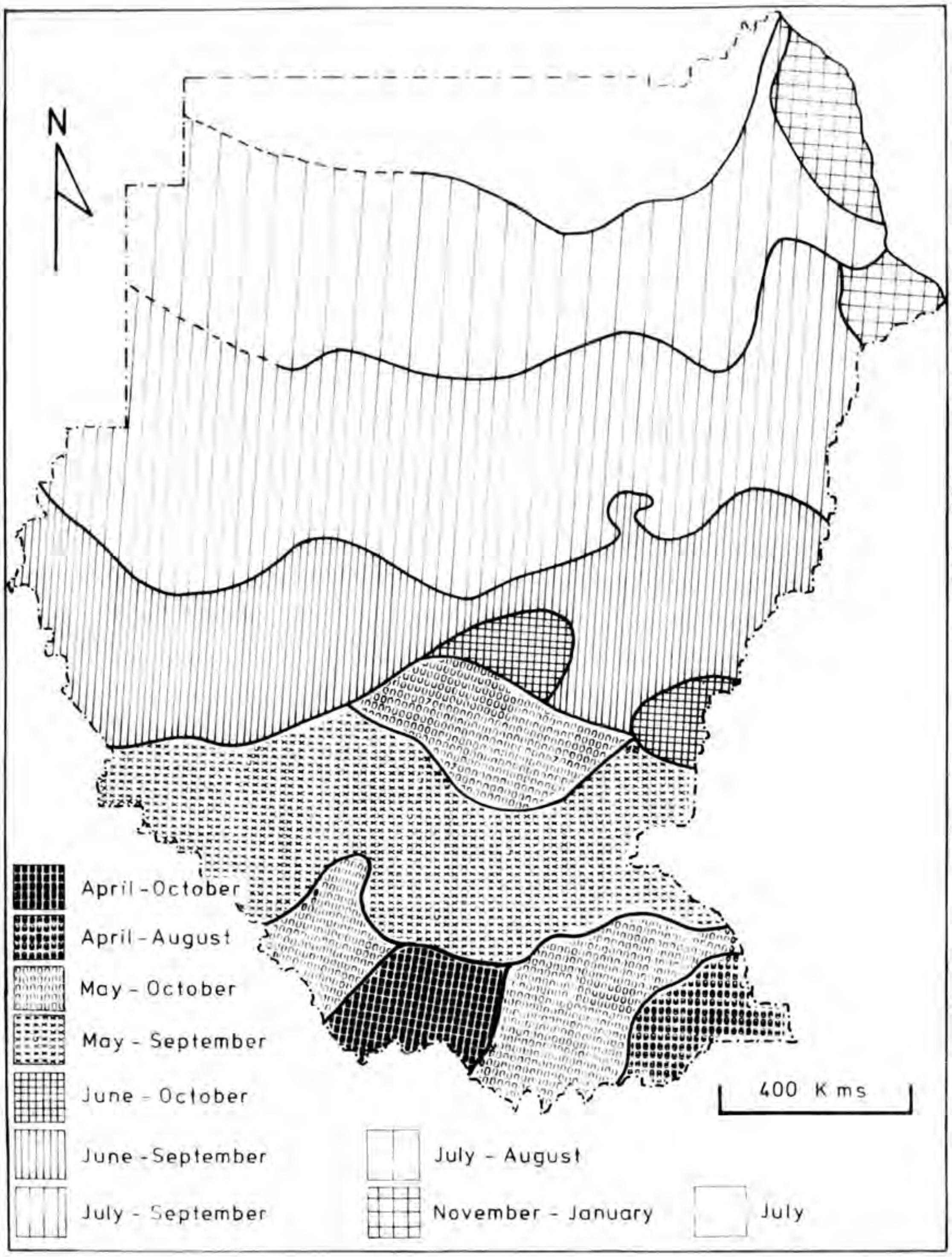


Fig.3.24 THE RAINY SEASONS



takes 6 months to reach its northernmost limits and only 3 months to withdraw from the Sudan.

From Figure 3.23 which shows the monthly rainfall distribution at 18 selected stations over the Sudan, it can be observed that in most areas, August is the rainiest month of the year and July is the next rainiest. Before and after these months the amounts decrease away till a demarcating point between the dry and the wet seasons can be suggested. The distribution of rainfall during January, April, July and October is discussed here in more detail on the assumption that those months are fairly representative of the different seasons of the year. The remaining months rainfall distributions are shown in Figure A.2.

January taken as a representative of winter is a dry month and the meagre rainfall here is almost totally confined to small areas in the Sudan. As can be observed from Figures 3.25 and 3.26 the incidence of rainfall occurs only to the south of latitude 7^{o}N and in the vicinity of the Red Sea coastal area. The latter area enjoys rainfall above 18 mm, highest at Port Sudan with a value of 23 mm. In the south the highest rainfall is only 15 mm recorded at Nagishot. The dryness of this month (and winter) is related to the withdrawal of the I.T.C.Z. and the south westerly winds, giving the opportunity for the dry north easterlies to dominate the country. It is to these winds crossing the Red Sea from Arabia and to those blowing from the south in the course of their way out of Arabian High that the rain over the Red Sea area is related.

The April rainfall situation is different from that of January. During this month the rain belt shifts northward following the advance of the I.T.C.Z. which is averaged at latitude 11^{o}N (see Figs. 3.25, 3.26). Most of the Sudan, however, remains dry and rainfall north of latitude 9^{o}N is hardly above 20 mm. This amount decreases to only 4 mm north of latitude 12^{o}N. The heaviest amounts of rainfall occurring in this month are received at the extreme south; heaviest at Yambio and Li Yubu with 148 mm. and 142 mm respectively.

In July, representing summer, the I.T.C.Z. and the consequent rainy belt reach northern Sudan. As is previously mentioned, July and August are the core of the rainy season in most places in the Sudan. The picture given by the annual rainfall is generally preserved (see Fig.3.27) as correlates positively with the seasonal rainfall ($r = 0.89$). It is noted that rainfall of July shows strong negative relationships with latitude ($r = 0.87$), and with July average temperature ($r = 0.92$). The longitudinal and relief factors are of less significance although on a local scale, especially in the case of relief, more significant relations may be observed. Greatest values of rainfall are found in south western Sudan. Raga, Wau and Maridi receive 210 mm, 205 mm and 194 mm respectively. Latitude 16^{o}N marks the 43 mm ishoyet and from there northwards rainfall decreases until it approaches zero at the northern boundaries out of the I.T.C.Z. The lowest amount of rainfall is recorded at Wadi Halfa, 1 mm. Over the Red Sea, near Port Sudan the I.T.C.Z. bends rapidly southward and the south easterly currents seldom reach the coast where the wind at 2,000 m above sea level from the north west

g. 3.25 JANUARY AND APRIL RAINFALLS (MM)

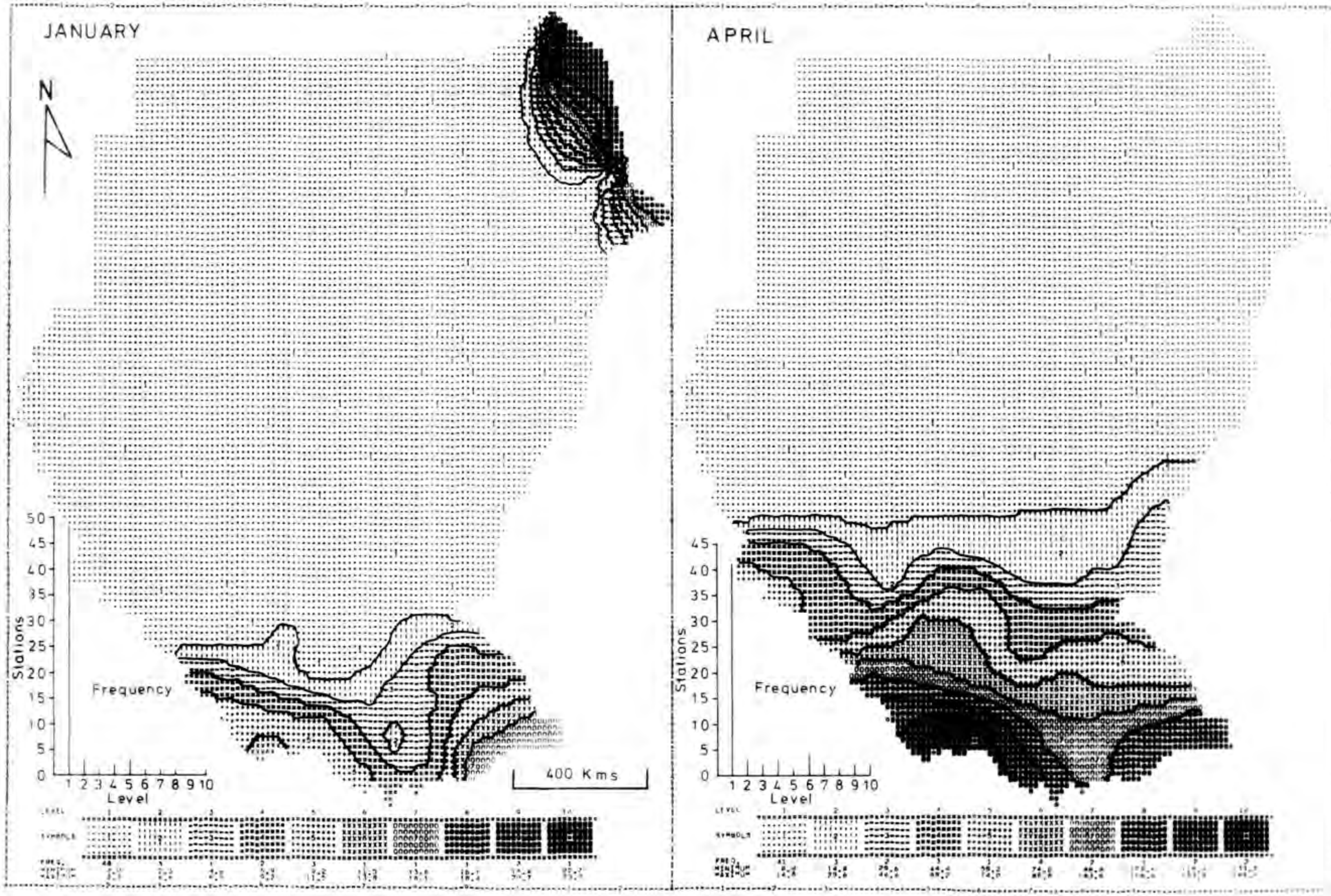


Fig. 3.26 RAINFALL IN 4 MONTHS (MM)

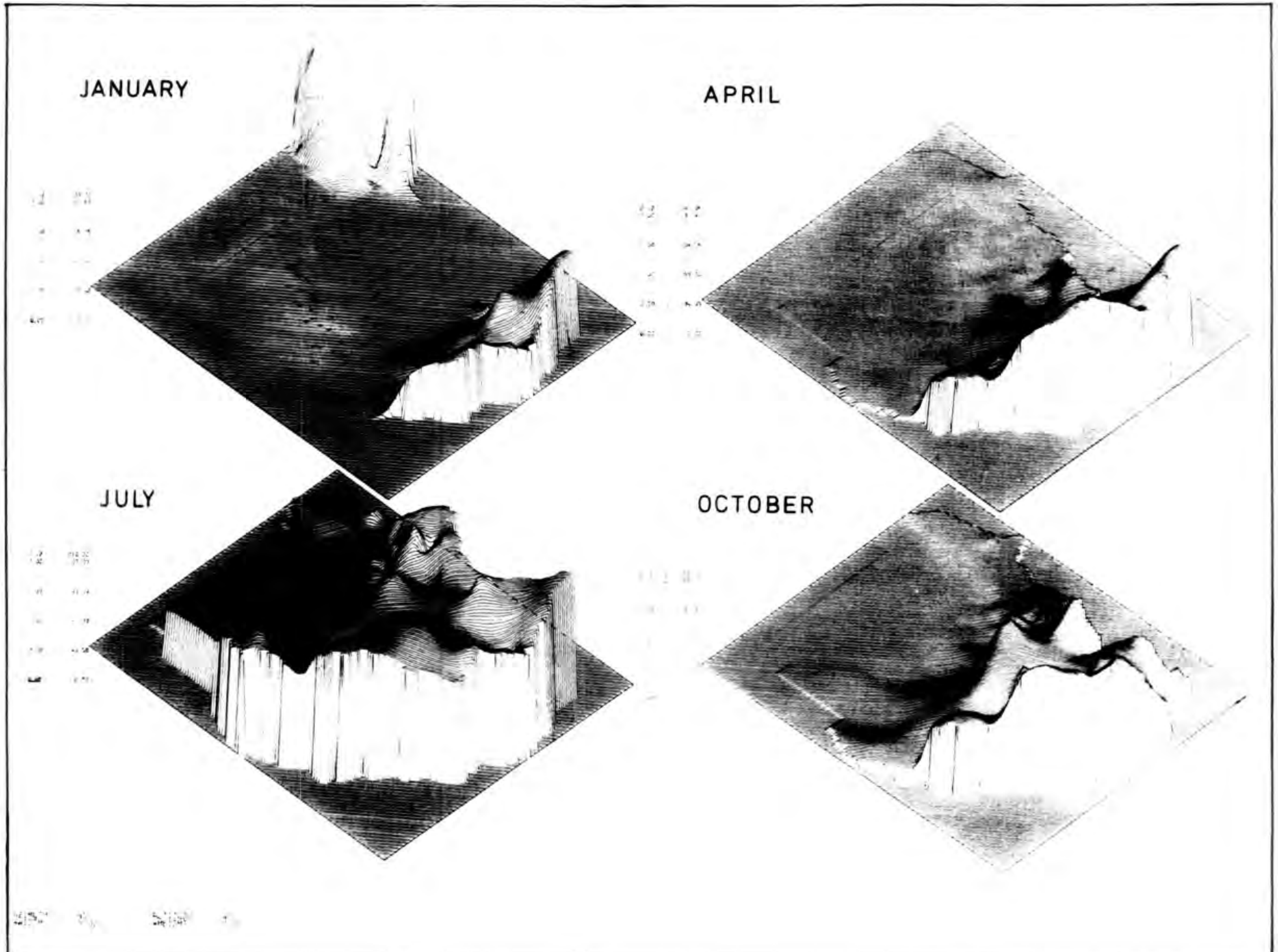
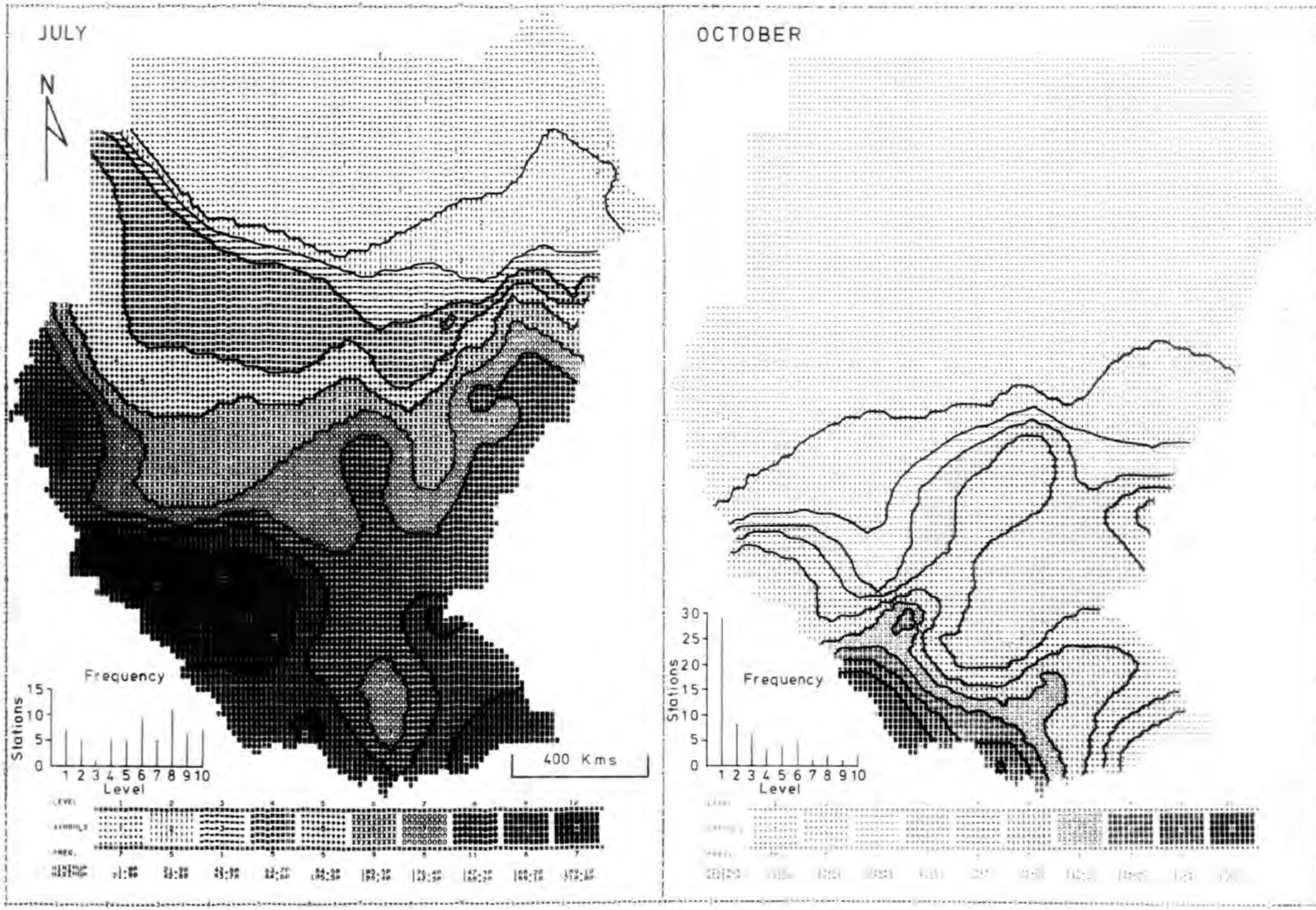


Fig. 3.27 JULY AND OCTOBER RAINFALLS (MM)



resulting in dry conditions (El Fandy, 1949).

October represents the retreat of the rainy season. The I.T.C.Z. lies approximately on latitude 14°N and Figure 3.27 shows that this latitude marks the isohyets of less than 20 mm and occurrence of those showers is mostly related to oscillation northwards during the month. The highest amount of rainfall, as expected, is in the south western corner of the country at Li Yubu, Yambio and Yei with 192 mm, 180 mm and 172 mm respectively. The isohyets tend to show a general latitudinal order as they show lower values northward. The area north of latitude 10°N receives rainfall less than 76 mm except at Rashad and Kurmuk on the foothills of the Ethiopian plateau with values of 94 mm and 100 mm respectively.

The diurnal incidence of rainfall over the Sudan, as described by Pedgley (1969a, 1969b), varies widely even over topographically uniform areas. He suggested a distance of 700 km away from the Ethiopian plateau for the day-time convection being a dominant control on rainfall formation where a maximum found in the late afternoon or early evening. Even the diurnal distribution throughout the day is noticed nearer to the Ethiopian mountainswith still a weak maximum at day-time existing at most places. A weak secondary maximum in the early morning is widespread. Oliver (1965) noted that the diurnal incidence also varies from month to month but the variations are less significant than the diurnal ones.

The highest rainfall recorded in one day during 30 years since 1941 at the 18 selected stations for each month is shown in Figure 3.23. The highest ever recorded rainfall was at Kosti in central Sudan with 193 mm on 30.7 1953 followed by Malakal with 176 mm on 16.9 1948 and En Nahud with 170 mm on 17.7 1951. It can generally be observed that in areas of heavier rainfall amounts, in the eastern, southern and western edges of the country, as expected, the highest records of showers were less than the average during the core of the rainy season and more than the average before and after the rainy season. In central inland areas with the exception of August, the highest records were almost always higher than the average. In the areas north of latitude 15^{o}N, because of low averages heavy showers are more likely to exceed the average.

3.8 Evaporation and transpiration

3.8.1 General

Evaporation is a very important element in the water balance of an area. The knowledge of evaporation, particularly in arid and semi arid areas like the Sudan, is very important for the planners in the field of agriculture and water resource projects to develop better water utilization methods. Three main conditions must be restored to permit evaporation to continue; those are :

1. there must be a supply of water at the evaporating surface,
2. there must be a supply of energy, and
3. there must be a sink for water vapour through existence of a gradient in vapour pressure and a transport mechanism in the atmosphere to remove the evaporation.

Evaporation from bare soil involves complex soil and atmospheric factors. This complexity is more pronounced when considering transpiration from plants where a new dimension is added through the physical and biological complexity of the plant (Penman, 1948; Sibbons, 1962).

Evaporation is carried a step further by the introduction of the concept of 'potential evapotranspiration' which is erected to avoid the effect of the nature of the ground on evaporation when the surface is partially wet. This idea is defined by Penman (1956) as:

> "...the amount of water transpired in unit time by a short-green crop, completely shading the ground of uniform height and never short of water."

The nature of evapotranspiration and potential evapotranspiration complexity makes it very difficult to measure these variables. Many different approaches have been adopted for the purpose of reaching results as representative as possible to the real world. Of these approaches are the empirical methods which intend to develop formulae for the estimation of evapotranspiration from meteorological data (Palmer and Havens, 1958; Chang, 1965; Ward, 1971; Woodhead, 1974).

Direct measurement is most widely carried out by evaporimeter, particularly the Piche type which crudely, as stated by Ward (1971), provides a measure of the drying power of the air rather than the actual evaporation. The second method is using evaporation pans, of which the most famous are the U.S.Weather Bureau class A pan and the British Meteorological Office sunken pan. Both instruments employ a free water surface. Potential evapotranspiration is measured by lysimeters. However, general doubts are cast about the representativeness of those instruments of the environment (Berry, 1969). The British Meteorological Office (1956) stated that "measurements made with any small instrument which cannot be regarded as an indistinguishable part of the surface under observation should not be accepted as a reliable indication of the rate of removal of the vapour from the surface."

The alternative methods to direct measurement of evapotranspiration can be grouped into the following approaches:

1. An aerodynamic approach, based on the physics of vapour transfer;
2. An energy budget approach;
3. An empirical approach, using one or more common climatic factors.

The empirical methods of Thornthwaite and Penman are adopted here and the results of their estimations of evapotranspiration are compared with those coming from measurement instruments.

3.8.2 Measured evaporation

Piche evaporation

Piche evaporation data are available for many stations from which 19 stations are selected for their relatively long records, in most cases covering over 25 years. Table 3.8 shows that the highest values of evaporation in the extreme north of the Sudan are generally recorded during June. The values of highest evaporation are recorded in the preceding

Table 3.8 Average Piche evaporation at 19 Selected Stations (mm)

Station	Location	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Port Sudan	N	8.9	9.0	8.9	10.0	12.6	15.2	17.3	17.0	12.4	8.3	8.2	8.7
Dongola		9.0	10.7	13.5	16.5	18.9	19.9	17.1	15.7	17.3	15.7	11.4	9.1
Karima		15.4	18.5	22.5	25.4	25.4	25.6	21.6	19.6	24.1	22.5	18.1	15.0
Atbara		14.1	16.7	21.0	23.5	24.1	23.7	19.4	17.6	20.0	19.1	15.7	13.6
Shambat		13.5	15.8	19.1	21.7	20.2	18.6	13.9	10.0	11.7	15.2	15.5	13.0
Kassala		9.1	10.4	13.4	15.0	15.2	13.1	8.7	6.3	7.6	10.6	10.5	9.1
Wad Medani		13.3	15.9	19.5	21.6	20.4	18.6	11.8	7.0	7.8	11.2	13.9	12.6
Gedaref		13.6	15.6	19.0	19.5	16.0	11.8	7.3	4.7	5.6	9.2	13.8	13.6
El Fasher		11.9	13.9	16.4	17.9	17.1	15.3	9.6	6.0	9.1	13.5	12.9	11.4
Geneina		16.5	19.5	21.2	21.1	18.1	13.5	7.0	3.5	5.8	12.2	16.2	14.9
El Obeid		15.6	17.9	20.7	21.1	18.9	15.2	9.7	5.8	7.3	13.2	16.8	15.0
Kosti		13.3	15.1	17.7	18.8	16.5	13.5	8.2	5.1	6.2	10.2	13.3	12.6
Abu Naama		14.3	16.9	19.3	19.0	16.5	11.3	6.0	3.6	3.9	7.0	12.7	13.6
En Nahud		13.0	14.6	16.6	16.3	13.6	9.8	6.3	4.3	5.8	10.1	13.3	12.3
Ed Damazin		13.5	16.3	19.4	18.7	14.9	8.4	6.0	3.1	3.6	5.4	10.1	12.0
Ghazala Gzt		15.7	18.3	20.2	19.9	17.2	11.0	5.7	3.7	4.8	9.9	14.8	15.2
Malakal		18.5	20.8	19.4	14.9	9.5	6.2	3.8	2.9	3.2	4.5	10.2	15.5
Wau		11.3	12.7	11.6	9.2	6.2	4.3	3.2	2.9	3.5	4.2	7.4	10.0
Juba	S	11.0	11.8	9.9	7.0	4.7	3.8	3.0	2.9	3.7	4.4	5.9	8.7

Highest values are underlined

Source : 1941-1970 Climatic Normals, Meteorological Department, Sudan.

month as moving southward from region to region. They occur during May in northern Sudan, during April in north central Sudan, during March in southern central Sudan, and during February in the extreme south. In general the highest monthly averages are found over Karima, Atbara and Shambat with values of 25.6 mm, 24.1 mm and 21.7 mm respectively.

An obvious pattern of minimum values recorded can be viewed through the general decrease in evaporation with southward movement showing comparatively lower records at the stations to the east and west of similar latitudes. Except at the extreme northern Sudan the lowest evaporation values are recorded in August, the wettest month of the year, lowest at Malakal, Wau and Juba with values of 2.9 mm each. In the extreme north the lowest values occur in December and they are always above 9.0 mm. It is observed that, except in the extreme driest north and the extreme wettest south, September shows values second lowest after August. At Port Sudan on the Red Sea coast with climatic condition different from the rest of the country, previously discussed, shows the highest values of evaporation (17.3 mm) during July and the lowest (8.2 mm) during November, the wettest month of the year.

Class - A pan evaporation

Measurement by class A pan is limited to a small number of stations. Two of the selected stations for investigating evaporation by different methods had data from a class A pan : Shambat and Wad Medani. At Shambat the values range between 17.8 mm and 10.2 mm whereas they range between 18.0 mm and 7.3 mm at Wad Medani (see Table 3.9). A close relationship between monthly Piche and class A pan is noted.

Table 3.9 Measured Evaporation and Calculated Evapotranspiration at 4 Stations (mm)

	Dongola			Shambat				Wad Medani				Juba		
	Piche	Thornth-waite	Penman Eo	Class A	Piche	Thornth-waite	Penman Eo	Class A	Piche	Thornth-waite	Penman Eo	Piche	Thornth-waite	Penman Eo
January	12.2	0.8	2.8	10.2	12.4	1.7	3.8	10.3	11.8	2.3	3.6	10.2	4.7	4.9
February	14.9	1.4	3.8	12.1	14.6	2.7	4.4	12.9	14.2	3.6	4.7	11.0	7.0	5.4
March	18.2	3.1	5.0	15.2	18.3	5.0	5.1	16.2	17.9	6.2	5.4	9.5	7.2	5.5
April	21.1	5.2	5.8	17.1	20.6	7.7	5.9	17.3	19.6	8.6	5.7	7.0	6.6	5.1
May	24.3	8.7	6.5	17.4	19.8	11.4	6.3	18.0	19.4	11.0	6.4	5.2	5.3	5.3
June	25.0	9.6	6.8	17.8	19.7	12.7	6.7	16.8	18.0	10.1	6.3	3.8	4.6	4.5
July	21.8	10.3	6.7	14.9	15.5	10.2	6.4	10.8	11.8	6.8	6.6	3.1	4.0	4.3
August	23.3	11.0	6.7	13.2	12.5	8.8	6.3	7.3	8.0	5.5	5.7	3.1	3.8	4.5
September	25.0	10.8	6.0	13.5	14.0	10.2	6.4	7.7	8.4	6.4	5.4	4.0	4.6	5.3
October	22.6	6.7	5.1	13.9	16.4	8.2	5.7	9.7	10.9	7.0	5.9	4.8	5.0	5.2
November	16.1	2.5	3.8	13.0	16.4	4.3	4.7	10.0	12.8	4.8	5.4	6.1	5.2	5.2
December	12.1	1.1	2.8	10.4	12.8	2.2	3.8	10.2	11.2	2.7	5.0	9.4	4.9	5.1

Calculated from the Sudan Meteorological Department 1968-72 monthly meteorological records, monthly and annual agrometeorological reports.

The correlation coefficient between them is 0.87 at Shambat and even stronger (0.96) at Wad Medani. It is also observed that Piche values are always exaggerated but this exaggeration is reduced to a minimum during the rainy season in both stations.

3.8.3 Estimation methods of evaporation

The methods adopted here for estimation of evapotranspiration are those developed by Thornthwaite (1948) and Penman (1948). The limitation of the Thornthwaite formula comes from its total dependence on temperature. Polton, King and Tanner (1960) attacked this particular dependence and suggested the application of the energy balance method whenever radiation data are available. Sellers (1964) described Thornthwaite's concept of potential evapotranspiration as being a "poor at best" in humid areas and is completely unrealistic in desert regions. Penman's method on the other hand gained support from experimental evidence (Chang, 1965). The recognition and inclusion of the most effective climatic factors in Penman's formula made it more plausible.

Thornthwaite formula

$$PE = 1.6 \left(\frac{10\ T}{I}\right)^a$$

where PE = potential evapotranspiration (mm)

T = mean monthly temperature ($^\circ C$)

$$I = \sum_{1}^{12} \left(\frac{T}{5}\right)^{1.514}$$

$$a = 0.000\ 000\ 675\ I^3 - 0.000\ 0\ 771\ I^2 + 0.01792\ I + 0.49239$$

Penman formula

Evapotranspiration estimation according to the Penman formula is mainly dependent on radiation (or sunshine), air temperature, vapour pressure and wind speed. The equation is as follows:

$$Eo = \frac{AH + 0.27E}{A + 0.27}$$

where Eo = evaporation from open water (mm)

H = daily heat budget (net radiation)

E = daily evaporation

A = slope of saturated vapour pressure curve of air at absolute temperature (^{o}F)

H and E in the above equation can be calculated as follows :

$$H = R(1-r)(0.18 + 0.55\ S)-B(0.56-0.092\ ed^{0.5})(0.10+0.90\ S)$$

$$E = 0.35\ (ea-ed)(1+0.0098\ W2)$$

where R = mean monthly extraterrestrial radiation (from Chow, 1964)

r = estimated percentage of reflecting surface, for Eo it is 0.05.

S = estimated ratio of sunshine %

B = a coefficient depending on temperature (Chow, 1964)

ed = saturation vapour pressure in mm/Hg.

ea = saturation vapour pressure at mean air temperature in mm/Hg

W2 = mean wind velocity at 2 m above the ground (mph)

Applying these formulae to the Sudan, 4 stations along the country from north to south are considered here. Monthly data for 5 years (1968-1972) are employed the same way as by Smith (1964) in Yorkshire, England. The restriction to this period is due to the availability of data where that period is the best covered by data for all methods giving an opportunity for better comparisons.

The calculation of Penman's Eo using the monthly averaged data is made to test the usefulness of such a step in giving a general idea from short time and less manual calculations. The monthly averages are easier to obtain. They are available in the published monthly or annual meteorological reports. Comparison of the results obtained from the daily data with those from the monthly data may suggest particular values of correction when such an approximate method (monthly averaged data) is used.

3.8.4 Comparisons of measured and estimated evaporation

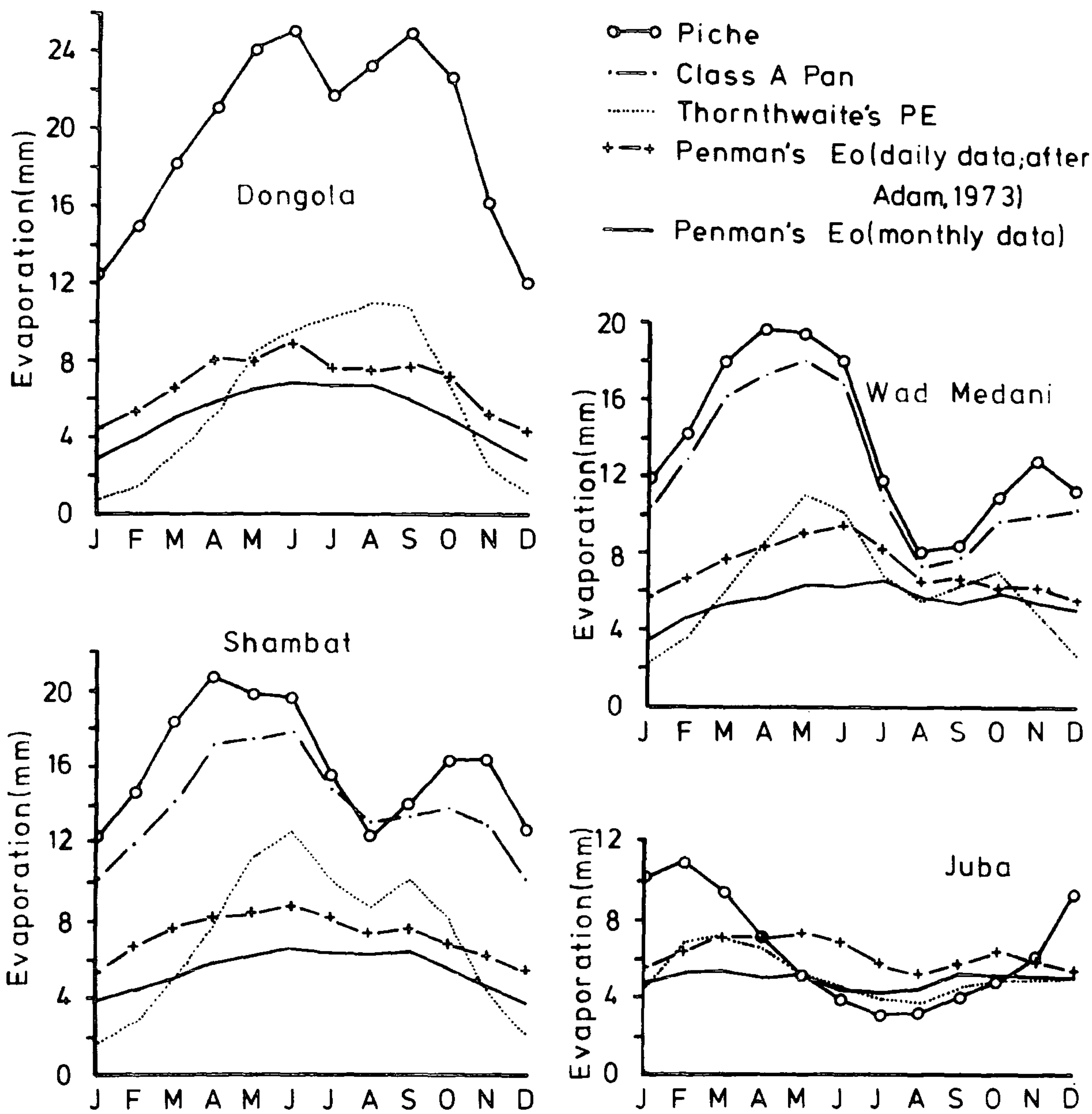
The mean monthly measured and estimated evaporation and evapotranspiration are shown in Table 3. 9 and Figure 3.30 which shows discrepancies both in the individual values and in the seasonal phasing of the curves. All the methods show lower values during winter at the two northern stations (Dongola and Shambat). At Wad Medani lower values occur during winter for estimation methods while the measurement methods show summer with the lowest evaporation value. In the south, at Juba, the picture is totally reversed. Here all the methods show the highest values in the dry season (winter) and the lowest in the wet season.

A big gap between the measured and estimated evaporation is observed. Measured evaporation, always being higher, ranges between 8 mm and 25 mm in the north and the centre of the Sudan. This also indicates the higher ranges compared with estimated evaporation. Thornthwaite estimated evapotranspiration has lower values than measured evaporation and it ranges between 0.8 mm and 12.0 mm. It has higher values and ranges than Penman's which ranges between 3 mm and 7 mm, considering all the stations together.

The discrepancy between Thornthwaite and Penman is highest during summer at the two northern stations (Dongola and Shambat) and before the rainy season at Wad Medani and Juba. The closest values given by both methods are observed at Juba for most of the year (between May and January). The reasons behind such a pattern in the south are assumed to be the prolonged humid conditions, the relatively small temperature range and,as described by Adam (1973), the wind factor becoming insignificant compared with the north. Because Thornthwaite's method totally depends on temperature (compare Figure 3.7 with 3.28) dramatic seasonal changes in evaporation are noticed. The very low evaporation values given by Thornthwaite's formula in winter at Dongola, compared with Penman's, are, as stated by Adam (1973) due to the fact that Thornthwaite gave no consideration to the dryness of the air or the wind effect.

The normal calculations of Penman's Eo are daily-based ones for more accurate results. Comparing the values of Eo based on monthly calculations made in this study with the

Fig. 3.28 MEASURED AND CALCULATED EVAPORATION AT 4 STATIONS



daily calculated Penman's Eo for some stations in the Sudan made by Adam (1973), it can be seen that the monthly data calculations always give values lower than daily data calculations. The difference reached 1.5 mm at Wad Medani (see Figure 3.28). Although the daily calculated Eo kept a nice agreement with the monthly calculated Eo it showed relatively closer values to the measured evaporation at the three north stations (Dongola, Shambat, Wad Medani). At these stations closer values of Thornthwaite's and Penman daily calculated Eo in summer, and wider in winter than those of Thornthwaite's and Penman's monthly calculated Eo are observed. In the south, at Juba, the Penman's daily calculated Eo showed closer values to other methods' results than monthly calculated Eo only in the period between January and April.

The general trends of evaporation through the year indicate high correlations between the different methods in the north, at Dongola, where coefficients above 0.88 are found (see Table 3.10). Piche and class A pan evaporation at Shambat and Wad Medani show correlation coefficients 0.87 and 0.96 respectively. Similar strong relationships might be found in other areas of the country. However, class A pan evaporation shows stronger correlation with estimated evaporation than does Piche. Penman's and Thornthwaite's show the best relationships with coefficients above 0.84 in the north and then drop to only 0.65 in the south. It must be mentioned here that correlation coefficient discussion does not negate the facts that with the southward movement the discrepancy between the methods becomes smaller, these

Table 3.10 Mean Daily Evaporation Correlation Coefficients

Correlated methods	Station			
	Dongola	Shambat	Wad Medani	Juba
Piche - Pan (A)	-	0.87	0.96	-
Penman Eo - Piche	0.91	0.44	0.34	0.53
Penman Eo - Pan (A)	-	0.75	0.36	-
Thornthwaite PE - Piche	0.88	0.49	0.58	0.63
Thornthwaite PE - Pan (A)	-	0.74	0.61	-
Penman Eo - Thornthwaite PE	0.89	0.91	0.84	0.65

N = 60

All significant at α = 0.01

Pan (A) = class A pan (American type)

coefficients only describe the trend. And although the correlation may be high because of the similar rhythm of the curves the gap may be quite big.

If one takes Penman as a base as recommended by many workers in the field of evaporation, the result given by measurement instruments, Piche and class A pan, always highly overestimate evaporation. Thornthwaite's underestimates evaporation in cooler conditions of winter, and overestimates in the hotter conditions in northern stations in the Sudan. For more accurate Penman estimation, however, daily based calculations are necessary. Monthly calculated Eo, although having the disadvantage inherent in depending on the average, seems acceptable for the purposes of generalization. The difference between daily and monthly calculated Eo can be averaged from large data size set and can be used for correlation.

In this chapter a general survey of the major climatic elements and factors affecting them have been discussed. That knowledge was noted to be of special importance as a background to the present study where relationships between climatic elements and crop yield are considered. It has been confirmed that the complexity of the relationships between these climatic elements, and the problems related to their measurements and records, add to the complexity of their relationships with crop yield as they will be elaborated upon later in this study.

CHAPTER FOUR

CLIMATIC CLASSIFICATION OF THE SUDAN

4.1 General

In this chapter the climatic elements described in Chapter 3 are discussed in a comprehensive, simplified way, and climatic classification will be taken as a suitable context for this purpose. The necessity of climatic classification and the application of different methods of classification to the Sudan are described in this Chapter. The results of these applications are compared in the view of the advantages and the limitations of each method, particularly with reference to the Sudan.

Climatic classification is a general technique with which, as stated by Barrett (1974, p.359), "... a reasonable representation of climatic reality in map and/or tabular form" can be achieved. This supports the view of Thornthwaite (1948) who stressed the use of what he described as the truly active climatic factors. Grigg (1965) noted that the prime aim of classification is to enable inductive generalizations to be made. In practice, the success in meeting this aim is only partial because nature resists simple categorical schemes. Still, seeking climatic regionalization is desirable for a general understanding of climatic conditions and to establish climatic frameworks (Chang, 1959; Miller, 1961; Strahler, 1969). Within these generalized and simplified frameworks detailed studies of climates can be undertaken. Different climatic classifications can meet different purposes such as investigation of the climatic consequences, particularly on agricultural potentialities of a region (Hare, 1951).

Due to the importance of climatic classification for workers in different fields, and for geographers in particular, many scientists have approached the topic from different angles. They have tried to establish a satisfactory classification in as real a form as possible. These classifications can be divided into two main groups as follows:

1. Effective or applied classifications, and
2. Genetic classifications

The most famous classifications in the first group are those of de Martonne, Köppen and Thornthwaite with their different modifications. In the other groups those of Hathner, Allison, Flohn and Strahler are the outstanding ones.

The attack upon the prevalent classifications of the first group was presented by Flohn (1969) and Strahler (1969). They claim that climatic classification based on the causes of climate are more useful than those based on its effects. The desire for a genetic approach to climatic classification was expressed earlier by Haurwitz and Austin (1944) though they expected that a purely genetic classification would not be satisfactory for it might include too many different climates in one group. Trewartha (1968) advocates that the genetic approach cannot do justice to the complex climatic pattern of the earth. He does not think that it is advisable to drop that approach completely but to take it as a supplement to careful observation. Chang (1959) and Miller (1961) supported the latter idea by placing the genetic classification in the realm of pure meteorology and climatology. Critchfield (1966) stated that it is more difficult to measure the cause of climate than to measure its elements.

The applied climatic classification approach appears to have the advantage over the genetic one for its practicality as the elements can easily be weighted. Beside that it has the ability to identify different climatic groups which could otherwise be lost in the large groups of the genetic approach. In the present study the applied climatic classification approach is adopted for it helps in recognizing climatic differences of smaller regions within the Sudan.

In the present study three climatic classification methods are applied to the Sudan. The first two are the widely applied classifications of Köppen and Thornthwaite. Because of the status of these classification methods in climatology, their characteristics and applications to the Sudan are discussed here. The third method of climatic classification, which for the first time is being applied for the Sudan, is dependent mainly on factor analysis and cluster analysis in identifying climatic regions of the country. The three methods are described and the results of each for the Sudan are compared with the others. Regions which emerged from the classifications are shown on maps, accompanied by discussion of the usefulness of each method in regionalizing the climate of the Sudan.

4.2 Köppen's climatic classification

4.2.1 General

Köppen's modified classification of 1937 was adopted by many climatologists and applied to many places in the world. His approach is to relate the distributions and types of vegetation over the earth to those climatic elements that are most important for plant growth. He took de Candolle's plant regions and attempted to find their climatic correspondences. This brought severe criticism as being arbitrary for ignoring climatic control and search for arbitrary values of climatic elements. Köppen's system is also attacked as being too simple and not systematic, for he applied different criteria for climatic identification, though basically the classification is concerned with the relation between precipitation and temperature (Thornthwaite, 1943; Carter and Mather, 1966).

Köppen identified five major groups of climatic types. These are :

A. Tropical rainy climates - coldest month $> 18^{o}C$

B. Dry climates (BS = dry steppe; BW = dry hot desert)

C. Warm temperate rainy climates, coldest month between $-3^{o}C$ and $18^{o}C$ and warmest month $> 10^{o}C$

D. Cold snow-frost climates, coldest month $< -3^{o}C$ and warmest month $> 10^{o}C$

E. Polar (snow) climates, warmest month $0^{o} - 10^{o}C$

The subdivision of each major type is made first due to the seasonal distribution of rainfall. Examples of this are :

f = no dry season, s = dry summer, and w = dry winter. The second base of subdivision is added temperature characteristics such as in B dry climates where the 18^{0}C value of temperature represents the boundary between hot (h) and cold (k) conditions. Further details about Köppen's subdivisions can be found in Strahler (1969), Critchfield (1966) and Barry and Chorley (1976).

4.2.2 Köppen's climatic classification applied to the Sudan

Applying the Köppen formulae for tropical areas to the Sudan, three main climatic regions emerge. These are the tropical savanna (Aw), the dry steppe (BS) and the dry hot desert (BW). The boundary between regions Aw and BS was identified from the following formula:

$$r = o.44t - 3.5$$

where r = mean annual precipitation (inches)

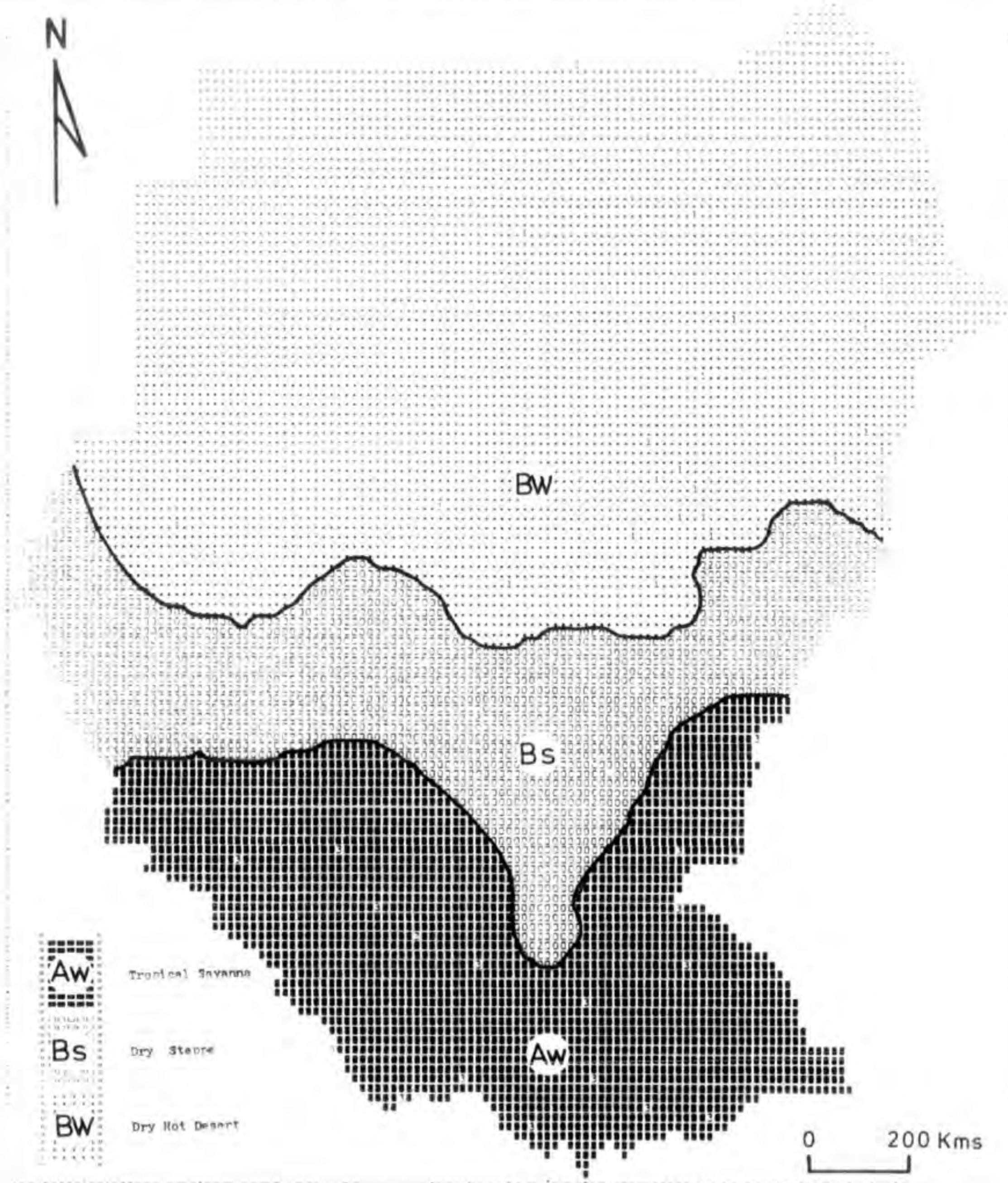
t = mean annual temperature (^{O}F)

Within the B climatic group the differentiation between BS and BW is based on the same variables of the last formula with different values :

$$r = \frac{0.44t - 3.5}{2}$$

From Figure 4.1 it can be seen that the resultant regionalization of the Sudan by Köppen's method describes most of the country as a dry area. This dry area extends from the extreme north of the country southward to around latitude 10^{O}N. Within this area latitude 14^{O}N can roughly be considered as the boundary between the desert (BW) in the north and the dry steppe (BS) in the south.

Fig.4.1 KÖPPEN'S CLIMATIC REGIONS



Although boundaries between Köppen's climatic regions of the Sudan generally show latitudinal order, yet they acquire northerly positions in the east and the west and a remarkable bulge southward along the White Nile area down to around latitude 7^{o}N. The boundaries which are drawn according to the ratios between actual and calculated rainfall values are more affected by rainfall than by temperature due to the greater variability of the former (see Chapter 3, Tables 3.3, 3.7). Geneina in the west has a greater amount of rainfall (559 mm. p.a.) than El Fasher (286 mm.) to the east of it, and Gedaref in the east has a greater amount (579 mm.) than Hag Abdalla to the west of it. The differences in temperatures between these areas are insignificant. The bulge of the boundary southward along the White Nile to include Malakal and Shambe is due to the relative dryness of these areas compared with those to the east, south and west while there is again no significant difference in temperature (Chapter 3, Tables 3.3, 3.7). The reason behind this relative dryness has been discussed in Chapter 3.

The southern third of the country is classified as a tropical steppe type which is characterized by a dry winter. This region, as described in Chapter 3, has considerably higher amounts of rainfall and lower temperatures and hence higher moisture indices to be classified as Aw by Köppen. (see Table 4.1).

TABLE 4.1 ANNUAL RAINFALL(RF") ,KÖPPEN'S(R) AND THORNTHWAITE'S(IM) MOISTURE INDICES

NO	NAME	RF"*	R	IM
1	WADI HALFA	0.2	31	-100
2	STATION 6	0.3	32	-100
3	PORT SUDAN	4.5	23	-95
4	ABU HAMAD	0.7	34	-99
5	DONGOLA	0.9	32	-99
6	GEBEIT	6.8	31	-88
7	KARIMA	1.7	34	-98
8	TOKAR	1.7	34	-84
9	HAIYA	5.1	33	-93
10	ATBARA	2.8	34	-97
11	DERUDEIB	4.6	34	-95
12	SHENDI	4.7	34	-95
13	AROMA	9.0	33	-90
14	SHAMBAT	6.7	33	-93
15	KASSALA	12.6	34	-87
16	HALFA GEDIDA	14.4	33	-84
17	ET TURABI	10.3	33	-87
18	ABU QUTA	9.7	33	-88
19	QURASHI	10.6	33	-88
20	SODIRI	8.1	32	-72
21	WAD MEDANI	14.5	33	-82
22	EL MANAGIL	10.5	33	-87
23	KUTUM	12.7	29	-72
24	GEDAREF	23.2	33	-73
25	DUEIM	11.1	33	-87
26	HAGABDALLA	16.2	33	-79
27	EL FASHER	11.4	31	-81
28	SENNAR	18.9	33	-77
29	GENEINA	22.4	31	-61
30	EL OBEID	15.5	32	-77
31	KOSTI	15.9	33	-82
32	SINGA	23.3	33	-73
33	ZALINGEI	26.6	30	-45
34	ABU NAAMA	23.1	33	-70
35	EN NAHUD	16.1	32	-77
36	NYALA	18.8	32	-72
37	RASHAD	25.1	32	-51
38	ROSSEIRIS	29.3	33	-64
39	ED DAMAZIN	29.5	33	-63
40	ER RENK	21.0	32	-71
41	GHAZALA GZT	18.9	32	-72
42	KADUGLI	29.4	33	-62
43	KURMUK	38.7	32	-46
44	MALAKAL	31.5	33	-58
45	AWEIL	35.0	32	-52
46	NASIR	32.0	32	-56
47	RAGA	37.5	31	-36
48	AKOBO	39.9	33	-51
49	WAU	49.8	32	-37
50	TONJ	43.1	32	-37
51	SHAMBE	29.2	32	-57
52	PIBOR	38.1	33	-50
53	RUMBEK	38.1	32	-48
54	BOR	36.2	32	-50
55	LI YUBU	59.1	31	+7
56	MARIDI	56.4	30	+7
57	JUBA	39.5	32	-46
58	YAMBIO	58.6	30	+8
59	TORIT	49.9	32	-38
60	NAGISHOT	47.2	25	+49
61	YEI	54.9	30	+5

* RF"=RAINFALL IN INCHES

4.3 Thornthwaite's Climatic Classification

4.3.1 General

The 1931 classification

Following the guidance of Penck and Köppen, Thornthwaite, from the available evaporation data in USA, erected a formula to produce a better moisture index than those which existed before. The Thornthwaite method is credited with deriving regions according to moisture indices rather than from vegetation or soil criteria as made by his predecessors (Carter and Mather, 1966). The main factors considered by Thornthwaite in this classification are the precipitation effectiveness (P.E) and the thermal efficiency (T-E), but as stated by Haurwitz and Austin (1944), with temperatures sufficiently high to maintain vegetation, as in Sudan, the precipitation effectiveness indices rather than thermal efficiency establish the climatic boundaries. Thornthwaite's formula for calculating a P-E index of a place is as follows :

$$P\text{-}E = \sum_{n=1}^{12} 115\left(\frac{P}{T-10}\right)^{\frac{10}{9}}$$

where P-E = precipitation effectiveness index

P = mean monthly precipitation (inches)

T = average monthly temperature (^{o}F)

n = 1 to 12 is a sum over 12 months

The basic 5 regions identified on the basis of the values of P-E are the wet (A), the humid (B), the subhumid (C), the semi arid (D) and the arid (E) regions.

The 1948-1955 Classification

Thornthwaite's most important contribution is his 1948 classification. It is based on the concept of evapotranspiration that is mentioned in Chapter 3, and the moisture budget. It is noted that while in Köppen's and Thornthwaite's 1931 classifications the plant was viewed as a meteorological instrument for measuring climatic character, here it is regarded as a physical mechanism by means of which water is transported (Trewartha, 1968). The new formula for the estimation of potential evapotranspiration (PE) is :

$$PE = 1.6\left(\frac{10T}{I}\right)^{a}$$

where T = average monthly temperature, $^{\circ}C$

$$I = \sum_{n=1}^{12}\left(\frac{T}{5}\right)^{1.154}$$

$$a = 0.000\,000\,675\ I^{3} - 0.000\,0771\ I^{2} + 0.0\,1792\ I + 0.49239$$

This empirical formula for calculating evapotranspiration depending on temperature alone, as expected, reflected results different from the actual evapotranspiration.

The monthly water surplus (s) or deficit (d) is determined from a moisture budget assessment which is a comparison between water supply (r) and water need for evapotranspiration (PE). The moisture index (Im) is given by :

$$Im = \frac{100s}{PE} - \frac{60d}{PE}$$

However, Thornthwaite and Mather, in 1955, dropped the weighting factor of a deficit by 0.6 which was originally supposed to allow for the beneficial action of a surplus in one season when moisture is stored in the subsoil. The formula then became :

$$Im = 100 \frac{s-d}{PE}$$

They stated that a deficit can begin as soon as any moisture is removed from the soil by evapotranspiration. In calculating this index, adjustments should be made for the formula which is set for a 30-day month with 12 hour days.

4.3.2 Thornthwaite's climatic classification applied to the Sudan

In the present study, based on Thornthwaite's methods and using data collected from 61 stations in the Sudan, the same as those used in Köppen's classification, two climatic classifications have been produced. As can be seen from comparing Figures 4.2 and 4.3 although there is some similarity between the two classifications there are noticeable differences. The earlier one which is almost discarded now has more ability to show more regions in central Sudan, but it is unable to do so in the south in comparison with the 1948-55 classification.

According to Thornthwaite's 1948-55 classification, the majority of the Sudan is dominated by the arid type of climate (E) in the north and the semi arid type (D) in the south. The limiting boundary between these types is roughly latitude 12^{o}N in addition to a small closed area (D) around

Fig.4.2 THORNTHWAITE'S 1931 CLIMATIC REGIONS

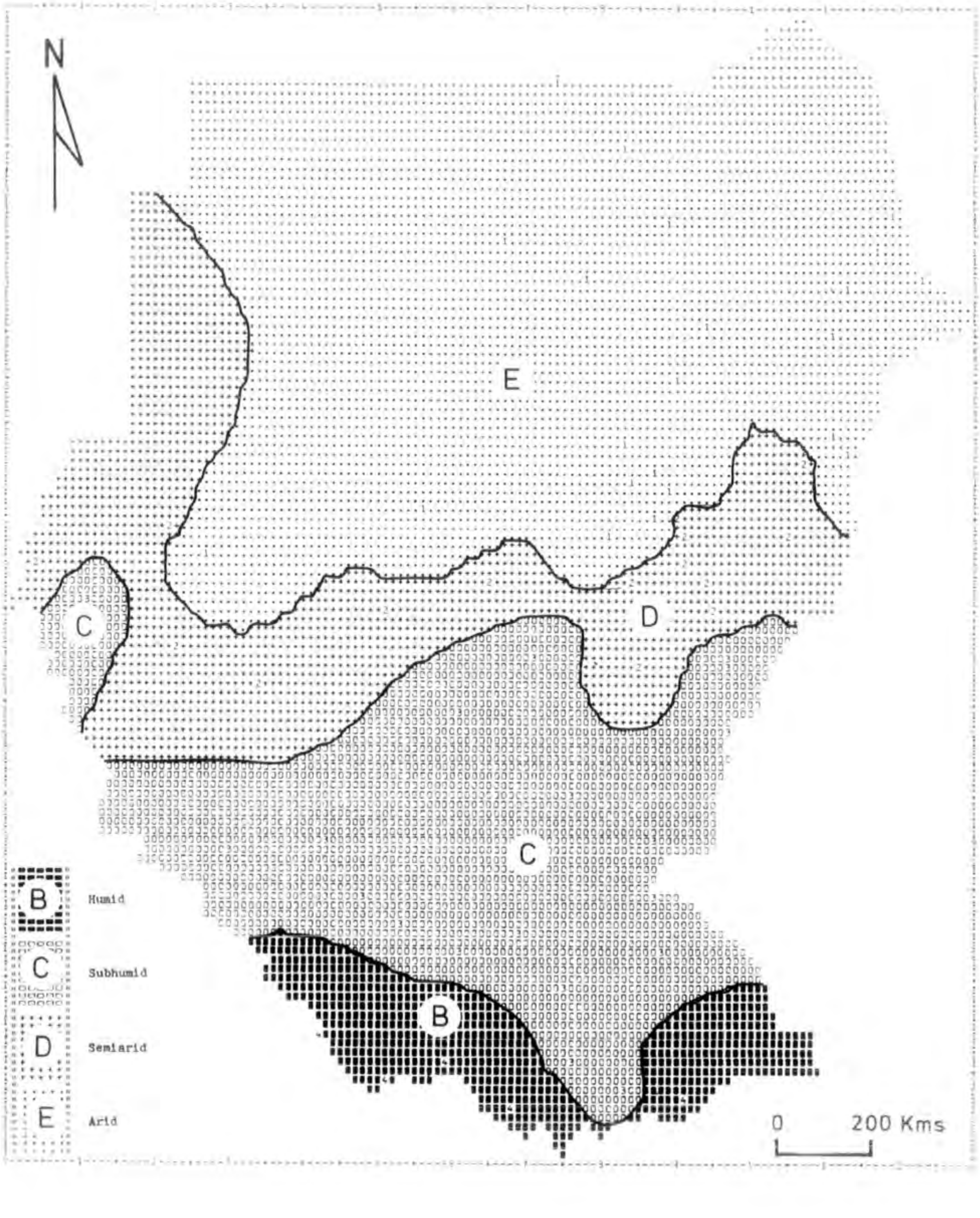
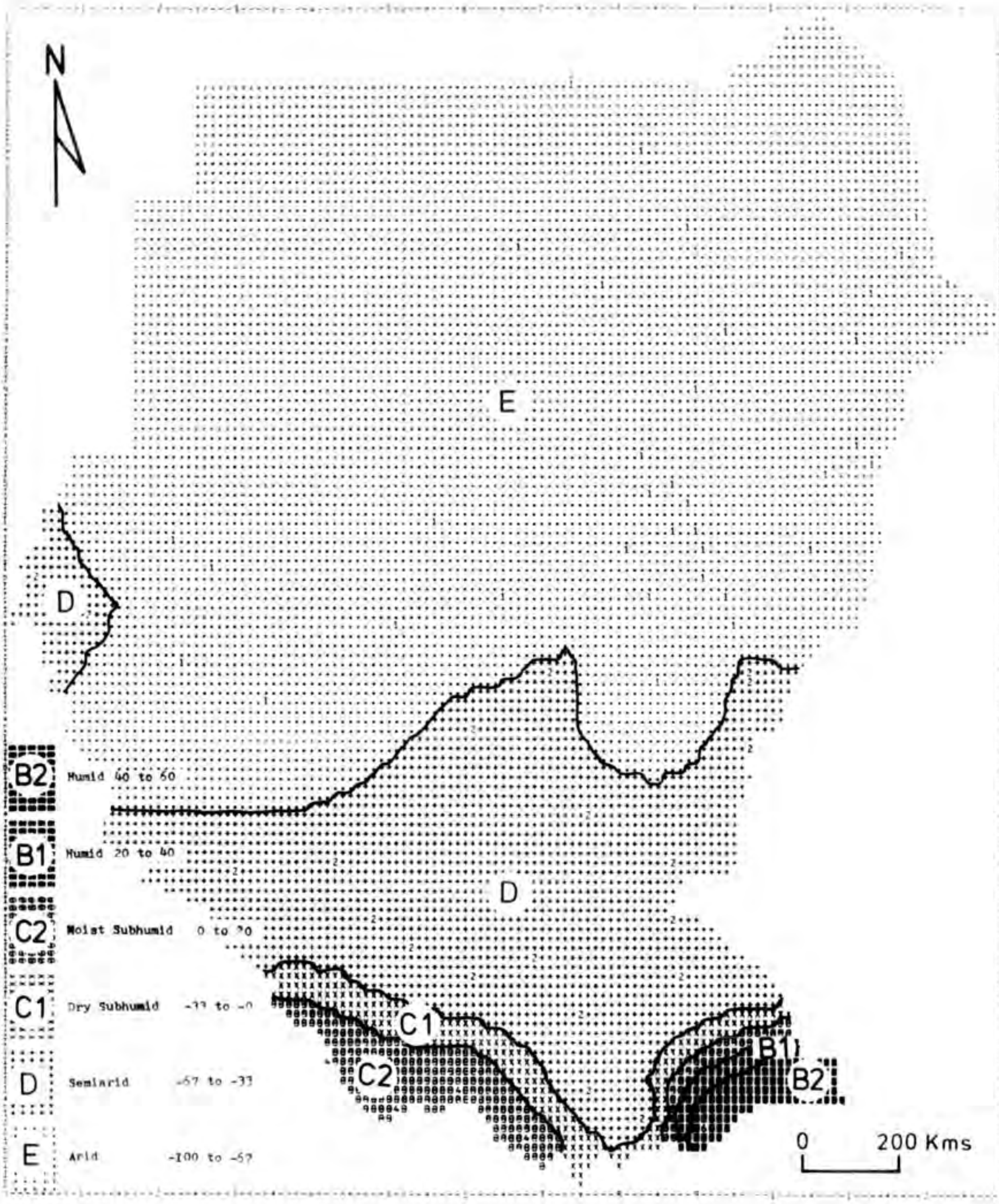


Fig.4.3 THORNTHWAITE'S 1948-55 CLIMATIC REGIONS



Geneina next to the western boundary of the country (see Figure 4.3 and Table 4.1). The other four types are limited to the extreme south. They grade with the extreme moistness towards the borders. Those types are the dry subhumid (C1), the moist subhumid (C2), and the humid (B1) and (B2) climates. The humid climates are only represented by the Imatong area in the extreme south eastern corner of the Sudan.

The Köppen and Thornthwaite classification are found generally useful for many places for generalization, simplification and presentation of climatic phenomena. Although Thornthwaite's has the advantage over Köppen's in many aspects, it has its own limitations. According to Barry and Chorley (1977) and Oliver (1981) in the tropical and semi arid areas Thornthwaite's method is not very satisfactory. Generally Thornthwaite's method has been criticized as being a derivation from a limited area with different conditions from many of the areas where it has been tried. Sellers (1965) stated that in areas with temperatures higher than 26.5°C (applicable to Sudan) the method has drawbacks. He mentioned the erratic results obtained from different applications of the method in different parts of the world. It is suggested that alterations and refinements of the method need to be performed to obtain better results (Brooks, 1948; Miller, 1961).

Both the Köppen and Thornthwaite methods are subjective for their *a priori* setting of critical limits to demarcate the climatic boundaries. Depending on arbitrary critical values and on only one climatic element to identify the regions, the results they both gave are considered unsatisfactory. The climatic differences shown in Chapter 3 have, in many cases as in the Red Sea area, been overlooked. More detailed inspection of the advantages and disadvantages of each of the climatic classification methods used in the study of climatic regionalization of the Sudan is given in the comparison section 4.5 of this Chapter.

4.4 Factor-cluster analysis technique

4.4.1 Factor analysis

Characteristics

The dissatisfaction with the previously mentioned climatic classification methods made it necessary to try a new method. This trial is thought to bring a different viewing angle for climatic classification together with giving a wider opportunity for comparability and hence a better understanding of the climate of the Sudan. Factor analysis and cluster analysis methods are chosen for this stage. The techniques are chosen because they have the merit of being developed from statistical theory with known mathematical behaviour, rather than the *ad hoc* methods developed by Köppen, Thornthwaite and others. In addition, digital computers can be used to achieve results which would otherwise need extensive and probably prohibitive manual calculations.

The complexity of most geographic problems with regard to the number of interrelated variables to be considered has made it necessary to adopt multivariate procedures in geographic analysis. Among those procedures, factor analysis has come to occupy an important position (Carey, 1966; King, 1969; Taylor, 1977). Factor analysis is a multivariate data analysis technique aimed at describing observed relations among numerous variables in terms of simple relations (Cattell, 1965). Here the data are simplified with respect to certain criteria, in such a way that one or more new variables (factors) are created, each representing a cluster of interrelated variables within the data set (Spence and Taylor, 1970; Goddard and Kirby, 1976). The method yields correlations or loadings between the original variables and the new factors, and also produces scores for the study cases. The examination of loadings and scores is assumed to allow for empirical interpretation of the new variables or dimensions. It is also assumed that the variation in a given variable is produced by a small number of factors and by a variation unique to itself (Goddard and Kirby, 1976).

The factor analysis technique is generally described as being empirical and a strong inductive or descriptive one (King, 1966; Rees, 1971; Taylor, 1977), and not a causal model (Janson, 1969). Mather (1976) stated that any attempt to interpret factors as "cause" or "dynamic forces" is meaningless and futile. He added that any such interpretation must rise out of further investigation or prior knowledge. Janson (1969) believes that the technique does not replace a careful theoretical and conceptual analysis of a problem but it may be a part of such analysis.

In spite of its advantages shown here and in the following sections, the factor analysis technique has its own limitations. In the course of generalizing and summarizing the observations by factor analysis, as few factors come out from the many variables, some information is inevitably lost (Meyer, 1971; Rees, 1971). It is also noted that although the technique in general is valuable for being objective, for it reduces personal judgement, yet it still includes some subjective practices. Of those practices are the selection of data, selection of programs and ordering the data into rank, indices or cardinal forms. The resultant factors will be dependent on the number of cases and the variables which are in the beginning liable to personal judgement (Chisholm, 1964; Megee, 1964). Janson (1969) mentioned that the technique has been attacked as being misleading for it accounts for the correlations between variables by common factors instead of doing that by causal relation between the variables themselves. He mentioned that even if the variables are clearly clustered, the possibility of a misleading situation cannot be totally avoided. Janson (1969) also pointed out that even when orthogonal factors are produced it does not mean they are independent but only that they are uncorrelated. King (1969) stated that the computation of factor scores is not a straightforward procedure in factor analysis, where only a part of the total variance of the original variables is accounted for by the common factor.

Labelling the factors is believed to be a major problem in the analysis (Megee 1965), and choosing a term, a word or a phrase sometimes becomes a difficult task and might lead to controversy. This problem is especially faced, as mentioned by Taylor (1977), when the variables are many. Megee (1965) here suggests giving only numbers to the factors as one of the ways out. This latter suggestion can be accepted in the more difficult situation, but always trials should be followed to select labelling factors for this helps convey their meaning.

Fields and areas of application

The factor analysis technique was originated in psychology and has been adopted in many fields of study amongst which is geography. Spence and Taylor (1970) described the technique as being the most efficient in ordination and it has been of value in regional taxonomy since first used by Kendall (1939) and Hagood et al. (1941). Berry (1963, 1965, 1966) and his associates, as reported by Megee (1964) and King (1969), made outstanding urban and regional studies which for the most part used factor analysis as an important stage in classification and regionalization of observations. Megee (1964, 1965) also used factor analysis in studies of regionalization of economic development giving a heavier load for the use of the technique in hypotheses testing. The technique was used by Spence (1968) in regionalization of British counties on the basis of employment data. It was also used by Goddard (1968) for analysing office location pattern in London city centre. Mabogunji (1965) used factor analysis to examine some of the demographic impact of colonial economic development on the Nigerian system. King (1966) used the technique in his cross-sectional analysis of Canadian urban dimensions. Goddard and Kirby (1976) reported that the technique was used by Rees (1970) to examine social space in Chicago.

In the field of climate, it is claimed that a true need arises for a classification ideally having reference only to climatic data and one which avoids any subjective judgment in delimiting the boundaries between different climatic types

(McBoyle, 1973). In this context it is thought that the factor analysis technique would be quite useful. McBoyle, quoting Stainer (1965), said that this technique provides "... a genuine rational climatic classification... based on climatic elements only and not... on external factors." Steiner (1965) used this technique to classify the climate of the U.S.A., McBoyle (1973) used it to classify the climate of Australia, and Russell and Moore (1976) used it in their study of the climate of South Africa and Australia, as well as other workers who used it in different parts of the world.

Factor method and computer procedure adopted

McBoyle (1973) whose approach is generally followed in the present study, selected Australia because of its vastness, compactness and its general lowness. He selected the year, January (summer) and July (winter) seasons as basic periods for the study of each year. He collected data for 20 variables for the three periods for each of his 66 selected climatic stations. Those variables were temperature (mean, maximum, minimum), rainfall, raindays, afternoon relative humidity and summer-winter ratios of these climatic elements. By factor analysis of the data McBoyle's study produced 3 main factors to describe the Australian climate, for which he took the first factor as an index of cool moist conditions with special emphasis on winter moisture and summer coolness. His second factor described a tropical summer rain index and the third factor was an index of Mediterranean type with winter rain related to the westerly wind belt. McBoyle then used the factor scores of his 66 stations as an input in a cluster analysis procedure based on Ward's (1963) method and produced sets of 10, 14, and 28 homogeneous climatic regions. McBoyle then compared his results with Köppen's classification of Australia and found the technique was quite useful and deserved applying elsewhere.

The computer programs through which the factor analysis is executed, produce a correlation coefficient matrix and then advance to reduce the variables to a small number of factors with different loadings from the original variables. The outcome is then passed through orthogonal rotation to result in factor scores which are used in regionalization. A detailed description of the procedure of factor analyzing will be given in the following discussion.

It is assumed that, as mentioned before, the variation in a given variable is produced by a number of factors (communality) and by a variation unique to itself. Using the principal axis method, factors are extracted with the first accounting for the maximum amount of variation, the second is then extracted from the residual correlation coefficient matrix accounting for the second amount of variance and so on (Goddard and Kirby, 1976). The number of factors chosen are only those with the sum of squared column loading (eigen values) greater than 1.0. The output will be an unrotated factor solution.

A varimax rotation is made to simplify the explanation of the factor structure by eliminating the intermediate values, between zero and one, and giving a result that has the highest factor loading i.e. either of high or low values. The varimax rotation is thought to be the best method, by which a series of orthogonal transformations of pairs of factors can simplify the columns of the factor loading matrix. The first advantage of rotation is that it is simple for it is accounted for by a single significant common factor. Another advantage over unrotated factors is that they are more stable in the cases when some variables are omitted (King, 1969; On-Kim, 1970; McBoyle 1973; Taylor, 1977).

The final step in factor analysis processing is to calculate the factor scores for each case from factor score coefficients derived from all variables and not just from those with high loadings. Those factor scores can be mapped to simplify the spatial interpretation of factor analysis.

Factor analysis of the climate of the Sudan

Generally, similar variables to McBoyle's (1973) are chosen for the present study, which uses the data for 61 stations. The number of variables are restricted to only 15 instead of the 20 used by McBoyle. The variables used in this study are listed in Table 4.2. These variables generally represent the two outstanding seasons of the year; the dry winter and the wet summer. Raindays, as found to be strongly correlated with rainfall means in January and July, are omitted, but preserved in the case of annual means for they give a general idea about the characteristics of rainfall. The winter - summer ratio variables used by McBoyle are viewed here to be important in the case of temperature. Precipitation

Table 4.2 Climatic variables used in factor analysis at 61 climatic stations

No.	Symbol	Explanation
1	TA	Mean annual temperature, ^{o}C
2	T1	Average January temperature, ^{o}C
3	T1MA	" " maximum temperature, ^{o}C
4	T1M1	" " minimum " , ^{o}C
5	T7	" July temperature. ^{o}C
6	T7MA	" " maximum temperature, ^{o}C
7	T7M1	" " minimum " , ^{o}C
8	TR	Temperature range, July-January, ^{o}C
9	PA	Mean annual precipitation, mm
10	P1	" January " , mm
11	P7	" July " , mm
12	PN	" annual no. of rainy days $>$0.1 mm
13	RHA	Average annual relative humidity (Noon), %
14	RH1	" January" " , %
15	RH7	" July " , %

ratios, because most of the stations have no rainfall in January, are of little value. The same is true of the relative humidity ratio since it is strongly related to rainfall. The other reason for restricting the variables is to make them compatible with the number of stations available and to reduce the possibility of multicollinearity that will be discussed in some detail later in Chapter 6.

Among the 61 selected meteorological stations, 23 stations have their data summarized in the climatic normals for the period 1941-1970, obtained from the Sudan Meteorological Department. The data for the remaining 38 stations have been collected from the Annual Meteorological Reports published by the Sudan Meteorological Department covering the period 1950-1970. In each of these reports each station has a monthly summary of the selected climatic variables. In this study the monthly values have been averaged for as long a period for each station as the records permit (see Table A.4).

Meteorological stations selected for this study differ in their age and the lengths of recording period for each element. Some stations, such as those included in the climatic normals, have long periods of records for most elements. Some other stations although having early beginnings, have suffered closure some time during the study period. An example of these is Wadi Halfa. Other stations, such as Nagishot started at a relatively early time, but have been closed in the later part of the period. In spite of that Nagishot is included in this study for its distinguished climatic elements. There is yet another type of station and those are the younger ones.

However, it can generally be said that the shortest record period is 10 years, with best records of rainfall followed by temperature.

In processing the data the SPSS (Statistical Package for the Social Sciences) package of computer programs described by On-Kim (1970) is used to produce the factor and cluster analysis. Then the resultant hierarchy is used in extracting regions which are shown in maps and block diagrams through the Symap and Symvu programs described by Muxworthy (1972).

From Table 4.3 it can be seen that factor 1 explains 64.6% of the variance. There are highly positively signed loadings on annual rainfall (0.86) and annual raindays (0.88), July rainfall (0.88) and relative humidity (0.85). The highest loadings of this factor are on temperature variables. These are July mean (-0.98), maximum (-0.96) and minimum (-0.97) temperatures, annual temperature (-0.75) and the range of July - January temperature (-0.71), all with negative signs. From this grouping it is suggested that this factor be an index of moisture-temperature condition with particular stress on the moistness and the coolness of summer. It is hence a "moisture and summer coolness index". The factor scores for this index for 61 meteorological stations are shown in Table 4.4

Figures 4.4 and 4.5 show the distribution of the scores of factor 1. It can be seen that the highest positive scores on this factor occur over the southwestern and the southeastern edges of the Sudan. In these areas the highest intensive rainfall combines with the longer rainy season and hence

Table 4.3 Rotated factor loadings

No.	Variable	% Communality over 3 factors	Factor I Moisture and summer coolness index	Factor II Winter warmth index	Factor III Humidity and winter moisture index
1	TA	99.92	-0.7574	0.6224	-0.1954
2	T1	91.41	0.2587	0.9154	0.0966
3	T1MA	88.12	0.3870	0.8092	-0.2767
4	T1M1	83.99	0.1143	0.7661	0.4899
5	T7	98.22	-0.9854	-0.0915	-0.0524
6	T7MA	96.59	-0.9626	-0.1837	-0.0751
7	T7M1	95.27	-0.9759	0.0199	-0.0022
8	TR	89.08	-0.7178	-0.6104	0.0056
9	PA	91.24	0.8662	0.3544	0.1908
10	P1	74.07	0.1707	-0.0159	0.8422
11	P7	92.28	0.8829	0.3691	-0.0838
12	PN	91.11	0.8803	0.3299	0.1654
13	RHA	98.51	0.5964	0.3042	0.7328
14	RH1	89.56	-0.1584	-0.0451	0.9321
15	RH7	94.60	0.8533	0.4216	0.2002
% of total variance or communality			64.6	18.1	17.4
Eigenvalue			8.87042	2.4848	2.38467

High factor loadings > 0.70 (underlined)

For interpretation of symbols see Table 4.2

TABLE 4.4 FACTOR SCORES OF FACTOR ANALYSIS FOR 61 CLIMATIC STATIONS

NO	NAME	FACTOR 1	FACTOR 2	FACTOR 3
1	WADI HALFA	-1.411698	-2.330564	-0.287420
2	STATION 6	-0.960319	-1.805862	0.195723
3	PORT SUDAN	-2.063675	0.018362	4.044733
4	ABU HAMAD	-1.507531	-0.633577	-0.476250
5	DONGOLA	-1.590177	-0.877751	-0.029942
6	GEBEIT	0.196487	-2.531593	1.878818
7	KARIMA	-1.644615	-0.567002	-0.416087
8	TOKAR	-2.295544	0.824407	3.495604
9	HAIYA	-1.229382	-0.312487	0.697043
10	ATBARA	-1.468241	-0.047977	-0.413218
11	DERUDEIB	-1.350103	0.305002	-0.063592
12	SHENDI	-1.296037	0.258389	-0.317345
13	AROMA	-0.943111	0.573499	-0.161755
14	SHAMBAT	-1.069114	-0.210596	-0.514099
15	KASSALA	-0.478456	0.638204	-0.582947
16	HALFA EL GEDIDA	-0.616039	0.271747	-0.382936
17	ET TURABI	-0.276247	-0.238891	-0.979251
18	ABU QUTA	-0.334710	-0.217885	-0.853238
19	QURASHI	-0.185772	-0.217177	-0.979879
20	SODIRI	-0.203987	-1.675320	-0.543639
21	WAD MEDANI	0.077125	-0.262659	-1.094017
22	EL MANAQIL	-0.548411	0.189078	-0.315145
23	KUTUM	0.461019	-2.723604	-0.266698
24	GEDAREF	-0.023111	0.807551	-0.496584
25	DUEIM	-0.621411	0.147483	-0.344747
26	HAGARDALLA	0.076862	0.070983	-0.625596
27	EL FASHER	0.014972	-1.488779	-0.618235
28	SENNAR	-0.221951	0.502420	-0.486709
29	GENEINA	0.813955	-1.040723	-1.316708
30	EL OBEID	-0.220641	-0.215431	-0.806268
31	KOSTI	-0.598179	0.661105	-0.445337
32	SINGA	-0.207483	0.733146	-0.577715
33	ZALINGEI	1.182700	-1.659101	-1.276594
34	ABU NAAMA	0.599792	0.560248	-0.974074
35	EN NAHUD	0.233547	-0.175674	-0.883596
36	NYALA	0.285152	-0.113181	-1.129998
37	RASHAD	-0.110400	0.518265	0.214114
38	ROSEIRIS	0.278312	1.092261	-0.473019
39	ED DAMAZIN	0.593744	0.758019	-0.850963
40	ER RENK	-0.175292	0.481557	0.100016
41	GHAZALA GZT	0.308478	0.328569	-0.716805
42	KADUGLI	0.229458	0.752024	-0.108584
43	KURMUK	0.728508	1.109939	-0.307716
44	MALAKAL	0.453323	1.069871	-0.074755
45	AWEIL	0.599967	0.864172	0.104099
46	NASIR	0.323683	1.146982	0.913272
47	RAGA	1.066150	0.048526	-0.434087
48	AKOBO	0.542077	1.535352	0.579506
49	WAU	0.693586	0.884149	-0.412839
50	TONJ	0.934601	1.083020	0.551097
51	SHAMBE	0.572612	0.023842	0.519502
52	PIBOR	0.465763	1.165505	0.341443
53	RUMBEK	0.420658	1.048525	0.648643
54	BOR	0.579124	-0.060605	0.768039
55	LI YUBU	1.013822	0.275106	1.122463
56	MARIDI	2.100019	0.134117	1.077698
57	JUBA	0.437157	1.278606	0.741347
58	YAMBIO	1.549916	-0.077716	0.967577
59	TORIT	0.760041	0.596284	0.488175
60	NAGISHOT	3.468149	-2.958315	1.963072
61	YEI	1.584527	-0.309201	0.628229

Fig.4.4 SCORES OF FACTOR 1 FOR 61 CLIMATIC STATIONS
(×100)

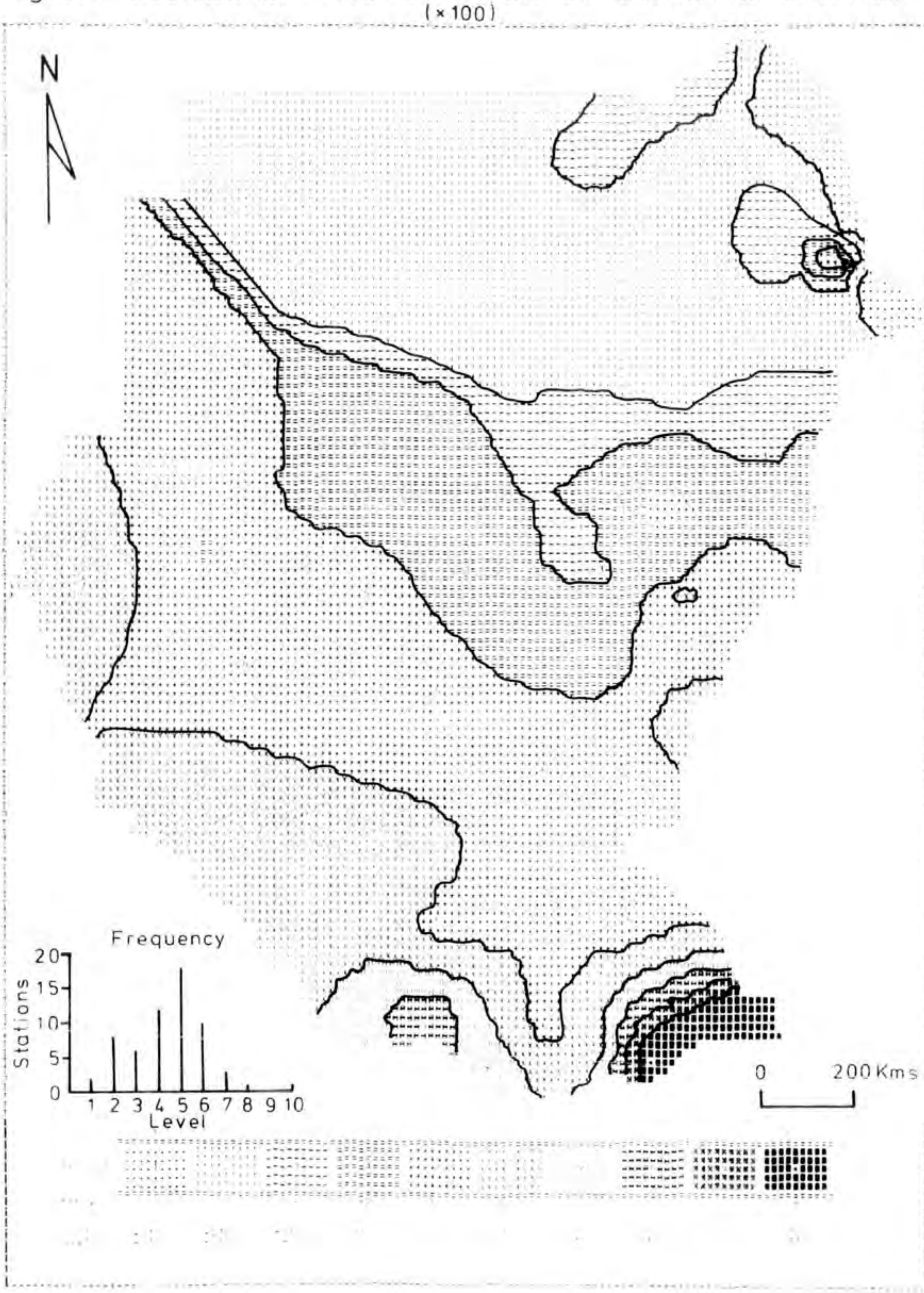
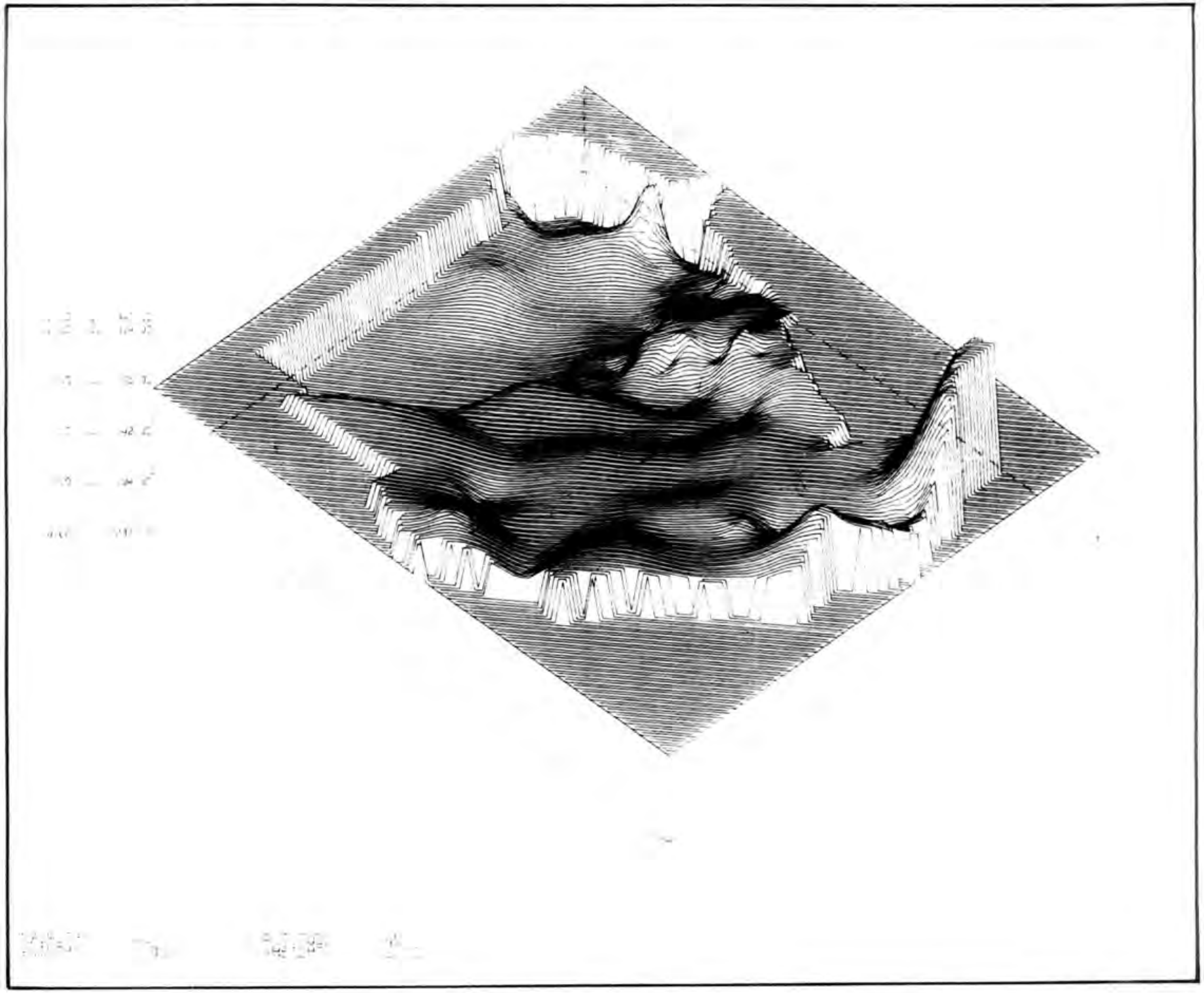


Fig.4.5 SCORES OF FACTOR 1 (×100) FOR 61 CLIMATIC STATIONS



relatively cooler temperatures in summer are expected. The climax, here, is at the southeastern corner of the country, the Nagishot area, where the lowest values of temperatures led to its highest scores of this factor (3.4). Low scores are shown in areas of drier climates with hotter summers tending to appear in the northern part of the country. The highest negative value is on the Red Sea coast (-2.3) where hot dry conditions prevail in the summer season, together with temperatures always high throughout the year. The relative dryness of the White Nile area, as mentioned by El Tom (1974) is also confirmed by this factor showing isolines bending southwards on that area compared with those to the east and west of it.

Factor 2 explains 18.1% of the total variance, and from Table 4.3 it can be seen that the highest loadings are on January temperatures, i.e. mean, maximum and minimum with positive values as 0.91, 0.81 and 0.76 respectively. This factor as it denotes special emphasis on winter warmths, can be described as a "winter warmth index".

From Figures 4.6 and 4.7 a general line can be drawn running from southwest through the centre to the north east of the Sudan. This line roughly separates the positive scores from the negative scores. The hot winter conditions are shown by most of the stations located to the east of that line; the highest score (1.5) is at Akobo in the south east. An exception to that is the highest negative score, indicating lower winter temperatures, given by Nagishot (-3.0) in the extreme south east. The high altitude of this station means that its climate has much cooler winters than its surrounding area. Moving northwards temperatures drop resulting in changes of the scores to the negative side where the highest scores are at Kutum (-2.7) and Wadi Halfa (-2.3) in the northwest and the north, respectively. The relative nearness of these areas to the centres of high pressure areas and trade winds' origin seem to confirm this pattern. The local effect of the Red Sea on the north eastern coast is shown by high scores i.e. warmer winter conditions than others of the same latitudes. The relief effect that was mentioned in the case of Nagishot is also noticed at Kutum (-2.7) in the north west and Gebeit (-2.5) in the north east.

Finally, factor 3 accounts for 17.4% of the total variance. It is noted that this factor is quite close to factor 2 in its percentage of total variance (18.1%). The highest loadings of this factor are on January rainfall, January relative humidity and annual relative humidity with coefficients of 0.84, 0.93 and 0.73 respectively. This factor explains general humidity conditions with mainly rainy winters accompanied by high winter relative humidity (afternoon). This factor can be designated as "humidity and winter moisture index". The highest scores (Figs. 4.6, 4.7; Table 4.4) are shown in the Red Sea coastal area (4.0) followed by the extreme southern frontiers of the Sudan (1.9). In contrast to these two areas the remaining vast areas of the country have low scores of this factor.

In total the three factors chosen for this study explain over 99% of the total variance with the most important factor

Fig.4.6 SCORES OF FACTORS 2 AND 3 AT 61 STATIONS

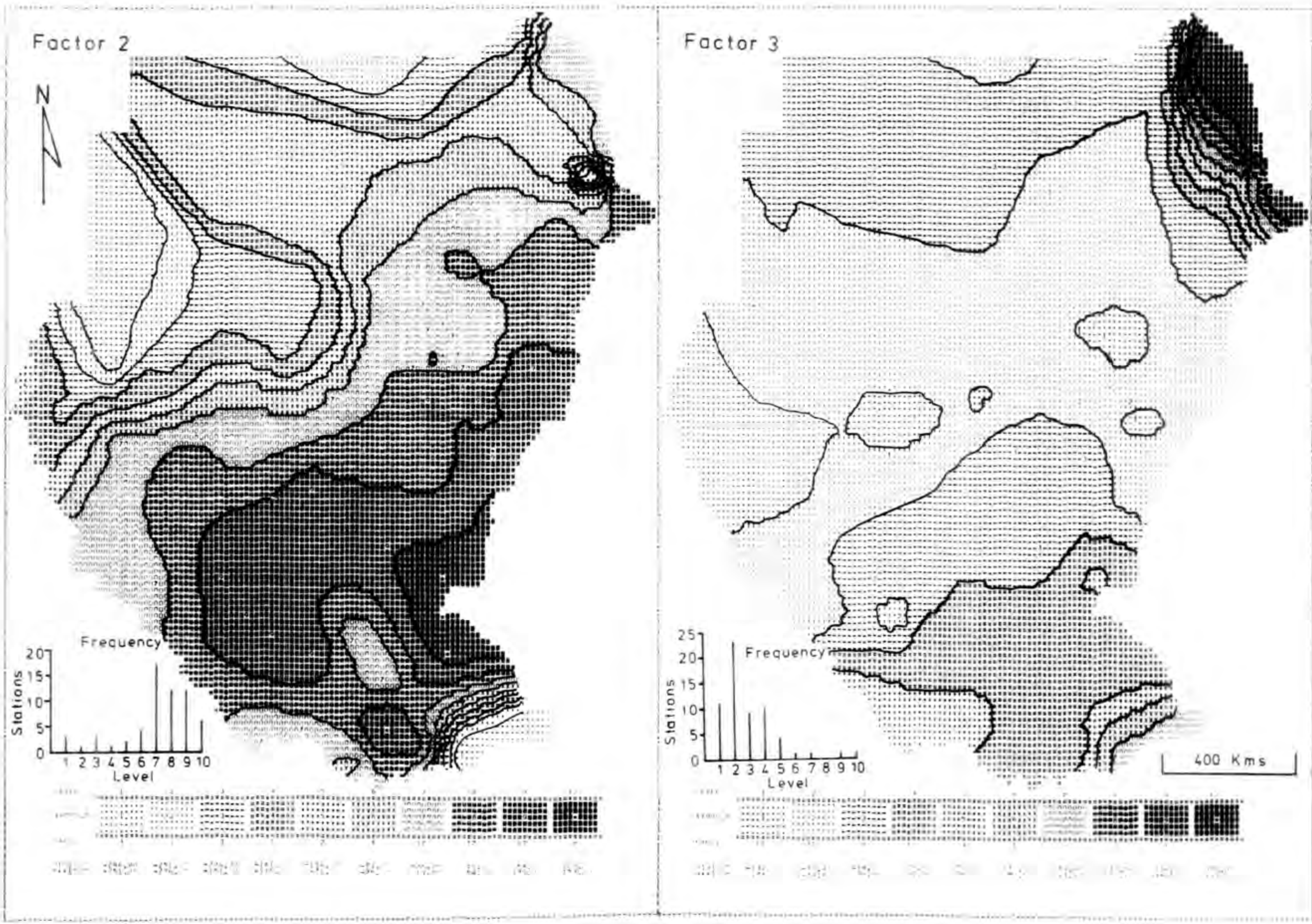
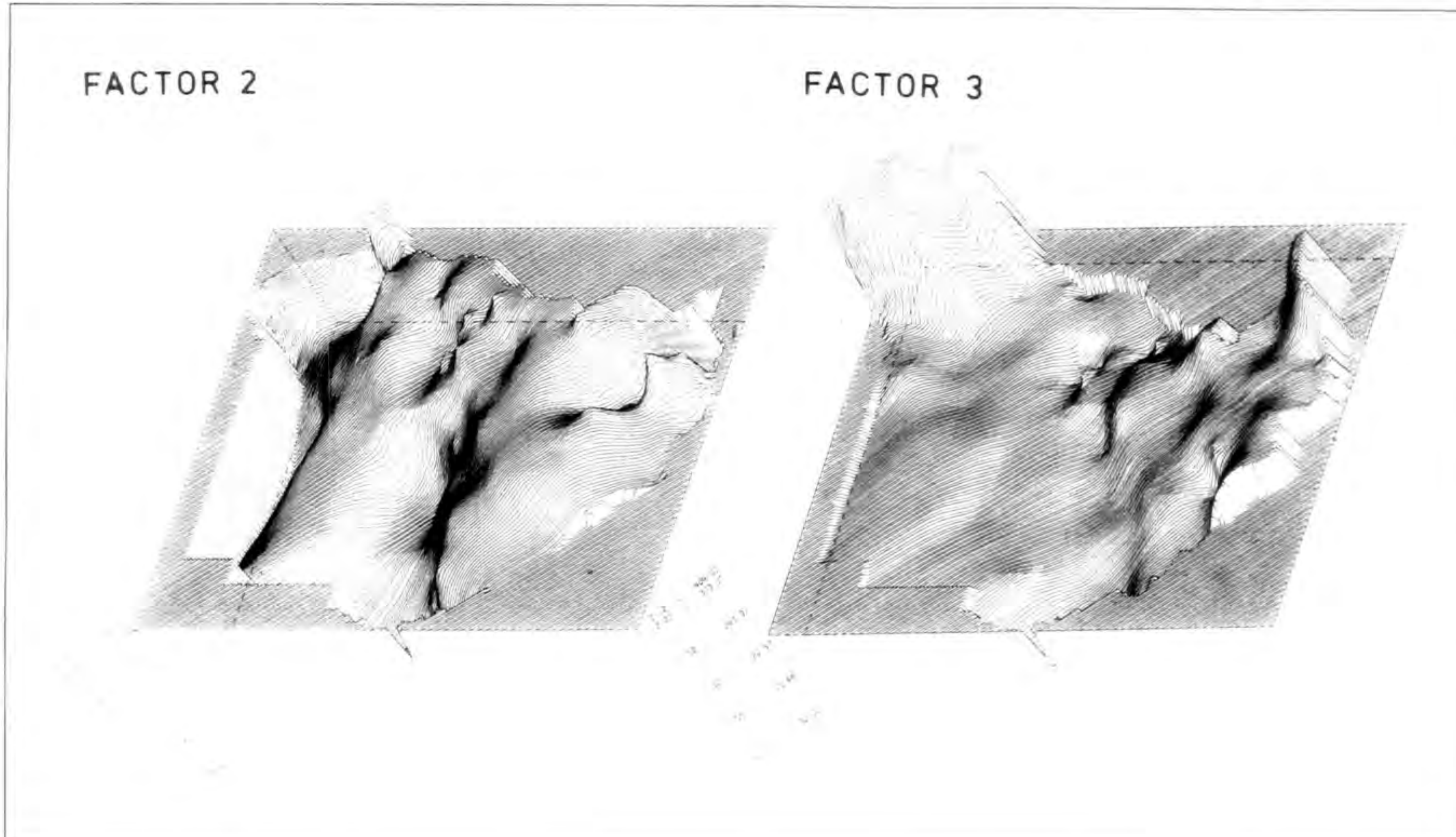


Fig.4.7 SCORES OF FACTORS 2 AND 3 FOR 61 CLIMATIC STATIONS



(factor 1) which denotes mainly moisture condition especially in summer. Factors 2 and 3 with similar powers of explaining the total variance, are far less important than factor 1. They both explain winter conditions, each identifying different aspects. Factor score coefficients (Table 4.5) can be used for calculating factor scores for other stations to add to the accuracy of the maps. All the coefficients in the column of the factor in consideration should be included and not only those with high loading variables.

4.4.2 Cluster analysis

Cluster analysis is a form of correlation analysis, a method of searching for relationships in a large data matrix. The technique is unlike factor analysis in that it does not involve artificial or abstract factors (Parks, 1966). The present study, following that of McBoyle (1973), includes both the techniques where the final step of the factor analysis (factor scoring) is followed by taking the factor scores as an input for cluster analysis to develop clusters for climatic regionalization.

One of the most famous cluster analysis methods is that developed by Ward (1963). Here a hierarchical grouping prodedure is followed to account for similarity of group members with respect to many variables. The purpose is to form each possible number of groups n, n-1, ...1, in a manner to minimize the loss of information. The first step is to combine the two clusters P and Q whose fusion yield the least increase in the error sum of squares, which is the sum of the distance from each individual to the centroid of its parent cluster n, resulting in n-1 groups. The next step is to examine the n-1

Table 4.5 Factor score coefficients

No.	Variable	Factor		
		1	2	3
1	TA	-0.11664	1.71804	-0.27173
2	T1	-0.17035	0.57452	0.16957
3	T1MA	0.20974	-0.41846	-0.11456
4	T1MI	0.01076	-0.52872	-0.00559
5	T7	-19.72784	7.51409	7.85040
6	T7MA	12.02025	-5.90341	-5.39895
7	T7MI	7.60561	-3.15732	-2.60074
8	TR	-0.26989	0.52896	0.10779
9	PA	0.41641	-0.20193	-0.58056
10	P1	0.33609	-0.08014	-0.11730
11	P7	-0.10043	0.16083	0.06871
12	PN	-0.36042	0.21061	0.24538
13	RHA	0.21814	0.51819	1.89852
14	RH1	-0.59320	0.07912	-0.07021
15	RH7	0.05382	-0.08606	-1.21875

* For interpretation of symbols see Table 4.2

groups to determine if a third member should be united with the first pair or another pairing made in order to secure the optimum value of the objective function for n-2 groups. This procedure can be continued until all original observations (n) become one group, the stage at which all the information is lost.

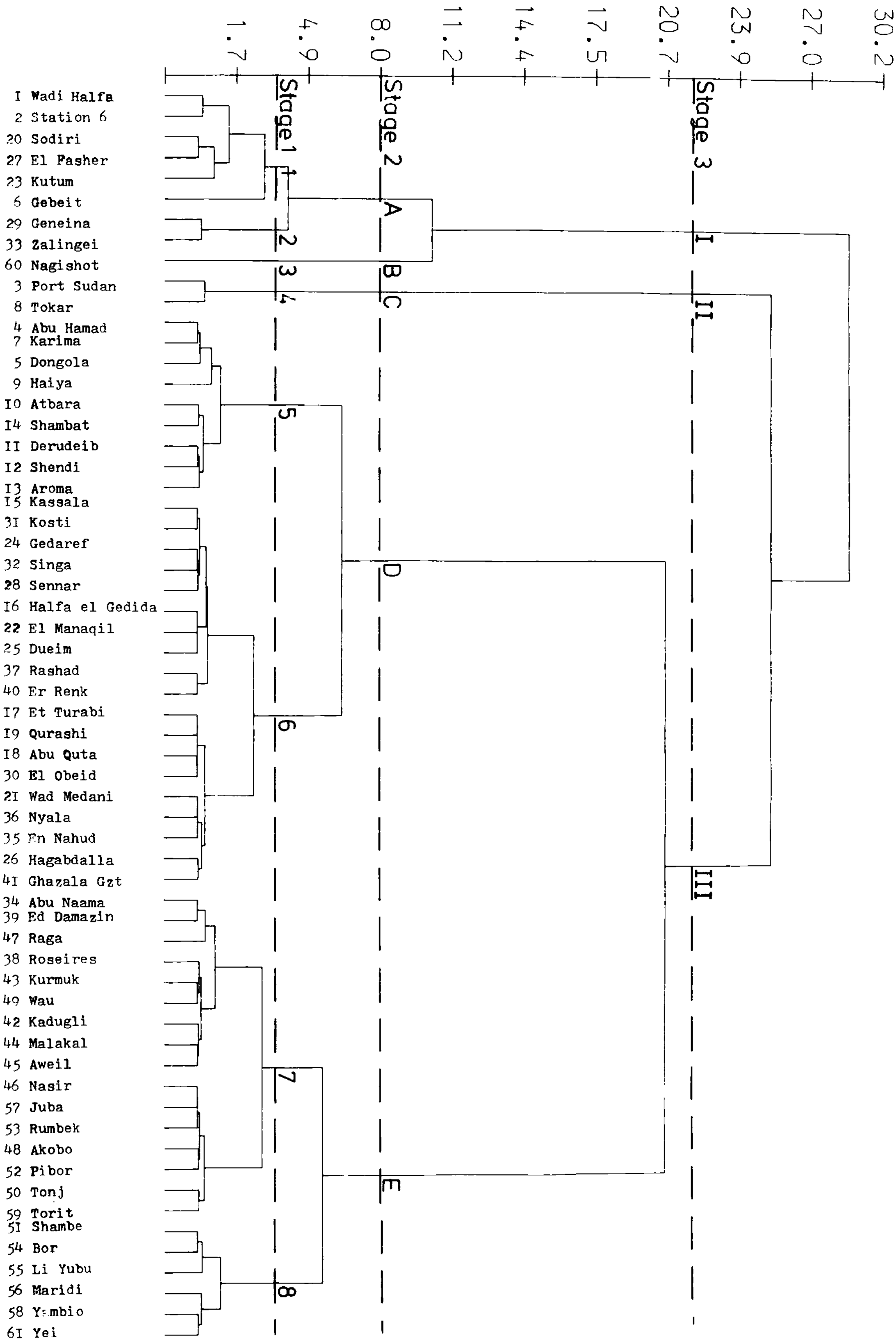
A linkage tree (dendrogram) can be drawn to show each stage of a grouping analysis, together with the build up of grouping in terms of the original observations. From that dendrogram distinct clusters can be picked out either by breaks in the diagram or by arbitrary lines. These groupings, as mentioned before, can be taken as a base for mapping the considered phenomenon (Berry, 1964; Goddard, 1968; Spence, 1968; Wishart, 1978).

4.4.3 Factor-Cluster analysis of climatic regions of the Sudan

The purpose of this study as mentioned in the previous section (4.4.2) is to take the factor analysis a step further. The scores of the three abstract factors from the 15 variables of the 61 stations were used as an input in the cluster analysis computer program based on Ward's 1963 method and invoked to link all the stations in groups so as to result in climatic regions. McBoyle (1973) drew attention to the fact that there is no guarantee through this method of grouping of obtaining contiguous regions. The resultant output dendrogram based on the data of the 61 climatic stations is shown in Figure 4.8.

The boundaries drawn on the country's map can either be looked at as demarcating regions with a degree of homogeneity

Fig. 4.8 HIERARCHICAL CLUSTERING OF 61 STATIONS IN THE SUDAN (WARD'S METHOD)



or viewing different climates from a position away from the boundaries. Three stages of grouping in the dendrogram tree are considered for the Sudan, beyond which the results will be of little use for this study which seeks generalizations. A larger number of regions will serve only studies of local purposes, while fewer will cause the bulk of information to be lost.

Eight climatic regions

From Figure 4.8 the first stage considered shows eight climatic regions in the Sudan. The first thing noticeable in studying the map produced from this clustering (Fig. 4.9), is the general east-west manner of boundary demarcation for the major regions, roughly at latitudes 16^{o}, 13^{o} and 7^{o}N. North of latitude 16^{o}N region 1 is shown as a fragmented area in the extreme north east, north and north west of the Sudan, the fragments separated by region 5. From Table 4.6 it can be observed that temperature emerged as one of the basic criteria to distinguish this region. Lowest values of winter temperatures are shown here with lowest scores on factor 2. The scores of factor 1 for the stations of this region are not homogeneous and they mingle with areas in other regions.

Region 2 of this procedure is shown as a small triangular locality in the extreme western Sudan, south west of the Marra Mountains. This region is characterized by a relatively higher degree of moistness than its surrounding area in that part of the country, for it lies on the windward side of the mountains, in the face of the moisture bearing south westerly winds. It also has different winter conditions from surrounding areas, especially those to the north east. In this season

Table 4.6 Value limits of climatic variables in 8 regions identified by factor analysis

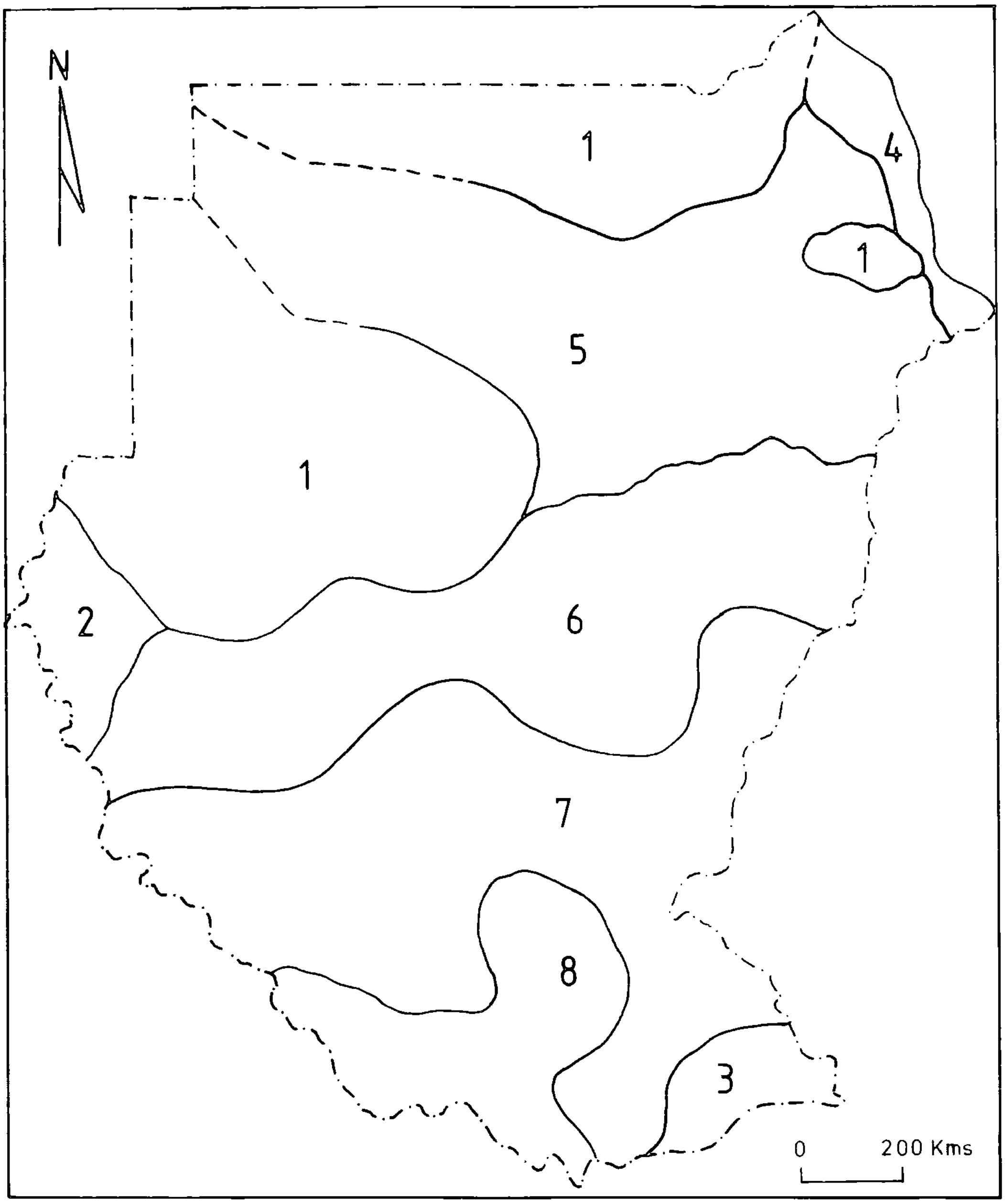
	Variable	1	2	3[1]	4	5	6	7	8
1	TA(°C)	23.3-26.4	24.0-25.7	18.0	28.4-29.9	27.6-29.8	26.5-29.2	25.8-28.1	24.6-27.4
2	T1(°C)	16.5-20.3	20.2-22.0	19.0	23.6-24.5	18.6-24.5	22.1-26.1	23.1-28.7	20.1-26.2
3	T1MA(°C)	24.0-30.6	32.2-34.0	24.3	27.3-28.6	27.8-33.9	30.6-34.9	34.4-36.8	33.2-35.7
4	T1M1(°C)	8.2-15.0	6.3-11.7	13.7	19.9-20.3	9.3-16.3	12.3-17.3	11.4-21.0	15.9-20.4
5	T7(°C)	26.5-32.9	25.1-26.4	16.2	34.3-34.4	30.1-34.4	25.0-29.9	24.8-27.1	22.6-26.3
6	T7MA(°C)	32.9-41.4	30.9-32.0	20.5	40.3-40.6	37.5-41.7	30.0-36.8	30.3-32.5	28.3-32.0
7	T7M1(°C)	20.1-24.7	19.3-20.8	12.4	27.9-28.5	23.8-27.2	19.9-24.0	19.4-21.7	16.9-20.9
8	TR(°C)	8.5-16.4	4.4-4.9	2.8	9.9-10.7	6.8-14.1	1.0-7.3	0.2-3.9	0.6-5.8
9	PA(mm)	3-316	559-665	1184	87-122	15-227	242-582	574-1188	729-1476
10	P1(mm)	0-2	0.0	15	18-23	0-0	0-0	0-9	1-12
11	P7(mm)	1-86	168-189	201	9-10	6-63	75-159	123-210	142-194
12	PN(mm)	1-32	54-62	99	12-13	3-21	20-63	54-100	45-117
13	RHA(%)	17-41	24-27	62	47-15	16-28	23-31	31-49	47-56
14	RH1(%)	15-57	11-14	46	63-67	20-32	13-27	17-33	27-34
15	RH7(%)	15-37	48-52	79	27-45	16-37	34-59	54-68	62-69

* For interpretation of symbols see Table 4.2

(1) Region 3 does not have a range of limits because it has only one meteorological station.

Source : Sudan Meteorological Department : (1) Annual meteorological Report, (2) 1941-1970 Climatic normals, Khartoum, Sudan.

Fig.4.9 EIGHT CLIMATIC REGIONS PRODUCED BY FACTOR AND CLUSTER ANALYSIS



the prevailing winds are the north easterly trade, cooler and relatively more humid on the windward side of the mountainous area than when they cross to the leeward side i.e. region 2 in this case, and lose some of their properties. From Table 4.6 it can be observed that this region is remarkably wetter than region 1. The annual rainfall here is twice that of region 1 at around 600 mm. Considering temperature, region 1 is always cooler in winter and hotter in summer than region 2. The difference between the two regions in terms of temperature in winter is 1.6°C between the highest limit of region 1 and the lowest limit of region 2 for the January maximum. The lowest record of July maximum temperature for region 1, 32.9°C, is almost 1°C above the highest value in region 2. Relative humidity shows higher values in region 1 in January, and lower values in region 1 in July.

Region 3 emerged in the extreme south-eastern highlands of the Sudan, the Nagishot area near the borders of Uganda. This area shows the highest scores on factor 1 (positive), high on factor 3 (positive) and highest negative score on factor 2. The distinction between this region and its neighbour, region 7, can be clearly defined on temperature. Temperature is the outstanding criterion for this distinction. In fact, lower temperatures in this region distinguish it from anywhere else in the Sudan. The average annual temperature is only 18.0°C whereas this value, in most areas of the Sudan, is exceeded by 6°C, and it shows a difference of about 12°C when compared with the highest values in the country. Relative humidity and January rainfall are higher in regions 3 than in region 7.

Region 4 picked out the Red Sea coastal strip as an area distinguished from any other part of the Sudan. The region is characterized by hot dry summers, and hot and relatively wet winters. The reason behind this, as shown in Chapter 3, is that in summer the moist south westerly winds lose most of their moisture before reaching this remote area from their source of origin, notwithstanding the fact that the Red Sea Hills stand as a barrier between those winds and the coast. In winter the coastal area is visited by the north easterly trades and the south easterly winds and both, passing over the narrow Red Sea, cause some rainfall in the course of their ascent of these hills. That winter rainfall, though low in general terms (20 mm.), is the highest in the Sudan.

The other regions (5, 6, 7, and 8) are more homogeneous with consistent north to south ordering, distinct from regions 2, 3 and 4 which emerge as small limited areas. This north to south ordering can directly be matched with factors 1 and 2 ordering, and it goes logically with the moistness of the regions. The basic difference between region 1 and the region next to it from the south, region 5, is mainly the mean annual temperature. It is noted that while the lowest value of temperature in region 5 is 27.6^{o}C, the highest one in region 1 is short of this by 1^{o}C. In region 5 the upper limit of mean annual temperature is 29.9^{o}C. It deserves noticing that the boundaries between these two regions in the northwestern corner of the country are shown by broken lines which are interpolated between widely spaced stations because of the lack of climatic data in that area. This interpolation performed by the Symap program is an artifact which does not necessarily represent the true situation. From here the lines may bend and join with each other as shown in Figures 4.9, 4.10 and 4.11 to result in one region covering the whole northwest as region 1 becomes unified.

Region 6 coincides with the important Central Ráinland agricultural area to the Sudan which includes the Gedaref area in the east and central Kordofan and Darfur in the west. And although the annual rainfall in that region (242-582 mm. p.a.) is not so reliable as to secure yearly guaranteed high agricultural production, yet this region is distinct from region 5 (15-227 mm. p.a.) where such a type of agricultural activity can hardly be found.

Region 7 is wetter than region 6 as it lies to the south of it. The rainfall within this region ranges between 574 and 1188 mm. p.a. It can be observed from Table 4.6 that the upper limit of rainfall in region 6 overlaps the lower limit of this region. Some parts of region 7 enjoy winter rainfall and more summer rainfall than those of region 6. The annual relative humidity of the region (31-49%) is always higher than that of region 6 (23-31%). Another remarkable distinction is that this region has higher day temperatures in January (34.4^{o} - 36.4^{o}C) than those of region 6 (30.6^{o} - 34.9^{o}C) for the same period.

Region 8 which occupies the southwestern corner of the Sudan is surrounded by region 7 from the north and the east. The centre of the boundary separating these two regions bulges in a northeastern direction permitting region 8 to include the swampy area of the southern Sudan. Table 4.6 shows that generally cooler and wetter conditions are found in region 8 if compared with region 7. The annual rainfall ranges between 729 and 1476 mm. in region 8 and between 574 and 1188 mm. in region 7. The considerable overlap here can be understood from the location and the orientation of this region, a clearly more humid than region 7, and the annual relative humidity of region 8 ranges between 47 and 56% amongst the stations while that of region 7 ranges between 31 and 49%.

This stage of grouping the meteorological stations of this study is believed to be the best between the stages as will be seen later. It also has the advantage over the possible grouping of the stations into eleven regions for generalization purposes, but for specific inspection of the climate for different purposes such grouping might be useful. As can be seen from Figure A.3, the eight region grouping, as a further step from the eleven regions grouping, is different in three areas:

1) The closed area of Gebeit in the extreme north east (1b) which is considered as a separate region in the eleven regions grouping is attached to region 1 (1a). Region 1b is characterized by having higher day temperature (24 ^{o}C) and lower night temperature (15 ^{o}C) in winter as well as it has higher night temperature (24.7 ^{o}C) in summer, than those of region 1a. Another difference is that region 1b receives winter rainfall and has a higher annual and summer relative humidity than that of region 1a.

2) The regions denoted as 6a and 6b by the eleven regions grouping are included in region 6 in the eight regions

grouping in which the region is permitted to run from the eastern to the western boundaries of the country. It can be seen that region 6a occupies the western part, while region 6b occupies the eastern part of the mother region (6), and region 6a extends southwards in its eastern part to include the stations of eastern Gezira along the Blue Nile. The main difference between these subregions is that winter temperature (January average) is always below 24^{o}C in region 6a while it is in most cases above that figure in region 6b.

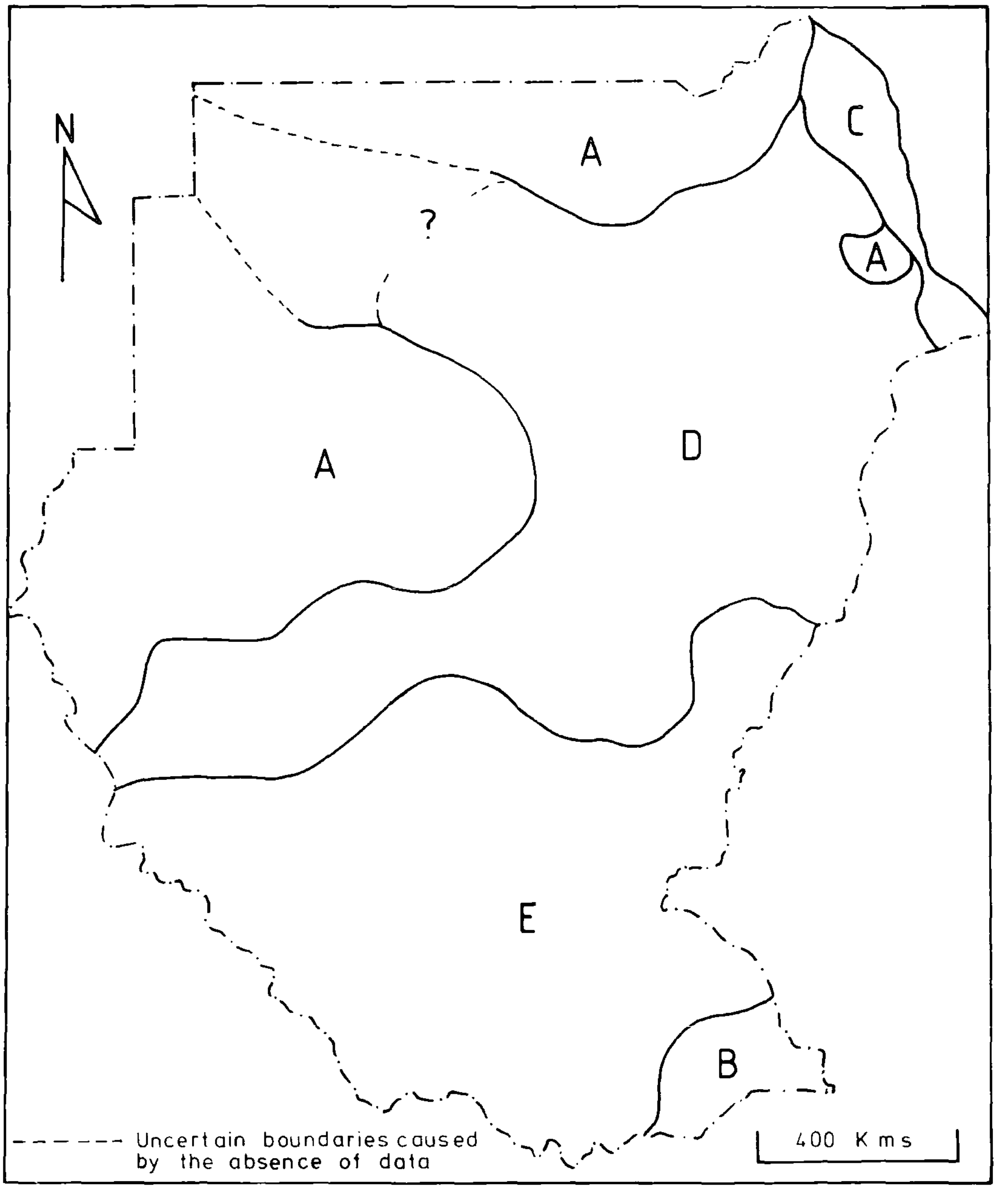
3) The regions denoted as 7a and 7b by the eleven regions grouping are the northern and the southern parts of region 7 in the eight regions grouping. The difference between these subregions is that region 7b receives winter rainfall, while region 7a is dry in this season. Added to that is the higher relative humidity (annual and January) and the higher amount of rainfall found in region 7b over that of region 7a.

This stage of grouping is followed by a stage which will simplify the regional climatic classification map and that will of course be accompanied by loss or information and a lesser degree of accuracy. However, it is useful for a quick summary of the country as a whole.

Five climatic regions

The second stage of grouping considered in this study resulted in fewer regions with larger clusters. It can be seen from Figures 4.8 and 4.10 that 5 regions emerged at this stage. From comparing Figure 4.10 with Figure 4.9 it is observed that some groups that are akin to each other are

Fig. 4.10 FIVE CLIMATIC REGIONS PRODUCED BY FACTOR AND CLUSTER ANALYSIS



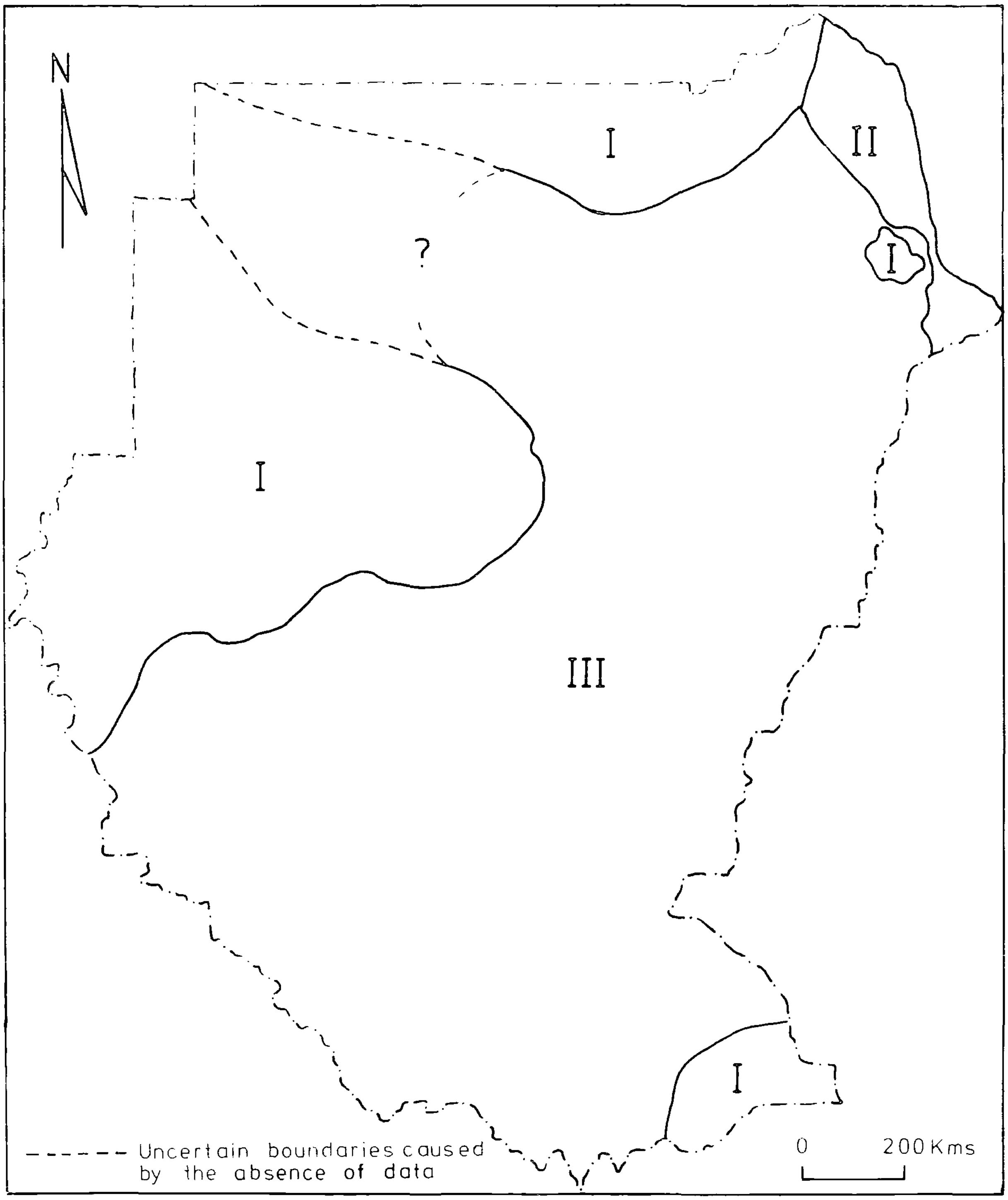
amalgamated together. Although, at this stage the general impression given by the previous stage regionalization is broadly preserved, this grouping led to the inevitable loss of information compared with the eight group scheme as mentioned earlier. The result is relatively more internally hetorogeneous regions. An example of this distortion is the showing of regions 5 and 6 of the first stage as a single region (D) in this stage and the difference was previously discussed. Another example of this distortion is the combination of regions 7 and 8 to become region E. Again although the general impression of a wetter region than the north is preserved, the inclusion of areas with lowest values of annual rainfall (574 mm.) of region 7 with areas having 1476 mm. in the southern part of region 8 is an obvious discrepancy.

However, this stage of regionalization identifies the generally dry north (A,D) and the relatively moist south (E) together with the uniqueness of regions B and C. The latter share more rainfall and higher relative humidity in winter as represented by January figures, but they differ in their general moistness, especially in summer. This stage is believed to be of some value for it gives a generally quicker summary of climatic regions of the Sudan.

Three climatic regions

Step 3 in Figure 4.8 is taken to examine the situation when all the observations are clustered in only three major groups. The result of this step is presented in Figure 4.11. In reality in a country as large as the Sudan these three regions can hardly be considered as satisfactory climatic

Fig. 4.11 THREE CLIMATIC REGIONS PRODUCED BY FACTOR AND CLUSTER ANALYSIS



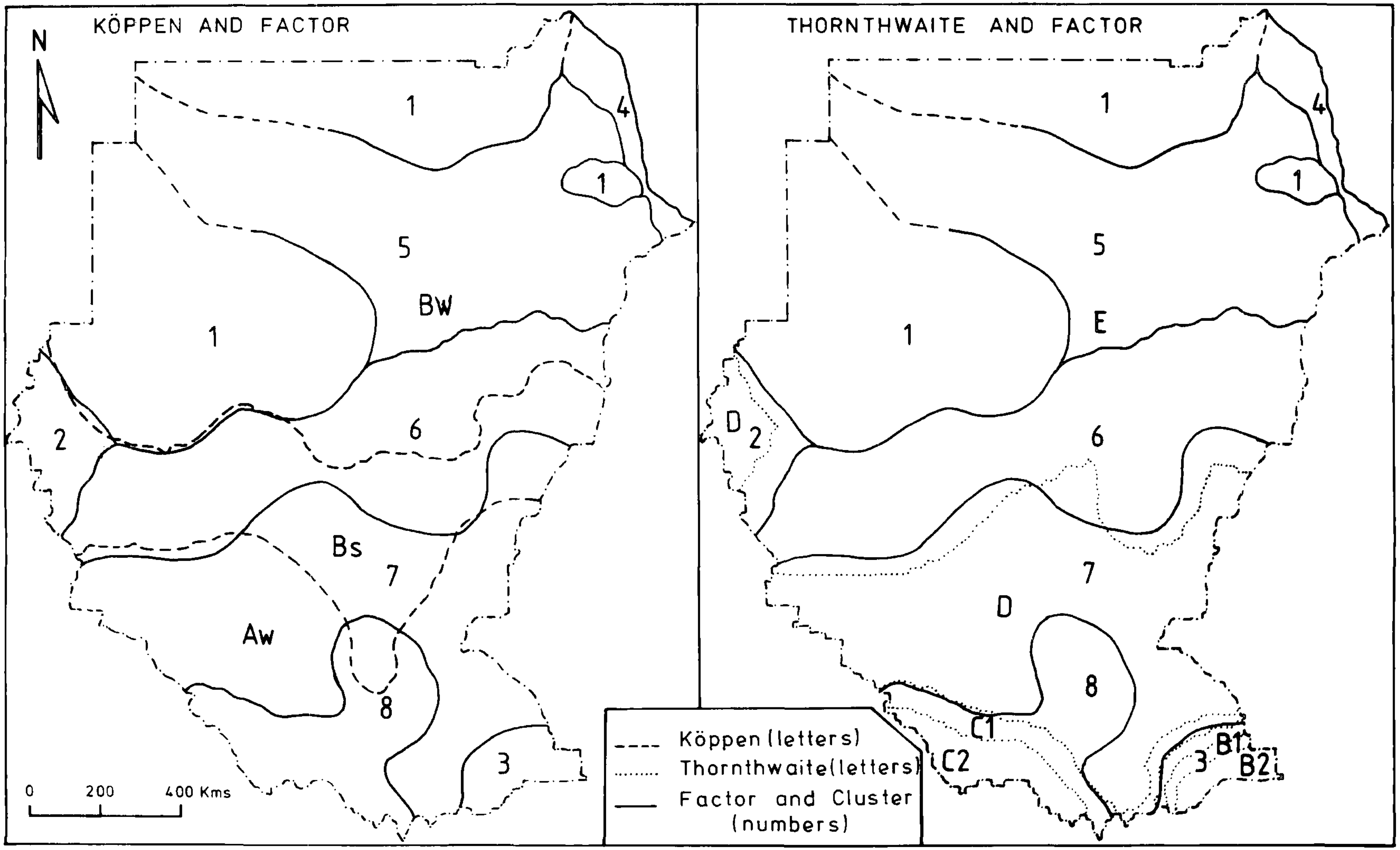
regions. However, some crude idea can be obtained from these broad regions. Region I is a result of combining regions A and B of the previous stage. The reason for including those regions, although they quite contrast with each other in terms of moisture, is that region A is akin to region B in terms of winter temperature conditions. Temperatures here are milder than those of the rest of the country. Region C of the Red Sea Coast remained distinct here also and is designated as region II. The distinctiveness of the Red Sea climate, elaborated on in Chapter 3, is because of its dry summer and rainy warmer winter in relation to the prevailing circulations over land and sea. Regions D and E are united in region III, to include the majority of lands of the Sudan. It seems logical to relate the latter regions (D & E) to each other for their broadly shared characteristics of summer rainfall pattern and lack of big differences in temperature inside the new region when compared with other regions.

4.5 Comparison among the three classifications

In this section a comparison among the factor-cluster analysis method identifying 8 regions, Köppen's and Thornthwaite's methods will be made. The comparison is dependent on Figure 4.12 which includes 2 maps each showing a pair of classifications.

Köppen's and Thornthwaite's methods identifying the tropic-to-equator order of regions of the Sudan is in the same way shown in the factor analysis regionalization. This order to a large degree denotes the significance of moistness

Fig. 4.12 A COMPARISON OF CLIMATIC REGIONS PRODUCED BY KÖPPEN'S, THORNTHWAITE'S, AND FACTOR AND CLUSTER ANALYSIS METHODS



in the Sudan climatic regionalization. Besides that, the factor-cluster analysis technique identified more climatic regions than did Köppen's and Thornthwaite's. Köppen's method described most of the Sudan as being either desert or dry steppe and so did Thornthwaite's method as it labelled the majority of the country as either arid or semi-arid. It is noted that Köppen's regions occupied more northerly latitudes than those of Thornthwaite's, and its boundaries in central Sudan had a tendency to bulge to the south in Central Sudan and are further north to the east and west. Thornthwaite gives more regions in the extreme south, while Köppen shows some differentiation of the northern lands that are ignored by the former. In the western Sudan, Thornthwaite identifies an area more humid than the interior lands which are missed by Köppen.

As can be observed from Figure 4.12 Köppen's boundaries fit nicely with those of the factor analysis in the western part of the Sudan and deviate from it towards the east with the largest discrepancy at the centre. Better agreement can be found by comparing the factor analysis with the Thornthwaite's boundaries in the southern half of the Sudan where they are both represented. First, the boundaries separating regions E and D of the former and between 6 and 7 of the latter classification are almost coincident. To the south, the Thornthwaite's C group is summarized by factor analysis as region 8 in the south west while his C and B regions are summarized by region 3 in the south east. A noticeable difference is that region 8 of factor analysis bulges northward to contain the swampy Sudd region into the wetter area, while

Thornthwaite excludes it, but still the tendency of being in the same direction can be picked up from the map.

Thornthwaite has shown more satisfactory detailed regions in the extreme south west and south east, based on the degree of moistness. Similar details for those areas can be picked up from the dendrogram (Fig. 4.8), but unless needed for special purposes deeper detail will suffer the disadvantage of spoiling the generalization and simplification recommended earlier in this chapter. Another similarity between factor analysis and Thornthwaite's method is that they both identify the remote western triangular region, with the difference of the factor analysis treating it as a separate region, whereas Thornwaite links it to climatic region D.

Köppen's general description of most of the Sudan as desert or dry steppes is believed to be unjust particularly for areas in the south when his boundaries of dry regions occupied deep southerly positions resulting in exaggeration of dryness. Thornthwaite is noticed to be more unjust for the north for he ignores the climatic differences between regions such as regions 5 and 6 identified by the factor analysis method. In this area it can be seen from Table 4.6 that the difference between the two regions is quite significant, especially in terms of moistness where the average annual rainfall of region 6 (412 mm) is more than three times the average of region 5 (121 mm). Besides that the two regions have significant differences in humidity and summer temperatures.

The factor analysis technique has the advantage over both Köppen's and Thornthwaite's methods by virtue of its ability to recognize more regions. The main reason for that is that factor analysis, calculated by computer programs, obtains its regions by numerical hierarchical methods using different climatic variables, whereas the other two methods apply different hierarchies of climatic variation depending on only one climatic element. The factor analysis technique made it easy to change the grouping from a general tropical description of the Sudan as examination of local differences in order to serve local purposes. This can be done where numerous regions can be obtained.

The factor analysis technique is also praised for outlining rational climatic boundaries not influenced by an external factor such as vegetation or soil type (McBoyle, 1973). It is a data-based technique where subjectivity is minimal at the selection of the data, but the wider variety of climactic variables used together with the dependence on what comes out from the factor analysis is outstanding compared with the boundaries for climatic regions in other methods.

The factor-cluster analyses need a computer to execute the complex calculations throughout their stages between climatic data input and climatic regions output. Köppen and Thornthwaite on the other hand are simpler in calculations which can even be made by hand. The factor analysis technique, as mentioned before, does not guarantee contiguous regions and this can sometimes be misleading. An example of this is that the small south eastern Imatong area came to be grouped with the regions of the north and north east, although the former is a wet region while the latter are in the dry conditions.

The factor analysis method is criticized for being a descriptive rather than a genetic one. However, its objectivity, summarization and simplification of climatic patterns is believed to be a credit. The technique, as mentioned earlier in this chapter, gives a new view of climatic regionalization. Its richness in climatic regions gives a better opportunity for detailed climatic investigation.

The general idea of the climate and the climatic regionalization of the Sudan made so far will be followed by a discussion of the possibility of estimating rainfall from satellite imagery. The real need for estimations using such techniques will be discussed in detail in chapter 5.

CHAPTER FIVE

ESTIMATION OF DAILY RAINFALL FROM SATELLITE IMAGERY

5.1 General

This chapter is devoted to the estimation of daily rainfall in different areas in the Sudan. There is a particular need for such a study in the Sudan for reasons given later in this section. Thirteen stations were used in this study, and different trials were made at modifying the model used and at matching the data of a place or time to another place or time according to different assumptions which will be discussed in the following sections. Estimation of monthly rainfall built on aggregation of the estimated daily rainfall, especially in areas where measurements are difficult, is also important. However, proceeding to fulfil this aim is dependent on the success of the daily rainfall estimation results.

Satellite imagery has greatly attracted workers in atmospheric science in their search for better estimation of rainfall in many regions of the world. The methods developed in this field include cloud brightness, areal summary statistics and the use of infrared imagery. Martin and Scherer (1973) give a summary of the development of those methods up to the early 1970's. Of the early exploratory studies, several reports relate infrared temperature and visual wavelength brightness to parameters such as precipitation. Radok (1966) in Indo-China, Lethbridge (1967) in the U.S.A. and Rainbird (1969) in the Mekong River basin are examples given by Martin and Scherer (1973) for those early studies.

Gerrish (1970) used a fixed location compositing technique to examine the relationship between ESSA satellite convective cloud cover and conventional parameters, including daily rainfall, for South Florida and Miami. Oliver and Schofield (1976) used infrared satellite imagery to estimate rainfall in the eastern U.S.A. One of the more widely used rainfall estimation methods is that developed and refined by Barrett (1970; 1971; 1973; 1975; 1977). The Barrett method is adopted in the present study and will be described in detail in this chapter.

In general, there are several advantages of remote sensing satellite imagery over conventional methods meteorological data collection, though it must not be inferred that they replace them (Barrett, 1974). Some of those advantages are:

1. the synoptic coverage of the globe;
2. the rapidity of the areal coverage;
3. the spatial continuity of the data over the globe;
4. the temporal development in weather by comparing images;
5. the internal homogeneity of the data and the accessibility to inhospitable areas (Barrett, 1974; Townshend, 1977).

Martin and Scherer (1973) note that the vast spatial domain sensed from outer space is the major advantage of satellite observations. Woodley and Sancho (1971) stressed the importance of satellite observations for their "... accurate weather forecasting and evaluating the heart of condensation input to global circulation." Barrett (1977) outlined the importance of satellite based rainfall mapping, particularly in developing countries, for answering several practical problems; for example those related to agricultural and hydrological plans. They are also assumed to be useful for large scale issues such as global agronomic and agrometeorological modelling.

Daily rainfall data are important for better weather understanding and also for hydrological modelling, flood control activities, irrigation development and pest control. They are of particular importance for planning agricultural activities because they give a detailed view of the changes and variability in rainfall. As Smith (1975) maintains "variability of agricultural production can often be related to the deviations from the normal seasonal climates." Daily rainfall totals are, therefore, often more important than monthly, seasonal or annual figures for short term agricultural planning such as irrigation, flood tackling, fertilization, spraying and weeding.

Satellite data offer particular advantages to the Sudan as they can help in solving practical problems. The network of raingauges in this vast country is spatially irregular. There is a concentration along the Nile and in the Gezira scheme area, while the distribution of raingauges is very sparse in the dry north and the swamp and forest areas of the south. In areas such as the latter, satellite data, as maintained by Barrett (1977), "...may be much superior to the unavoidably more or less subjective view of the rainfall mapper."

On these bases the following step of rainfall assessment based on the Barrett model is taken. First the model is taken as it was originally formed. After the results of this step are considered the model is entered into another stage where it is subjected to modification.

5.2 Preliminary rainfall assessment from satellite imagery

5.2.1 The Barrett model

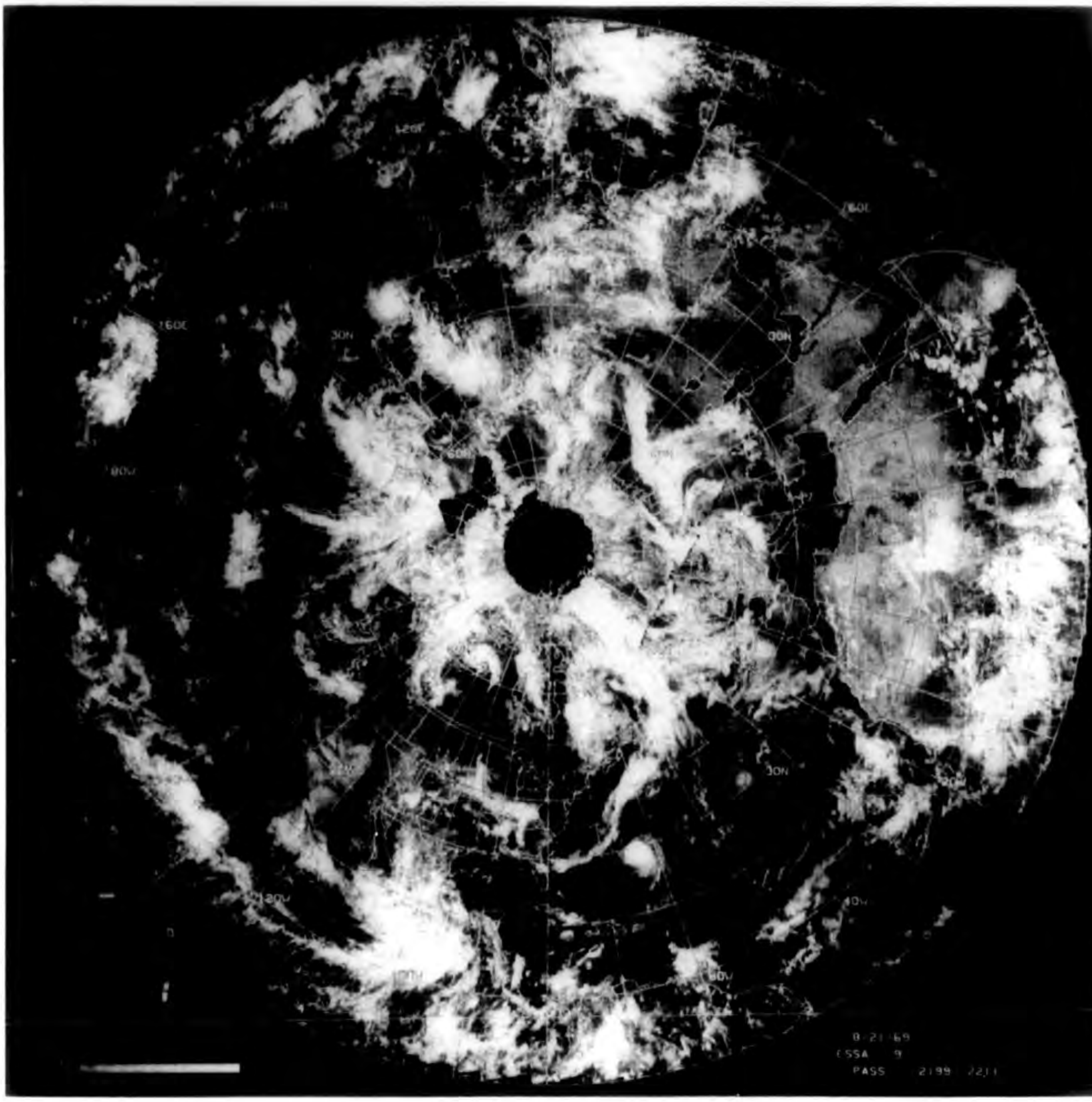
The Barrett model of rainfall estimation was one of the early serious attempts to use satellite imagery as a source of meteorological data. The model is calibrated according to weights given according to assumed characteristics of clouds and weather conditions. In applying the model to the Sudan to obtain daily rainfall estimation a multiple regression technique is used to select the best explanatory variables for each station. The approach adopted here is explanatory as well as predictive.

Daily Essa (Environmental Survey Satellite) 3 and 5 composite images were used for the period July - October 1967 for this study. Essa 3 and 5 were launched on October 2, 1966 and April 2, 1967 respectively by the Environmental Satellite Services Administration (ESSA) of the U.S.A. Each of these satellites was placed into a nearly circular, sun-synchronous polar orbit. The average altitude of Essa 3 was 1429 kms. and of Essa 5 was 1379 kms. The orbits of Essa 3 and 5 were inclined at 102^{o} and 101^{o} respectively with average nodal periods of 115.3 minutes. Thus each satellite makes between 12 and 13 orbits of the earth each day (NOAA, 1969, Barrett, 1974).

The cameras of the satellite are of the Advanced Vidicon Camera System (AVCS) type. Each picture produced covers an area of about 4 million square miles. The pictures are stored for later playback to one of the Command-and-Data-Acquisition (CDA) station on earth. Pictures taken every 260 seconds are usually of 12 frames to a pass. Each frame is electronically gridded by computer; the latitude and longitude lines and geographic boundaries are superimposed on the picture. Each picture contains information on the data and the time of the satellite pass (see Plate 1). The signals making up the picture taken by satellite are assigned numerical values to indicate the relative brightness of each picture element (pixel). These data are normalized for brightness, earth located and repositioned on a standard map projection. These maps are constructed in such a way that they overlap for each day. The digitized cloud maps used in this study are made from reduced resolution versions of the polar stereographic film mosaics.

The technical note of Anderson et al. (1973) on the use of satellite pictures in weather analysis and forecasting, was used as a manual for the study as it contained comparative weather satellite imagery illustrations with useful explanatory comments. This manual was useful in this study in understanding the general characteristics of the weather satellite imagery, the various cloud types, cloud patterns on different scales (meso-scale to planetary-scale), as well as relating these meteorological phenomena to the type of underlying surface.

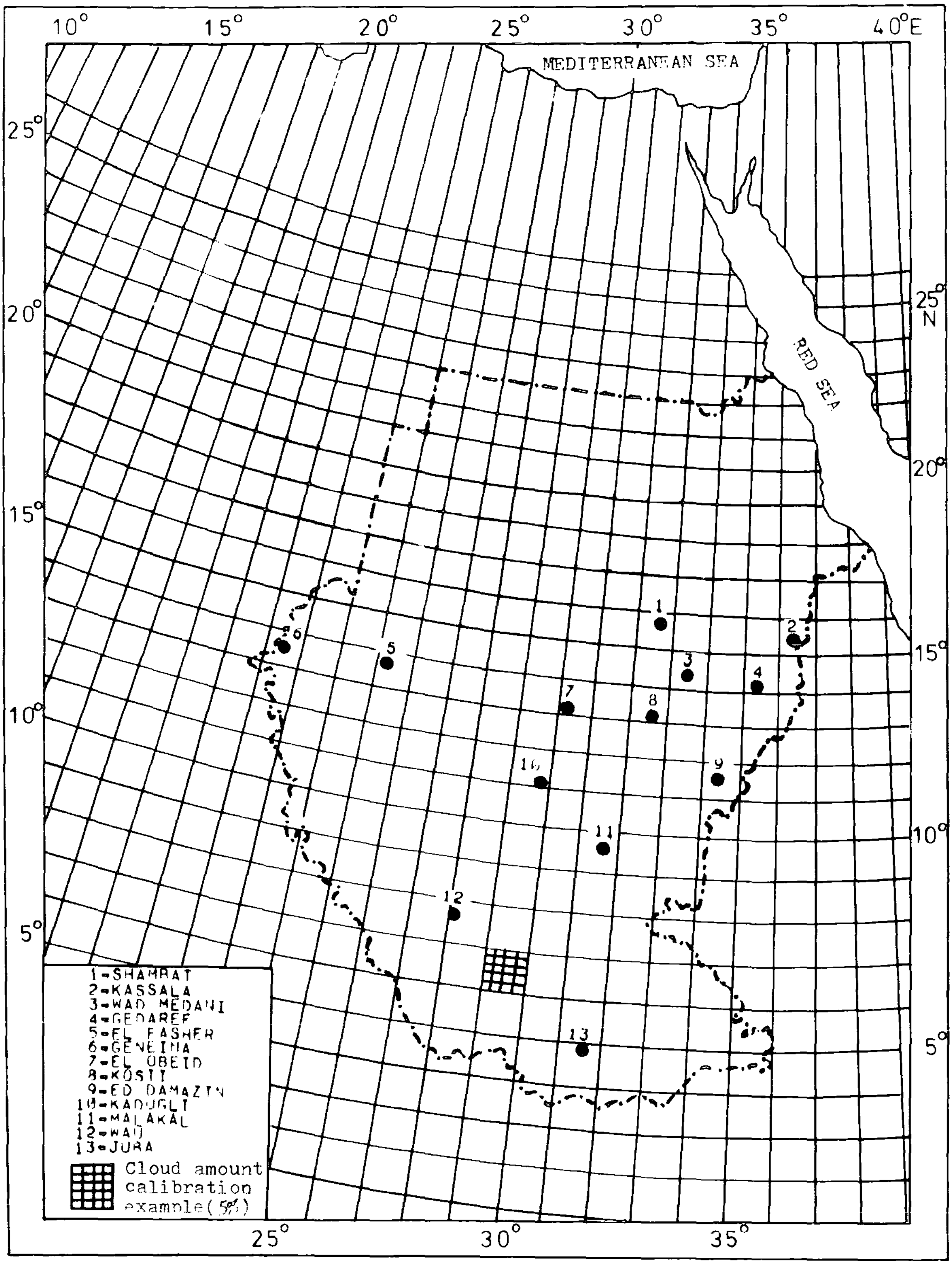
PLATE 1 ESSA METEOROLOGICAL SATELLITE IMAGE



The daily data used in this study were collected from Essa 3 and 5 35 mm. Master films positive transparencies for the period July 1 to September 30, 1967. The films were mounted in an overhead projector and a base map was outlined from the image they gave. On that map detailed gridding, station locations and measurement dimensions were provided (see Fig. 5.1). The projector was operated so that the required satellite transparency image fell properly on the base map fixed on the base of the projector cabin for calibration. It is noted that according to calculations based on the NOAA-KMRD (1969) manual, the image used in this study, the time of Essa 3 and 5 over the Sudan was at 12.00Z (Z = GMT + 2 hrs).

On the gridded base map each grid cell is called a 'gacell' if it includes a raingauge station and a 'satcell' if it does not (Barrett, 1975). After practical experiments it is belived that cells larger than 1^{o} latitude/longitude are unlikely to represent cloud and weather conditions related to isolated places such as the raingauge stations of the present study. Cells smaller than the 1^{o} latitude/longitude, on the other hand, are believed to be too small for practical calibration. On these bases a 1^{o} latitude/longitude cells grid was adopted in this study. One of the purposes considered here is the investigation of the feasibility of obtaining reliable results from different gacells that could be taken to estimate rainfall of the satcells akin to them. From the study period the data of three days were missing from the satellite and raingauge records. These are of: July 22 and 29, and August 5.

Fig. 5.1 BASE MAP USED IN SATELLITE IMAGE DATA CALIBRATION



Based on the Barrett (1975) model the following variables were measured for each day of the study period :

1. Cloud amount measured as the % of the gacell covered by cloud, ranging between 0% for a clear sky and 100% for a completely cloud covered sky, to the nearest 5% as the gacell was divided into 5 lines horizontally and 4 lines vertically (see Fig. 5.1);
2. The dominant cloud type, assigned a value from the list in Table 5.1;
3. A synoptic weather index, assigned a value from the list in Table 5.2.

The measurements obtained for the gacells were treated in two stages : the correlation and the regression analyses. From the regression the formulae obtained from relating observed daily rainfall with the satellite measurements were used for rainfall estimations.

The correlation and the multiple regression results were obtained through a computer program which is described in the SPSS manual (Nie et al., 1970). These results of correlation and regression analysis will be discussed below after a short description of each of these statistical methods. A critical detailed discussion of these methods will be given in section 6.3.3. An evaluation of the model adopted in this study will follow the results obtained from the statistical methods.

Table 5.1 Cloud type index (After Barrett, 1977)

Cloud type	Index
Cumulonimbus with Cirrus	10
Cumulonimbus	8
Layered Stratiform	5
Thick Altastratus	2
Cumulus congestus	1
Stratus	1

Table 5.2 Synoptic weather index (After Barrett, 1975)

Scale	Index	Characteristics
Synoptic	3	Associated with I.T.C.B.
Regional	2	Large scale organization of cloud but separate from I.T.C.B.
Local	1	Small scale, often isolated

Table 5.3 Variables used in rainfall estimation from satellite imagery

No.	Variable	Symbol
1	Cloud amount (%)	AM
2	Cloud type (Table 5.1)	TY
3	Synoptic condition (Table 5.2)	SY
4	The Station distance south of the I.T.C.B edge (kilometres)	DS
5	The distance of the nearest western cloud to the station (kilometres)	WE
6	The distance of the nearest southern cloud to the station (kilometres)	SO
7	The distance of the nearest South western cloud to the station (kilometres)	SW
8	The distance of the nearest eastern cloud to the station (kilometres)	EA

5.2.2 Correlation coefficients

The discussion in this chapter draws heavily on correlation of which the coefficient's formula is :

$$r = \frac{\frac{1}{2}\,\Sigma(a-\bar{a})(b-\bar{b})}{\sigma\, a.\sigma b}$$

where a and b are variables

Correlation permits comparison of data sets in terms of the extent to which a change in one is or is not reflected in another (Gregory, 1973). It must be noted that correlation alone does not indicate causal relationships (Brooks and Carruthers,1953; Cole and King, 1968; Spiegel, 1972; Gregory, 1973; Hammond and McCullagh, 1974). These causal relationships should be thought of in the light of knowledge from literature or from practical observation.

The satellite imagery calibrated data for cloud amount, cloud type and synoptic condition described in section 5.2.1 and in Tables 5.1 and 5.2 were related to the observed rainfall at 13 stations (see Fig. 5.1). The following discussion deals with the results obtained for each station in July, August and September.

<u>July</u>

From Table 5.4 it can be seen that most of the correlations between observed rainfall and cloud amount, cloud type and synoptic condition were very low and they rarely reached 0.5. Shambat is the only station which showed high positive correlations with values of 0.78, 0.61 and 0.62 for cloud amount, cloud type and synoptic condition respectively (all significant at $\alpha = 0.01$). Gedaref also showed

Table 5.4 Correlations between daily rainfall (mm) and cloud amount, cloud type and synoptic condition

No.	Station	July			August			September		
		AM	TY	SY	AM	TY	SY	AM	TY	SY
1	Shambat	0.78**	0.61**	0.62**	0.42*	0.43*	0.43*	-0.16	-0.15	-0.14
2	Kassala	0.66**	0.36	0.32	0.30	0.30	0.28	0.48**	0.47*	0.27
3	Wad Med-ani	0.12	0.16	0.22	0.28	0.26	0.07	-0.04	-0.04	N.P.
4	Gedaref	0.42*	0.55**	0.53**	0.39*	0.26	0.15	0.17	0.14	0.05
5	El Fasher	-0.07	0.03	0.00	0.06	0.12	0.29	0.42*	0.63**	0.35
6	Geneina	0.10	0.00	0.08	0.32	0.30	0.23	0.75**	0.60**	0.36
7	El Obeid	0.26	0.31	0.35	0.28	0.13	0.11	0.10	0.47*	0.14
8	Kosti	0.49**	0.31	0.36	-0.02	0.15	-0.12	-0.10	-0.10	-0.11
9	Ed Dam-azin	0.35	0.23	0.18	-0.08	-0.10	0.10	0.47*	0.51**	0.31
10	Kadugli	-0.19	-0.21	-0.12	0.48**	0.35	0.28	0.03	-0.17	-0.04
11	Malakal	0.35	0.20	0.18	0.40*	0.31	0.28	0.55**	0.07	0.32
12	Wau	-0.20	0.05	-0.12	-0.07	0.07	-0.11	-0.10	-0.08	-0.14
13	Juba	0.26	0.34	0.42*	0.28	0.20	0.16	0.46*	0.54**	0.07
No. Cases		29			30			30		

N.P. Calculation was not possible (invariable figures)
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

significant relationships between rainfall and cloud/synoptic variables in this month where the coefficients reached 0.42, 0.55 and 0.53 for cloud amount, cloud type and synoptic condition respectively. They are all significant at $\alpha = 0.05$ and the last two are significant at $\alpha = 0.01$. Within the remaining stations only the cloud amount rainfall correlation coefficients reached 0.66 and 0.49 for Kassala and Kosti respectively, and the rainfall-synoptic condition correlation coefficient reached 0.42 for Juba (all significant at $\alpha = 0.05$).

<u>August</u>

The results obtained for this month were poorer than those for July. Shambat is the only station showing significant correlations for all the three weather variables considered in this stage of the study. At this station the coefficients for all the variables were slightly higher than 0.40 (significant at $\alpha \doteq 0.05$). For the rest of the stations generally weak correlations were the characteristic of this month. The cloud amount is the only variable which showed significant positive correlations at Gedaref, Kadugli and Malakal with values of 0.39, 0.48 and 0.40 respectively (all significant at $\alpha = 0.05$).

<u>September</u>

For this month cloud amount and cloud type showed far higher correlation coefficients than did the synoptic condition variable. The strongest correlations between rainfall and cloud amount were obtained for Geneina, Malakal and Kassala with values of 0.75, 0.55 and 0.48 respectively (all significant at α = 0.01). Many of the remaining stations showed insignificant correlations between rainfall and cloud amount. Considering the cloud type the highest correlations were 0.63, 0.60, 0.54 and 0.51 for El Fasher, Geneina, Juba and Ed Damazin (all significant at α = 0.01). The synoptic variable correlations with observed rainfall never reached 0.5.

It can be observed from Table 5.4 that the results obtained for July and September were better than those obtained for August, although the latter is the rainiest month and hence richer in rainbearing clouds. The frequent clear skies observed from satellites are compatible with the less frequent rainfall observations in July and September and this seems to be one of the reasons for the higher correlation coefficients for these months compared with August. In general the relationships between rainfall and the weather variables considered in this study were logically positive especially when they reached or approached statistical significance. However, in the majority of cases, these relationships fail to reach any significance level. One of the reasons which are given in detail in sections 5.2.4 and 5.4.1, is the non-representativeness of weather conditions of the satellite imagery taken at 10.00 GMT. The unexpected negative correlations such as those between cloud amount or cloud type with rainfall, however, never reached any significance level to suggest any kind of reliable relationship.

The correlation analysis in this study was taken a step further by regression analysis. Besides investigating the most effective variables in controlling the dependent rainfall variable, regression formulae will be obtained for rainfall estimations for the different regions of the study area. These steps will help the overall evaluation of the usefulness of the model for the Sudan.

5.2.3 Regression analysis

Regression is a more comprehensive analysis beyond the correlation stage (Gregory, 1973; Dyer and Gilloly, 1977), and while correlations show the closeness of the relations among the variables, the regression method shows the nature of the relationship. It shows what change in the dependent variable (y) is associated with unit changes in the independent variables (Nie et al., 1970; Little and Hills, 1972). A regression line as defined by Hammond and McCullagh (1974) is a "line of 'best fit' on a scattergram". This line may be a summary of relationships and it can be used to estimate or predict a value of a dependent variable from values of a set of independent variables. The original method is characterized by applying the following equation :

$$y = a + b_1 x_1 + b_2 x_2 \; ..... + b_n x_n$$

where y = estimated value (= rainfall in this study),

$x_1, x_2 \ldots x_n$ = controlling variables,

a, $b_1 b_2 \ldots \; b_n$ = constants.

The standard error of the regression estimate is

$$Sy = \sigma_y \sqrt{1-r^2}$$

where S_y = standard error of y

σ_y = standard deviation of y

r = correlation coefficient

In the stepwise regression used here the controlling variables were entered on the bases of the partial correlation coefficients. The order of the variables in the regression equation indicated the relative importance of each variable. This order was not necessarily the same as in the simple correlation matrix.

The observed rainfall for the gacells was regressed on the satellite imagery weather variables for the gacells to obtain values for the following formulae which can be used in rainfall estimation :

$$R = a + bA + cT + dS$$

where R = estimated daily rainfall (mm),

A = cloud amount (%)

T = cloud type (Table 5.1)

S = synoptic condition (Table 5.2)

a,b,c and d = constants.

The results shown in Table 5.5 indicate that generally low coefficients of multiple correlation (R) were dominant for July, August and September. In July and at Shambat and Kassala only the coefficients of multiple correlation were relatively high. The values of R were 0.83 (R^2 = 0.69) for Shambat and 0.84 (R^2 = 0.70) for Kassala. For the majority of cases the coefficient of multiple correlation failed to reach 0.5. The strong correlations amongst the

Table 5.5 Regression analysis of daily rainfall (RF) in 1967

No.	Station	July				August				September			
		Ave. RF (mm)	R	R^2	S.E	Ave RF (mm)	R	R^2	S.E	Ave RF (mm)	R	R^2	S.E
1	Shambat	0.01	0.83	0.69	0.0	7.8	0.45	0.20	17.8	0.01	0.16	0.03	0.0
2	Kassala	2.0	0.84	0.70	3.4	2.5	0.32	0.11	5.4	1.4	0.73	0.53	4.1
3	Wad Medani	1.6	0.28	0.08	3.8	5.8	0.37	0.14	12.9	0.3	0.04	0.00	1.4
4	Gedaref	2.5	0.70	0.49	5.0	8.9	0.49	0.24	15.4	1.7	0.51	0.26	4.9
5	El Fasher	1.7	0.14	0.02	5.7	4.6	0.35	0.12	7.3	0.5	0.66	0.44	1.7
6	Geneina	2.9	0.14	0.02	6.3	8.3	0.33	0.11	13.5	1.0	0.83	0.70	1.5
7	El Obeid	2.7	0.36	0.13	5.9	3.2	0.36	0.13	10.3	0.3	0.66	0.43	1.3
8	Kosti	2.5	0.53	0.28	4.9	4.8	0.29	0.08	11.1	1.4	0.11	0.01	5.9
9	Ed Damazin	4.5	0.38	0.15	8.0	8.4	0.33	0.11	13.0	4.7	0.52	0.27	6.9
10	Kadugli	3.0	0.22	0.05	7.3	6.7	0.51	0.26	14.4	4.6	0.24	0.06	9.8
11	Malakal	8.6	0.45	0.20	18.8	6.3	0.40	0.16	11.9	7.0	0.59	0.34	11.1
12	Wau	3.0	0.39	0.15	6.5	4.6	0.43	0.19	7.0	6.8	0.15	0.02	20.0
13	Juba	7.3	0.45	0.20	14.6	6.3	0.31	0.10	10.8	7.3	0.56	0.31	12.3
	No. of cases	29				30				30			

controlling variable considered here (see Table A.5) might have led to the frequently slight contribution to the coefficient in the second and the third steps in the stepwise regression. The standard errors obtained were always relatively large and in many cases reached above 100% of the average observed daily rainfall.

From these results it became apparent that any attempt to estimate rainfall from the multiple regression equation provided at this stage would be fruitless. As a result the estimation of rainfall for the gacells was ignored. The modification of the model became a necessity to see whether any better results could be obtained. The aim of these trials as mentioned in section 5.1 was to investigate the feasibility of utilizing the rich satellite imagery data, through statistical models in estimating the daily rainfall, especially in the inaccessible parts of this vast country. An overall assessment of the Barrett model of this stage will be given in the following section before moving to the second stage of the model modification.

5.2.4 Assessment of the Barrett model applied to the Sudan

The poor performance of the model in the study areas in the Sudan, shown in sections 5.2.2 and 5.2.3, may be attributed to several factors :

(1) Accurate recognition of cloud type is a major problem in satellite cloud imagery and some errors of interpretation are to be expected (Harris and Barrett, 1975). Griffith et al. (1976) mentioned the specific

difficulties encountered in identifying the rain producing cloud such as cumulonimbus when they are masked by high cirrus clouds.

(2) The satellite passes were once-daily at the Sudan local time noon, whereas much of the active convective rainbearing clouds develop over the Sudan during the afternoon, and the picture may change during the course of the day. Over much of central and eastern Sudan, as mentioned by Oliver (1965), "a large proportion of the rain is received during the hours of darkness". Martin and Scherer (1973) stated that "... in many cases the once-daily pictures in an estimated scheme based on cloud type imply useful results down only to a synoptic scale".

(3) In the original model there is a disregard of topographical and regional influences (Martin and Scherer, 1973).

(4) In many cases the rainguage readings are representative only of the immediate environment, particularly if precipitation is from convective clouds, as in the Sudan. (Griffith et al., 1976). Over the Sudan, as maintained by Thompson (1965), "There is no evidence of travelling systems and in most cases rainfall develops over an area and sometimes later dies out. Rainfall is rarely considered as uniform over the area".

(5) Wind direction and speed are very important in relation to moisture and cloud movement over long distances in the Sudan. Neglecting these variables was due to the difficulty of their quantification from satellite evidence as the data obtained from the images are mostly non-synoptic (Barrett and Martin, 1981). Woodley and Sancho (1971) maintained that "... it is difficult, if not impossible to make quantitative measurements of precipitation extent and intensity by examining satellite cloud photographs."

(6) The spatial resolution of the 1967 Essa satellite, 2.5-3 kilometers, is rather coarse if compared with the current Tiros-N satellite with a resolution of about 1 kilometer.

Because of the poor performance of the model in its original form for the Sudan, further modification of the model was made. Several new variables were suggested to add to the explanatory and predictive power of the multiple regression equations and to answer some of the questions about the feasibility of the use of the model in the Sudan.

5.3 Further rainfall assessment from satellite imagery

5.3.1 Modification of the Barrett model

As was mentioned in section 3.4.1, wind system in the Sudan generally followsa simple pattern. In the rainy season the southwesterly winds proceed in the country while the north easterly trades retreat to northern latitudes causing the I.T.C.Z. to advance further north. This situation greatly affects weather and climate conditions, especially rainfall performance.

On these bases, the idea of including a wind movement effect has been developed. Because of the difficulty, mentioned in section 5.2.4, of obtaining reliable data for wind directions from polar orbiting satellite imagery, an indirect way has been adopted. This is by measuring the distances of clouds of considerable sizes from the raingauges. The measurements were restricted to the direction from which moist winds were most expected. Five variables were obtained, all related to station-cloud distances. Four of the variables are the distances of clouds to the west, southwest, south and east of a station, and the fifth variable is the distance of the raingauge station south of the I.T.C.B. edge. This latter variable was chosen on the basis that it hints at how far south of the Inter Tropical Convergence Zone the station was,and hence it indicates how far inside the humid section of the weather system the station was with more probability of having rainfall (see section 3.4). Latitude, longitude and altitude are important factors affecting rainfall. They can only be used when several stations are considered together. As this study considers the stations separately those factors were ignored.

The same procedure was used as in the previous stage of the model application. The main aspects of this procedure are correlation and multiple regression studies, and rainfall estimation based on multiple regression analysis. These stages will be discussed accordingly in the following sections, which will be concluded with a final assessment of the applicability of the model to the Sudan.

5.3.2 Correlation coefficients from the modified model

Three trials were made to obtain correlations between rainfall and the satellite imagery calibrated weather variables, based on the modified model (see Table 5.3). The first trial was made by relating the variables of each day at each station during July, August or September. The second trial was the same as the first one but the number of days considered here was larger as it covered the rainiest part of the whole period (July 1 to September 5). The third trial was the correlation of the satellite image calibrated weather variables of a day at a station with the rainfall of the following day over the same station. This trial was applied to August, the rainiest month of the year.

Trial 1

Tables 5.6,5.7 and 5.8 show correlations between rainfall and the variables listed in Tables 5.2 and 5.3 for 13 stations during July, August and September respectively.

Table 5.6 Correlations between rainfall (mm) and satellite image weather variables during July (1)

Station	AM	TY	SY	DS	WE	SO	SW	EA
Shambat	0.78**	0.61**	0.62**	0.22	-0.12	-0.14	0.00	-0.64**
Kassala	0.66**	0.36	0.32	0.36	-0.40*	-0.37	-0.36	-0.27
Wad Medani	0.12	0.16	0.23	0.19	-0.04	0.05	-0.11	-0.18
Gedaref	0.42*	0.55**	0.53**	0.55**	-0.35	-0.38*	-0.36	-0.35
El Fasher	-0.07	0.03	0.00	-0.09	0.37	-0.21	-0.17	-0.30
Geneina	0.10	0.00	0.08	0.24	-0.07	0.00	-0.22	0.18
El Obeid	0.26	0.31	0.35	0.04	0.05	-0.25	-0.28	-0.39*
Kosti	0.49**	0.31	0.36	0.10	-0.14	-0.21	-0.08	-0.19
Ed Damazin	0.35	0.23	0.19	0.29	-0.37	-0.35	-0.29	-0.29
Kadugli	-0.19	-0.21	-0.12	-0.19	0.20	-0.20	0.18	0.40*
Malakal	0.35	0.20	0.18	0.05	-0.31	-0.31	-0.37	-0.33
Wau	-0.20	0.04	-0.12	0.17	0.04	-0.9	0.07	0.28
Juba	0.26	0.34	0.42*	0.37	-0.26	-0.06	-0.32	-0.29

N = 29
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

(1) For interpretation of symbols and measurements see Table 5.3.

It can be generalized that, as expected, positive correlations were found between rainfall and cloud amount, cloud type, synoptic conditions and the station's distance south of the I.T.C.B. edge. Negative correlations were found with rainfall and distances of clouds from a station. This latter generalization of negative correlations could be guaranteed when the coefficients approached a significant level.

During July, as can be seen from Table 5.4, the relationships between rainfall and satellite image variables were generally weak. Shambat showed significant correlations between rainfall and cloud amount, cloud type, cloud distance from the east and synoptic condition with values 0.78, 0.61, -0.61 and 0.62 respectively. Kassala in eastern Sudan showed a fairly strong correlation between rainfall and cloud amount (r = 0.66). At Gedaref, also in eastern Sudan, rainfall displayed significant correlations with most of the varibles in the study. The highest coefficient reached is 0.55 for both cloud type and the station distance south of the I.T.C.B edge. None of the remaining stations showed a correlation coefficient reaching the value 0.5 and the majority of the variables showed values below 0.4. Wad Medani, Geneina and Wau in particular showed the lowest correlation coefficients obtained among the study areas for this month. In general, the assumptions held about the relationship between rainfall and satellite image weather variables considered here were observed. These relationships were positive with cloud amount, cloud type, synoptic condition and the station distance south of the I.T.C.B. edge and negative for the cloud distances from the station.

August is the rainiest month in the study area. As can be seen from Table 5.7, this month provided the lowest correlation coefficient, within the study period, (see also Tables 5,6 and 5.8). El Obeid was the only place where the correlation between rainfall and satellite image variables was above 0.5 and that was with the distance south of the I.T.C.B. edge ($r = 0.53$, significant at $\alpha = 0.01$). Shambat showed correlation coefficients slightly above 0.4 for cloud amount, cloud type and synoptic condition, and lower ($r = -0.37$) for the cloud distance from the east (all significant at $\alpha = 0.05$). Gedaref showed positive relationships between rainfall and cloud amount ($r = 0.39$) and the station distance south of the I.T.C.B. edge ($r = 0.40$). At Kadugli and Malakal the correlation coefficients of rainfall with cloud amount were 0.48 and 0.40 respectively (the first is significant at $\alpha=0.01$ and the second at $\alpha = 0.05$). El Fasher showed a negative relationship between rainfall and cloud distance from the south ($r = -0.47$, significant at $\alpha = 0.05$). Juba showed that rainfall was negatively correlated with cloud distances from the south west ($r = 0.46$) and from the east ($r = -0.39$), both significant at $\alpha = 0.05$. The assumed nature of rainfall relationships with satellite weather variables suggested for July also apply to August.

During September (Table 5.8) the highest coefficients for the related rainfall and cloud amount were 0.75, 0.55 and 0.48 for Geneina, Malakal and Kassala respectively, all significant at $\alpha = 0.01$. The coefficients of rainfall with

Table 5.7 Correlations between rainfall (mm) and satellite image weather variables during August (1)

Station	AM	TY	SY	DS	WE	SO	SW	EA
Shambat	0.42*	0.43*	0.43*	0.19	-0.23	-0.35	-0.22	-0.37*
Kassala	0.30	0.30	0.28	0.19	-0.39*	0.20	-0.09	-0.16
Wad Medani	0.28	0.26	0.07	0.35	-0.05	-0.15	-0.30	-0.14
Gedaref	0.39*	0.26	0.15	0.40*	-0.07	-0.30	-0.21	-0.35
El Fasher	0.06	0.12	0.29	-0.09	-0.05	-0.47*	-0.20	-0.32
Geneina	0.33	0.31	0.25	0.09	0.02	-0.33	-0.22	-0.15
El Obeid	0.28	0.31	0.11	0.53**	-0.25	-0.19	-0.18	0.20
Kosti	-0.02	0.14	-0.12	-0.10	0.19	-0.28	-0.32	0.06
Ed Damazin	-0.08	-0.10	0.10	0.01	0.04	0.10	-0.03	-0.25
Kadugli	0.48**	0.35	0.28	0.09	0.18	0.27	-0.31	-0.24
Malakal	0.40*	0.31	0.28	0.21	-0.31	-0.25	-0.02	-0.07
Wau	-0.08	0.07	-0.11	0.12	-0.06	0.08	0.19	0.15
Juba	0.29	0.20	0.16	0.01	-0.05	-0.46*	-0.35	-0.39*

N = 30

* significant at α = 0.05

** significant at α = 0.01

(1) For interpretation of symbols and measurements see Table 5.3.

Table 5.8 Correlations between rainfall (mm) and satellite image weather variables during September (1)

Station	AM	TY	SY	DS	WE	SO	SW	EA
Shambat	-0.16	-0.15	-0.14	-0.12	0.14	0.28	0.07	-0.16
Kassala	0.48**	0.47*	0.27	N.P.	N.P.	-0.30	-0.33	-0.35
Wad Medani	-0.04	-0.04	N.P.	-0.04	0.12	-0.17	0.26	-0.05
Gedaref	0.17	0.14	0.05	-0.8	0.09	-0.09	-0.26	-0.28
El Fasher	0.42*	0.63**	0.35	0.27	0.22	-0.26	-0.38*	-0.18
Geneina	0.75**	0.60**	0.36	0.46*	-0.09	-0.34	-0.39*	-0.58**
El Obeid	0.10	0.47*	0.14	0.54**	-0.34	-0.20	-0.22	-0.33
Kosti	-0.10	-0.10	-0.11	-0.06	0.10	0.28	0.14	0.05
Ed Damazin	0.47*	0.52**	0.31	0.02	-0.26	-0.15	-0.25	-0.17
Kadugli	0.03	-0.17	-0.04	-0.14	0.07	0.02	0.12	0.21
Malakal	0.55**	0.07	0.32	0.14	0.01	-0.14	-0.33	-0.39*
Wau	-0.10	-0.08	-0.14	-0.11	-0.04	0.12	0.20	0.17
Juba	0.46*	0.54**	0.07	0.32	0.15	-0.18	0.03	-0.22

N = 30

N.P = calculation was not possible (invariable figures)

* significant at $\alpha = 0.05$

** significant at $\alpha = 0.01$

(1) For interpretation of symbols and measurements see Table 5.3.

cloud type were strongest at El Fasher, Geneina, Juba and Ed Damazin with 0.63, 0.60, 0.54 and 0.52 respectively (all significant at $\alpha = 0.01$). In relation to distance variables the correlation coefficients never reached 0.5 except for Geneina and El Obeid. The distance of the station south of the I.T.C.B. edge gave correlation coefficients of 0.54 and 0.46 for El Obeid and Geneina respectively. The cloud distances from the SW showed significant negative correlations with rainfall at El Fasher and Geneina, -0.38 and -0.39 respectively. The cloud distance from the east showed a negative correlation with rainfall only at Geneina (r = -0.58) and Malakal (r = -0.39), where the first is significant at $\alpha = 0.01$ and the second at $\alpha = 0.05$. From this it can be observed that Geneina, in the west, had the strongest correlations between rainfall and most of the satellite image weather variables. It can be observed also from Table 5.8 that the generally assumed nature of the relationships between these variables suggested for July and August are applicable for September also.

After this trial which considers each month alone, another trial was made where the data collected from more than a month were used in the correlation process. The results of this stage are described below.

Trial 2

At this stage 8 stations were considered in the calculations of correlations between rainfall and the satellite image weather variables, for 63 cases obtained from the period between July 1 and September 5. This period includes the rainiest part of the season as shown in section 3.7.3 and Figure 3.23.

For this longer period, as can be seen from Table 5.9, the correlation coefficients were very low and in many cases no relationships were found. It can be observed that only at Gedaref, El Fasher and Malakal did the cloud distance factor come to be significant, but even here the correlation only reached 0.28 (Malakal). Statistics were confusing and correlations were very weak or no relationships occurred between rainfal and cloud amount, cloud type and synoptic conditions. It seems that because of the contrast between rainy-and-dry days throughout this long period, the relatively high correlations at certain times of the period were pulled down by low relationships at other times (compare with Trial 1). This trial suggested that periods longer than one month do not seem to be preferable for such a study in the Sudan.

Following this trial a third trial was made in the context of rainfall cloud/weather variables as obtained from satellite imagery. The results obtained are discussed below and will be followed by a selection from the trial which will be carried forward for regression analysis.

<u>Trial 3</u>

The data obtained from the satellite imagery were correlated with the following day's rainfall at 7 stations during August. The ideas was to examine whether specific weather systems worked for a longer period after the time the satellite image was taken. The results shown in

Table 5.9 Correlations between rainfall (mm) and satellite image weather variables for 63 days (1st July - 4th Sept., 1967) (1)

Station	AM	TY	SY	DS	WE	SO	SW	EA
Wad Medani	0.16	0.08	0.05	0.07	-0.01	-0.16	-0.05	-0.06
Gedaref	0.21	0.15	0.10	0.02	-0.09	-0.27*	-0.23	-0.27*
El Fasher	0.01	0.08	0.16	0.26*	-0.01	-0.27*	-0.06	-0.29
Geneina	0.17	0.13	0.17	0.04	0.03	-0.14	-0.15	-0.04
El Obeid	0.18	0.02	0.01	0.11	-0.09	-0.17	-0.12	0.04
Ed Damazin	-0.01	-0.03	-0.06	0.16	-0.09	-0.04	0.18	-0.06
Malakal	0.07	0.07	0.16	-0.09	-0.28*	-0.08	-0.10	-0.24
Juba	0.04	0.17	0.16	N.P.	-0.11	-0.17	-0.06	-0.08

N = 63

N.P. = calculation was not possible (invariable figures)
* significant at $\alpha = 0.05$
(1) For interpretation of symbols and measurements see Table 5.3

Table 5.10 Correlations between satellite image weather variables of a day and the rainfall (mm) of the following day over the same station during August (1)

Station	AM	TY	SY	DS	WE	SO	SW	EA
Wad Medani	0.06	0.03	0.11	-0.09	0.21	-0.11	0.32	0.16
Gedaref	-0.23	-0.22	-0.27	-0.21	-0.19	0.36	-0.18	0.58**
El Fasher	-0.13	-0.10	0.15	0.30	0.03	-0.40	-0.34	0.01
Geneina	-0.19	0.01	0.00	-0.08	0.28	0.49**	0.26	0.02
El Obeid	-0.02	-0.10	-0.03	0.16	0.16	0.34	0.25	0.14
Ed Damazin	-0.49**	-0.48**	-0.42*	-0.33	0.02	0.27	0.18	0.01
Juba	0.00	0.03	0.14	-	-0.09	0.04	-0.11	-0.12

N = 29
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$
(1) For interpretation of symbols and measurements see Table 5.3

Table 5.10 reveal that from this data sample no such relationship could successfully be shown. Low correlation coefficients were mostly obtained for rainfall and cloud amount, cloud type and synoptic conditions. Ed Damazin showed significant negative correlations between these variables with coefficient values of -0.49 for cloud amount, -0.48 for cloud type and -0.42 for synoptic condition. Gedaref showed a fairly strong positive correlation between rainfall and distance of cloud from the east (r = 0.58). These results do not appear to represent the general condition realistically and they are the reverse of what is believed to be the pattern from conventional observation. They are also in opposition to the results obtained for the same day rainfall-satellite image variables relationship of Tables 5.6,5.7 and 5.8.

Although such results seem surprising, one cannot be sure that they are incorrect so long as the once-daily satellite image cannot give an account of the situation of the whole day in such changeable weather conditions. In addition to this the Essa 3 and 5 passes over the Sudan, were roughly at noon (local time), as mentioned in section 5.2.2 while rainfall readings were taken at 6 a.m. in the morning of the next day. For the next day's rainfall reading in fact 42 hrs. elapsed after the satellite picture was taken. Gerrish (1970), obtaining similar results from his study of Miami and Florida, maintains that "Persistence forecasting should not be used more than 24 hrs in the future. There was a rapid decrease in accuracy on the second day and no correlation by the third day."

From the previous discussion it seems advisable to follow the first trial, on monthly day-to-day rainfall/satellite-related data, as it proved to be the best of the 3 trials. The results of this stage were carried forward in subsequent stages of regression analysis and rainfall estimation.

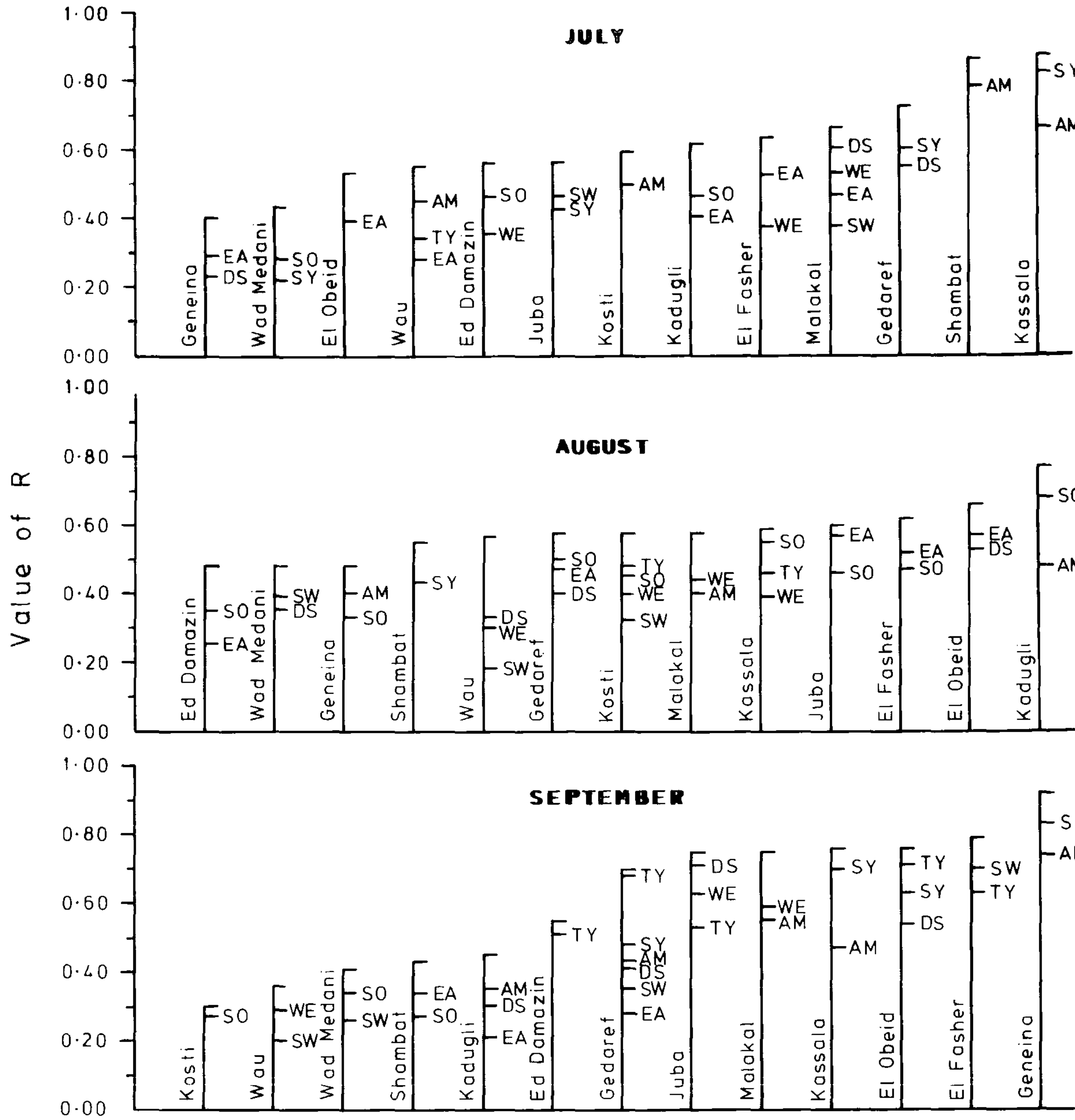
5.3.3 Regression analysis and rainfall estimation (the modified model)

Regression analysis

Based on the understanding of regression properties discussed in section 5.2.3, rainfall was regressed on the variables specified for this study in Tables 5.1, 5.2 and 5.3. The results of the multiple regression for the 13 stations of this study are shown in Table 5.11. The contribution of the most important variables to the coefficients of the multiple correlation identified by the stepwise regression procedure are shown in Figure 5.2.

During July the coefficients of multiple correlation hardly reached 0.7 except at Shambat, Kassala and Gedaref. In general they ranged between 0.87 (R^2 = 0.75) at Kassala and 0.4 (R^2 = 0.16) at Geneina. August coefficients of the multiple correlations for all the stations ranged between 0.77 (R^2 = 0.6) at Kadugli and 0.48 (R^2 = 0.23) at Ed Damazin, and the majority of the stations considered in the present study had values below 0.6 (R^2 = 0.36). In September, a large contrast between the stations can be seen by comparing the coefficients obtained at Geneina and Kosti, with R = 0.92 (R^2 = 0.85) and 0.3 (R^2 = 0.09) respectively. It is noted that in September, the lowest coefficients of the

Fig.5.2 COEFFICIENTS OF MULTIPLE CORRELATIONS FOR RAINFALL AT 13 STATIONS



AM = cloud amount
TY = cloud type
SY = synoptic condition
DS = station distance south of I·T·C·B
WE, SO, SW and EA = distances respectively the nearest west, south, southwest and east
┌ = contribution of the remaining variables

Table 5.11 Regression analysis of daily rainfall (RF) based on the modified model

No.	Station	July				August				September			
		Ave. RF (mm)	R	R^2	S.E.	Ave. RF (mm)	R	R^2	S.E.	Ave. RF (mm)	R	R^2	S.E.
1	Shambat	0.0	0.86	0.75	0.0	7.8	0.55	0.31	18.5	0.0	0.43	0.19	0.0
2	Kassala	2.0	0.87	0.75	3.4	2.5	0.59	0.34	5.2	1.4	0.76	0.58	4.1
3	Wad Medani	1.6	0.43	0.18	4.1	5.8	0.48	0.23	13.4	0.3	0.42	0.18	1.3
4	Gedaref	2.5	0.72	0.52	5.4	8.9	0.58	0.33	16.0	1.7	0.70	0.49	4.5
5	El Fasher	1.7	0.63	0.39	5.1	4.6	0.62	0.38	6.9	0.5	0.78	0.62	1.4
6	Geneina	2.9	0.40	0.16	6.3	8.3	0.49	0.24	13.9	1.0	0.92	0.85	1.2
7	El Obeid	2.7	0.53	0.27	5.9	3.2	0.66	0.44	9.1	0.3	0.77	0.59	1.2
8	Kosti	2.5	0.59	0.35	5.2	4.8	0.58	0.34	10.6	1.4	0.30	0.09	6.4
9	Ed Damazin	4.5	0.56	0.31	8.0	8.4	0.48	0.23	12.8	4.7	0.55	0.30	7.5
10	Kadugli	3.0	0.61	0.37	6.5	6.7	0.77	0.60	11.8	4.6	0.45	0.21	10.0
11	Malakal	8.6	0.66	0.44	17.1	6.3	0.58	0.34	11.5	7.0	0.75	0.56	10.1
12	Wau	3.0	0.55	0.30	6.6	4.6	0.57	0.33	6.9	6.8	0.38	0.14	21.4
13	Juba	7.3	0.56	0.32	14.7	6.3	0.60	0.37	10.1	7.3	0.75	0.56	10.7
	No. of Cases	29				30				30			

multiple correlation, < 0.5, occurred in an elongated north-east - southwest area including Shambat, Wad Medani, Kosti, Kadugli and Wau surrounded by the rest of the stations having higher coefficients. The significance of this result needs further test and explanation based on a larger data set.

In general, the majority of the stations showed very low values of R^2. In fact throughout the study period they hardly exceeded 0.8 except at Geneina in September (see Table 5.11), and only Shambat can be included when the R^2 above 0.7 is considered. The standard error in particular, as can be observed from comparing Table 5.5 and 5.11, remained high or slightly improved on those of the first stage of the model application. It can be observed also from Figure 5.2 that in almost all cases the main contribution to each multiple correlations coefficient was made by only two variables after which the contribution of additional variables became insignificant. It should be noted that these variables differ in their contribution to the multiple correlation coefficients for different stations. It can also be observed that the contributions of the cloud amount and cloud type to the multiple correlation coefficients were in many cases very small. The stepwise regression, because its nature is to choose the most important variables to the dependent variables, in many cases ignored important variables such as cloud amount and cloud type. This particular problem will be discussed in section 5.4.2.

Although these results proved to be better than those obtained in the first stage of the model application (see Table 5.5), they are not encouraging enough to build up reliable formulae for rainfall estimations. However the rainfall estimations provided below were made to show empirically the degree of success of the model in the area during the period considered in this study.

Rainfall estimation

The formulae obtained for the stepwise multiple regressions for the 3 months at the 13 meteorological stations of this study (see Tables A.6, A.7 and A.8) were used to make rainfall estimations. The results are shown in Figures 5.3, 5.4 and 5.5, and the correlation coefficients between observed and estimated rainfall are shown in Table 5.12. It should be noted here that in the estimation process the negative relationships between rainfall and cloud distances from stations sometimes resulted in negative values of estimated rainfall in which case they were converted to zero values. It is also noted that as the coefficients of multiple regression were in many cases weak, the discrepancies between observed and estimated rainfall were considerable.

In July, as can be seen from Table 5.12 and Figure 5.3, the best estimations of rainfall, based on the formulae in Table A.6, were obtained for Kassala, Shambat and Gedaref where the correlation coefficients between the observed and the estimated rainfall were 0.87, 0.86 and 0.72 respectively. The lowest correlations, on the other hand, were obtained at Geneina and Wad Medani with coefficients of 0.4 and 0.43 respectively. For the vast majority of the stations the correlation coefficients never reached 0.7.

In August the correlation coefficients between observed

Table 5.12 Correlations between observed and estimated rainfall (mm)

No.	Station	July	August	September
1	Shambat	0.86	0.55	0.44
2	Kassala	0.87	0.59	0.76
3	Wad Medani	0.43	0.48	0.42
4	Gedaref	0.72	0.58	0.70
5	El Fasher	0.63	0.62	0.78
6	Geneina	0.40	0.48	0.92
7	El Obeid	0.53	0.66	0.77
8	Kosti	0.59	0.58	0.31
9	Ed Damazin	0.56	0.48	0.54
10	Kadugli	0.61	0.77	0.46
11	Malakal	0.66	0.58	0.75
12	Wau	0.55	0.57	0.38
13	Juba	0.56	0.58	0.75
No. of cases		29	30	30

0.38 significant at $\alpha = 0.05$

0.48 significant at $\alpha = 0.01$

Table 5.13 Correlations between observed and estimated rainfall (mm) at test stations based on formulae of the nearest stations

Formula source	Test station	July	August	Sept.
Wad Medani	Shambat	0.42*	0.13	0.06
Gedaref	Kassala	-0.22	0.15	-0.10
El Obeid	Kosti	-0.18	0.31	-0.10
Malakal	Kadugli	0.04	-0.18	0.24
Juba	Wau	0.10	-0.05	-0.01
No. of Cases		29	30	30

* significant at $\alpha = 0.05$

Fig. 5.3 OBSERVED AND ESTIMATED DAILY RAINFALL (MM) DURING JULY, 1967 FOR 12 STATIONS

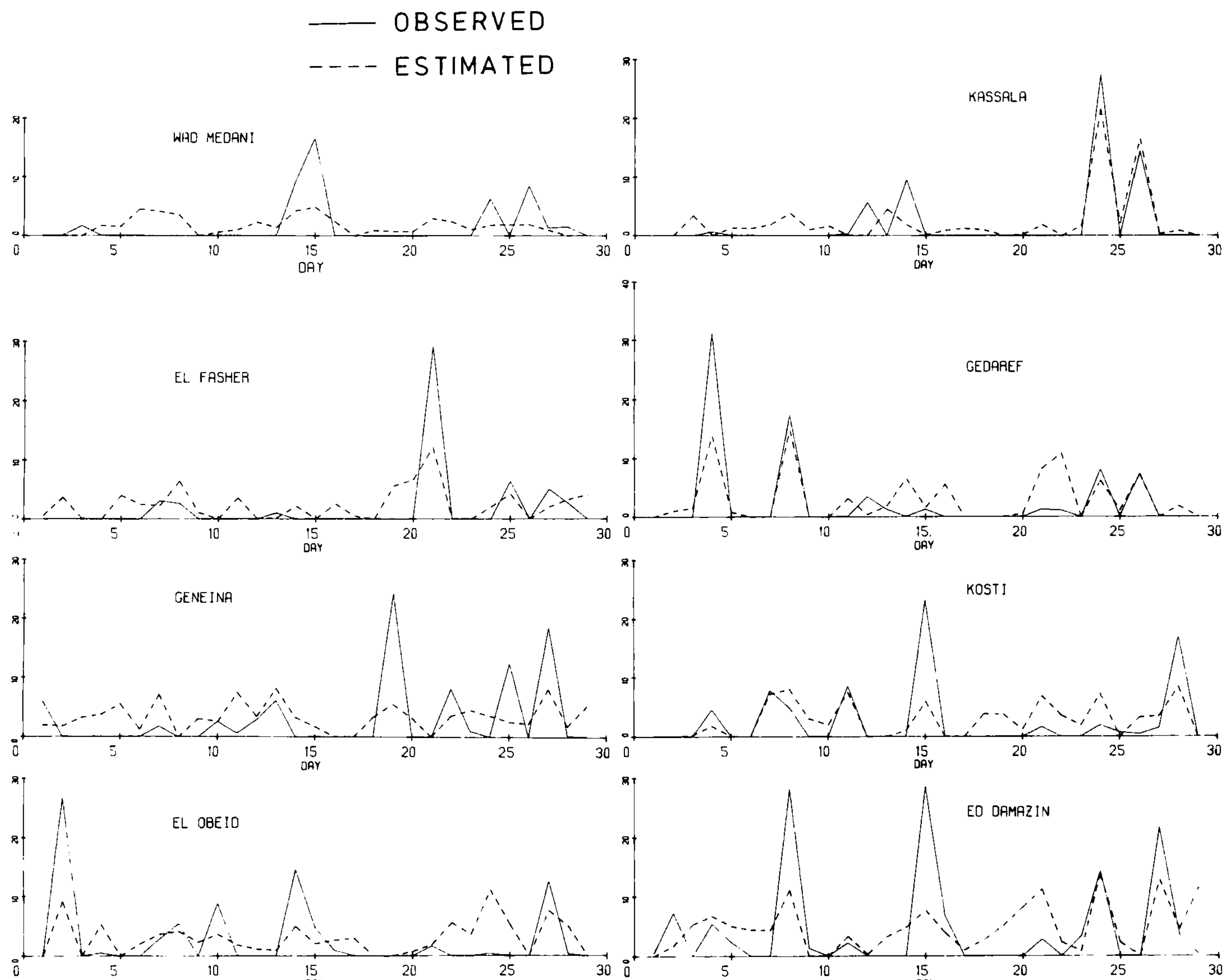


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Fig.5.3 (CONTINUED)

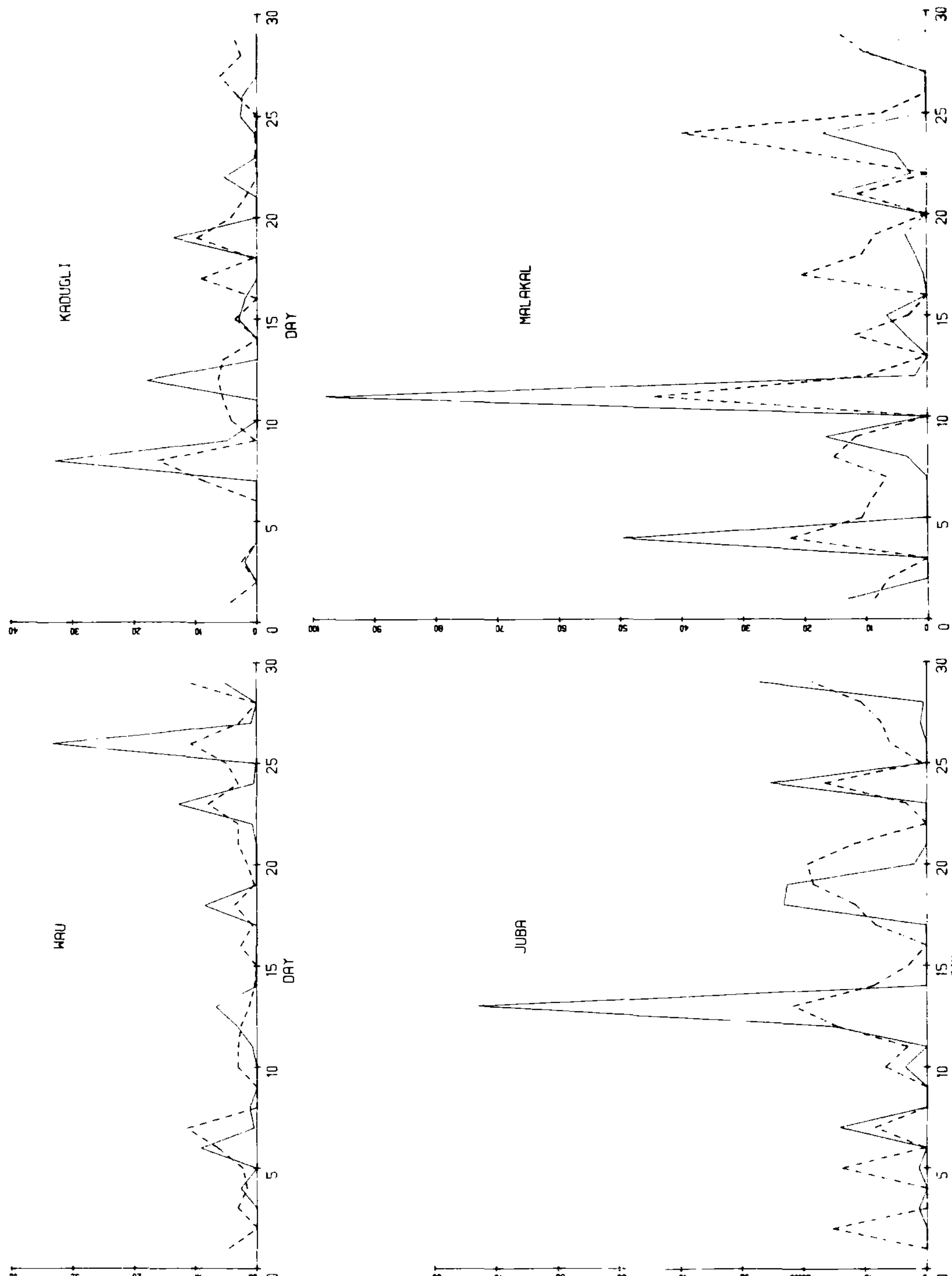

Fig.5.4 OBSERVED AND ESTIMATED DAILY RAINFALL(MM) DURING AUGUST,1967 FOR 13 STATIONS

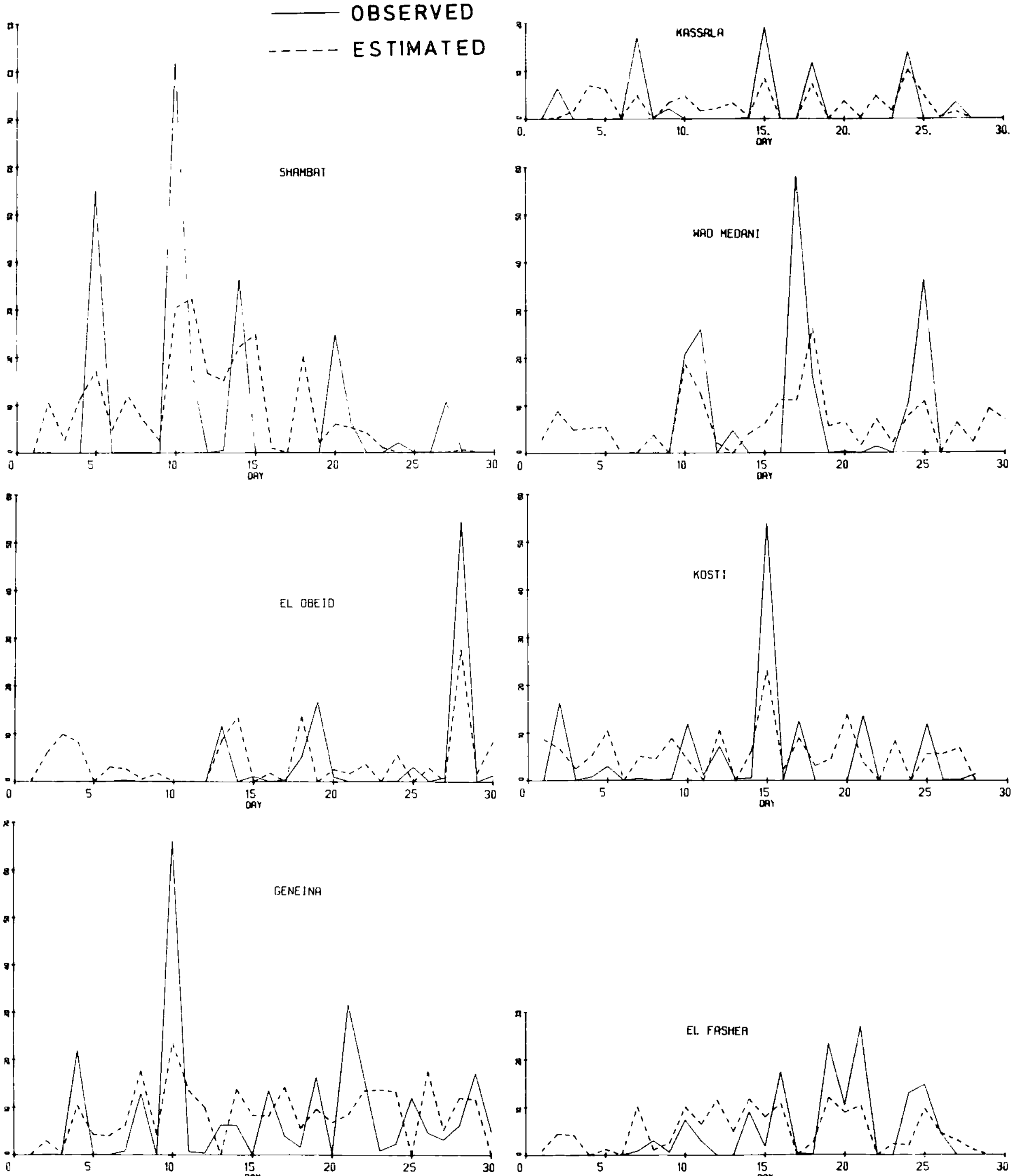

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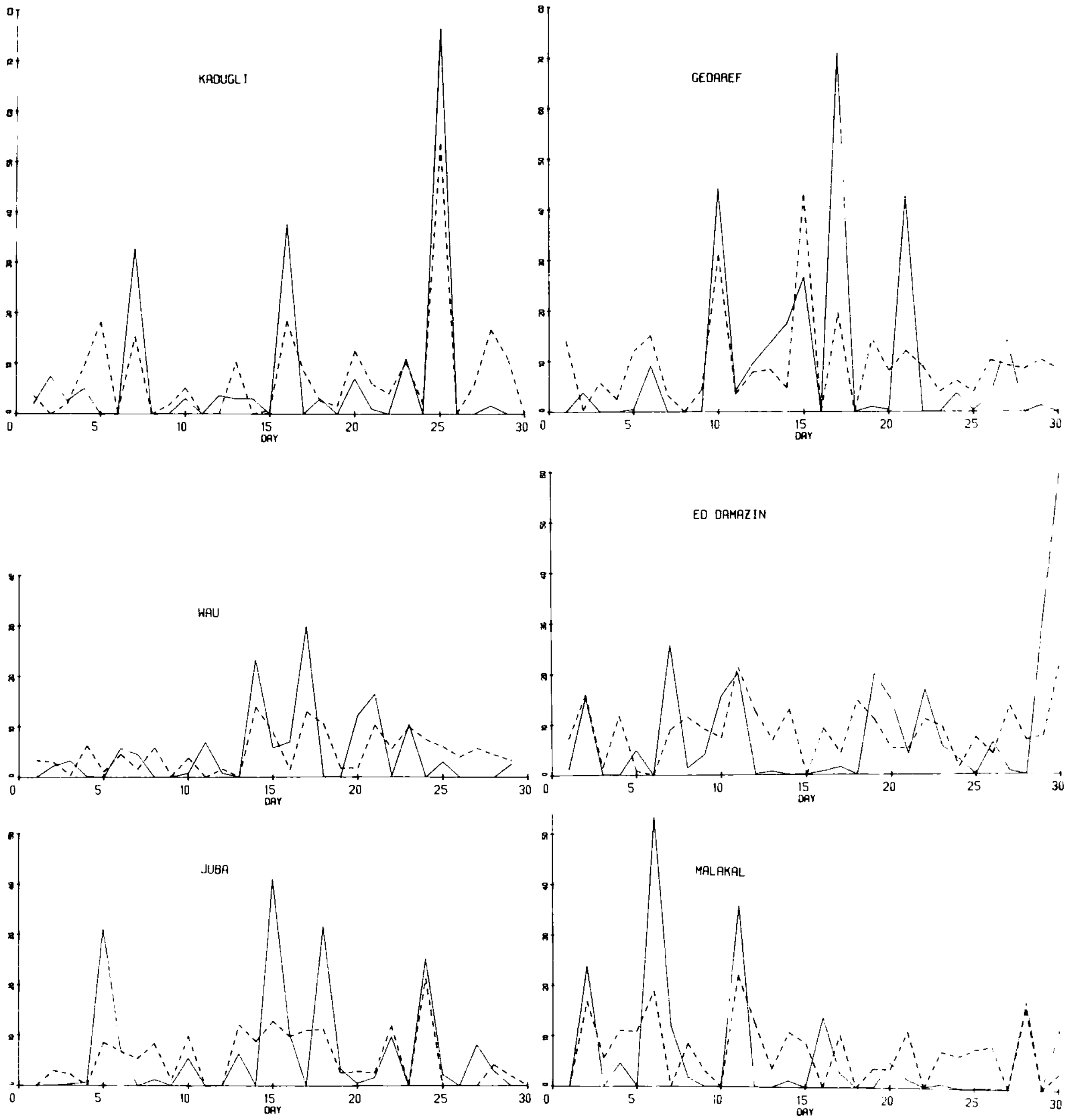
Fig. 5.4 (CONTINUED)



and estimated rainfall fell between the highest and lowest values obtained for July. The highest correlation coefficients were at Kadugli, El Obeid and El Fasher had values of 0.77, 0.66 and 0.62 respectively (all significant at $\alpha = 0.01$).

September showed the largest contrast between the stations in the correlation coefficients of observed and estimated rainfall. Geneina, El Fasher and El Obeid showing the highest correlations with values of 0.92, 0.78 and 0.77 respectively. Kosti, Wau, and Wad Medani, on the other hand, showed the lowest coefficients, 0.31, 0.38 and 0.42 respectively. These latter results are expected to be low as the contributions of the independent variables of these areas in the coefficients of the multiple regression were smallest (see Table 5.11 and Figures 5.2, 5.3). It should be noted here that at Shambat, with dry conditions in this month and in July, both the recorded and the estimated daily rainfall totals approached zero values, and because of this they could not be presented in the proportionately drawn graphs of these months.

Within the process of estimating rainfall from the controlling variables considered in this study, another step was taken to estimate the daily rainfall of a place (test station) from a formula designed for the nearest place in this study (formulae source), and then correlating the resultant estimates with the observed rainfall of the test station. Five pairs of stations were used and the results are shown in Table 5.13. It can be seen that poor results were obtained, and in many cases the values showed negative

Fig. 5.5 OBSERVED AND ESTIMATED DAILY RAINFALL (MM) DURING SEPTEMBER 1967 FOR 12 STATIONS

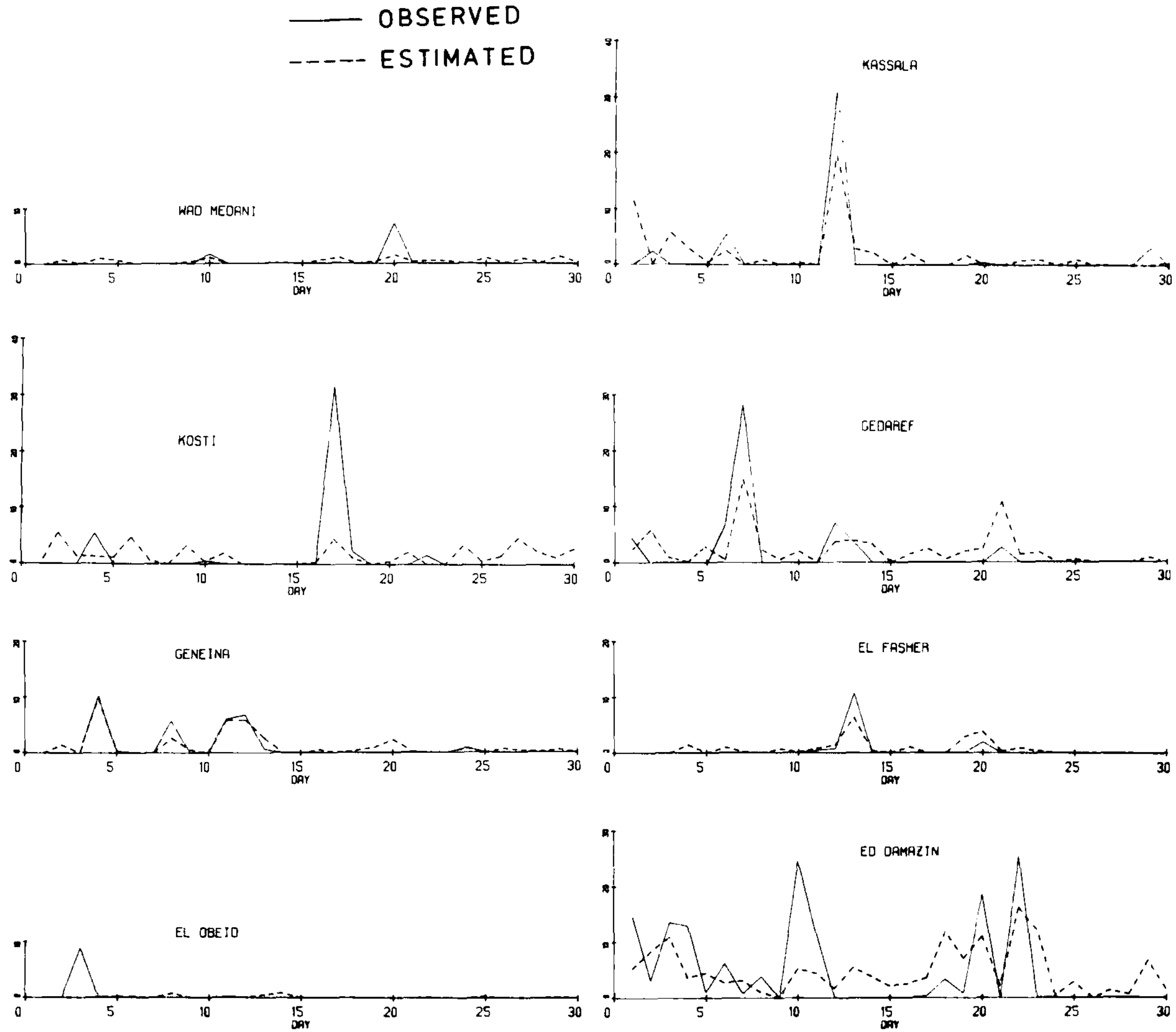


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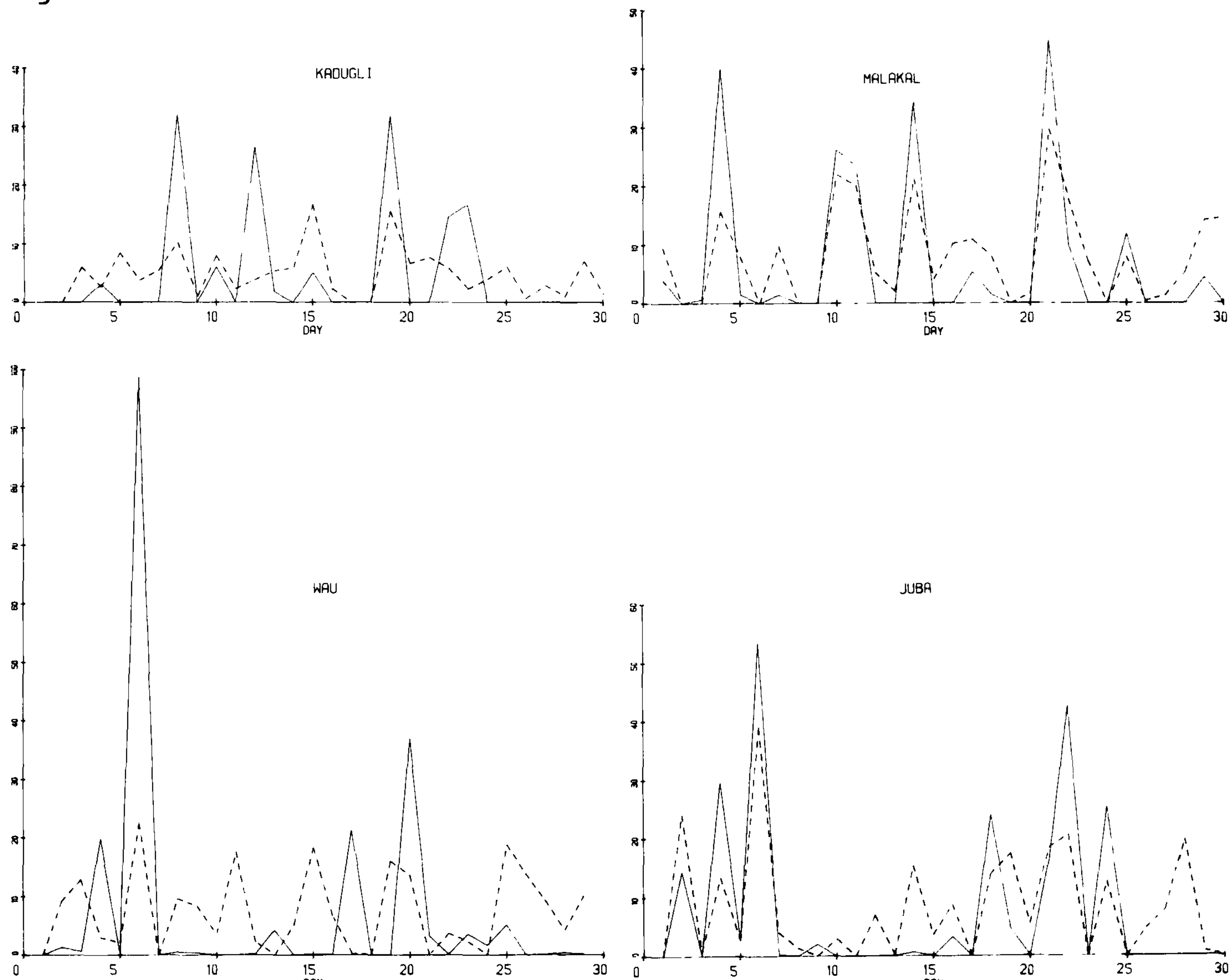
Fig. 5.5 (CONTINUED)



signs. The only place which showed a significant correlation coefficient was Shambat with a value of 0.42 in July. It should be noted here, although each selected pair included the nearest stations to each other within the study area, they are still quite distant (over 180 kms). Better results would have been achieved if the actual daily rainfall of nearer rainguages had been obtained.

It can be generalized in this section of observed and estimated rainfall correlation, that there were always underestimations of the heavy showers over the study areas (see Figs.5.3, 5.4 and 5.5). This situation decreases the reliability of such a model, especially when considering the showery nature of the rainfall over the Sudan as mentioned in section 3.7.2.

One of the uses of the model is to establish reliable equations for rainfall estimation from the data for those cells with raingauges. The equations can then be applied to those cells without raingauges (satcells). In this way the satellite imagery may help in closing the gaps of rainfall measurement and contribute to a better understanding of daily rainfall for the different purposes defined in section 5.1. Unfortunately, because of the poor performance of the model and the lack of rainfall data, the mapping of the estimated rainfall in the satcells from gacells in the area did not seem a sensible course because of the generally low R^2 values. It is also not useful to extend this trial to obtain estimated monthly rainfall totals, for the same reason of the discouraging daily rainfall estimates. Some of the reasons for the shortcomings of the model and its failure to provide the optimum results aimed at, have been shown in section 5.2.4, and in addition some further reasons will be given below.

5.4 Evaluation of the modified Barrett model

5.4.1 Problems related to the variables and the measurements

The modification of Barrett's model proved to be of some use, and the results it gave for the Sudan were better than those given by the original model. However, the disadvantages related to the basic model which are mentioned in section 5.2.2 are applicable to the model at its modified stage also. The following criticisms can be added :

(1) There was some subjectivity in the angular resolution of the cloud direction from the station. The measurements of cloud direction were made on almost vertical, horizontal and diagonal lines considering the main directions from which clouds contributing to rainfall were expected, rather than a finer direction measurement.

(2) The size and type of cloud might be affected by their distances from the station. The longer distances of relatively smaller clouds are thought to be of less or no effect than the larger clouds with shorter distances from a station, because of the changes of clouds as they move.

(3) The synoptic condition is changeable to such a degree that it might be completely different from that viewed by satellite in a very short time. Winds

may take different directions causing considerable deflections of observed clouds either towards or away from a station. This situation may lead to different results from those expected. There is a difficulty of estimating daily rainfall totals as performance of similar cloud fields can be different from one day to the next (Barrett, 1973).

(4) The 1^{o} latitude/longitude gacells, although proved to be the best in this study, sometimes caused measurement problems, for example when clouds lie on the border line with neighbouring cells. The quantification of the part of clouds that occur over the unit under consideration may be misleading and may show different results from those expected.

Besides these, there are problems related to the correlation and regression techniques used in the modelling, which are discussed below.

5.4.2 Problems related to the statistical methods

Although the correlation method is useful, it does not imply causal relationships between variables (Gregory, 1973; Hammond and McCullagh, 1974). As has been mentioned in section 5.3.2, significant correlations between rainfall and other variables sometimes occur when they are not expected. This sort of correlation might happen because both variables have correlation with an omitted third variable.

The regression shows residuals that cannot be explained by the variables. The larger the residuals the worse the model will be, and a need to think of some unconsidered variables which may help in explaining much of the residual variance becomes real. The regression also suffers from the problem of multicollinearity (see section 5.2.3), the situation when one explanatory variable is a linear function of one or more of the other explanatory variables. This problem reduces the degree of reliability of the regression equations and in estimations (Cheswick and Cheswick, 1975). An example from this study is the very strong relationships among cloud amount, cloud type and synoptic condition variables which frequently occurred at different stations of this study (see Table A.5) These variables, although sometimes having a fairly strong correlation with rainfall, did not contribute much to the coefficients of the multiple correlation. It can be seen from Tables 5.4 and 5.5 at Ed Damazin in September that the correlation coefficients of cloud amount, cloud type and synoptic condition were 0.47, 0.51 and 0.31, respectively, while they all contributed only 0.52 in the coefficient of the multiple correlation. Another example is from El Fasher in September where the cloud type was the first variable entered in the regression ($r = 0.63$) and both cloud amount ($r = 0.42$) and synoptic condition could only raise the coefficient of the multiple correlation by 0.03. It is a real problem in multiple regression analysis to find totally independent explanatory variables. Sakamoto (1981) stated that "this problem could lead to unstable coefficients as well as to incorrect signs". As the problem of multicollinearity is sometimes impossible to solve, it is also difficult to distinguish between serious and not serious multicollinearity (Haushek and Jackson, 1977). However, Mather (1976) mentions that this problem is not critical if the regression is being used in a descriptive (curve fitting) manner.

Another problem is that related to the number of variables determined to be considered in the regression formulae. Little and Hills (1972) state that "adding or eliminating variables is a difficult problem, and no practical method is known for finding the best set of a given size out of a large number of variables. In this respect and using the stepwise regression, the determination of those variables can somewhat successfully be made by discarding the almost redundant variables coming at the bottom of the multiple correlation coefficients' hierarchy. Besides these, some other problems related to statistical modelling will be discussed in chapter 6 and the successive chapters where the approach is used in the assessment of climate crop relationships.

It can generally be said that although the model of estimating rainfall described in this chapter is useful, it is not advisable to rely upon it at this stage. There is a question about how successful the model will be in tropical areas. It is expected to be successful where rainfall is mainly associated with advective rather than convectional processes as in tropical areas-like Sudan-(Barrett, 1973). The poor results shown here indicate that the model needs further modification and testing. However, the model stands as a basis for further development on the way to successful rainfall estimation. It can be suggested here that some conventionally measured variables such as wind directions and wind speeds at each station might help in building a better model.

Some hope for better quality satellite data comes from the geostationary satellites (e.g. Meteosat). This type of satellite has the advantage of providing the user with a final image every 30 minutes. Equipped with the Visible Infrared Spin-scan Radiometer (VISSR) the satellite provides high quality day/night cloud cover image data (Barrett and Hamilton, 1982). These rich data can potentially be used to obtain a comprehensive picture of cloud development throughout the day, especially in the afternoon and evening periods which are very important in assessing the behaviour of daily rainfall in the Sudan. From a study built on such far better data than those of Essa 3 and 5 considerable improvement or replacement by a better model can take place.

The different reactions of different variables to rainfall suggest that different mechanisms of rainfall in different areas may occur, and one cannot be sure before further testing of the satellite imagery and a closer study of weather controls at each station. The model should not be over criticized. The lack of a better network of raingauges decreases the degree of certainty as to whether the readings given by one raingauge are representative of the whole gacell or not. However, generally speaking the study of satellite imagery contributes to a comprehensive view of cloud arrangements and types, as well as disclosing the wide scale systems which in itself is a considerable benefit to weather studies.

The trial of assessment of the daily rainfall in some areas in the Sudan dealt with in this chapter is followed by a general description of the characteristics of agriculture as a prerequisite for the investigation of climate-crop yield relationships. The following chapter also deals with the properties, the advantages and the shortcomings of the statistical methods that will be used in the successive chapters as tools in this examination of climate-crop yield relationships.

CHAPTER SIX

AGRICULTURE AND CLIMATE - CROP RELATIONSHIPS IN THE SUDAN

6.1 Agriculture in the Sudan

6.1.1 General

The prominent kind of land use in the Sudan is the unimproved grazing which extends from north to south in the extensive savanna lands. Here short season cropping is the main agricultural activity. Horticulture and perennial crops are limited and sporadic alongside the River Nile, and on a limited scale along its tributaries. Perennial irrigated croplands are also dependent on the Nile watering, but the construction of dams on the Nile made it possible to include further large areas in this classification. However, agriculture contributes 41% of Sudan's Gross Domestic Product, about 90% of the total value of domestic exports, as well as employing over 80% of the country's labour force (Hoyle, 1976). Thus the Sudan can be described as an agricultural country.

Agriculture in the Sudan can be divided into two major sectors:

(1) A traditional sector with vast, extensive lands, entirely devoted to crops, mainly sorghum, millet, groundnuts and sesame; and

(2) A highly organized sector where irrigation from the Nile is used to grow cotton and other commercial crops.

However, only 3.3% of the total land, or only 9.3% of the total cultivable land, is annually cropped (Ministry of Agriculture, 1977). Most of the land is owned by the government and more than 27% of the cultivated land is managed by the governmental corporations which lease the land among the tenants according to traditional partnership (Ministry of Planning, 1970).

From the 1966-75 average figures, 10.8 million feddans of the Sudan's land were utilized for agriculture, and of this 18% was irrigated, 80.6% rainfed, and only 1.4% flooded (Ministry of Agriculture, 1977).

Irrigated area

The irrigated area, where the most intensive agriculture is practised, consists mainly of those large gravity irrigation schemes developed after the construction of dams on the Blue Nile and the other Nile branches flowing from the Ethiopian plateau (Ministry of Agriculture, 1977). Those areas are the Gezira, Suki, Khashm el Girba and the recently developed Rahad scheme. Smaller scale areas under different types of irrigation are the pump schemes spreading mainly along the White and Blue Niles. The smallest in scale in relation to irrigated lands are the private and cooperative pump schemes which are concentrated along the River Nile north of Khartoum. This latter type has almost replaced the traditional Persian water-wheel 'Saqiya' and counter-weighted lever (shaduf) cultivation depending on animal and human efforts.

Rainfed area

Rainfed agriculture occupies about 80% of the cultivated land (Ministry of Agriculture, 1977). Most of the practices of this type prevail in what is known as the Central Rainland area which is limited in the north by a line running from north of Kassala, through Wad Medani and north of El Obeid (Burnett, 1948). The southern limit is a parallel line running through Roseires, Kadok and westwards to the border (Burnett, 1948). The main mechanized farming schemes within the area are principally those of Gedaref in the Kassala province, Dali an Mazmum in the Blue Nile province and those in the Kordofan and Upper Nile provinces. The Central Rainland area is the scene of both government and private schemes. Traditional methods of cultivation prevail in this area. The organized sector in this area concentrates on sorghum, and to a lesser extent on sesame, while those crops together with groundnuts and millet are all familiar in the traditional sector.

In southern Sudan, where rainfall is the main way of watering crop lands, shifting cultivation is the main agricultural activity (Lebon, 1965).

Flooded area

The main flooded areas are those in the eastern Sudan : the Gash and Baraka deltas. This type is divided by Allan (1948) into two groups :

(a) Flush irrigated areas, waterfed by inundation through control works which regulate water distribution (Gash delta);

(b) Natural flooding without a successful control due to the nature of the stream (Baraka delta).

Only in these areas did early establishment of modern agriculture take place.

In general the organized sector, which includes most of the irrigated and mechanized farming areas, is responsible for producing all of the Sudan's cotton, wheat and castor oil, two thirds of the sorghum, the 50% of the groundnuts and sesame; in fact it accounts for about 80% of the country's total agricultural production (Ministry of Agriculture, 1977).

6.1.2 Systems of cultivation

It is in the irrigated areas where the most intensive forms of agriculture are practised. Here cultivable land is restricted and in most of the big schemes crop rotations with some fallow are applied. In small private holdings there is no fallow.

In the Central Rainland area of the Sudan the three traditional methods applied are :

(1) Shifting cultivation where land is cultivated for some years and then left for some other years. This type is mostly applied where the man/land ratio is small.

(2) 'Hariq' cultivation is the method of allowing grass to grow for 2-3 years and then burned after the first incidence of heavy rain of the growing season. The idea is to eradicate the newly developing grass. This type is a land consuming method, as is the previous one.

(3) Intensive cultivation which is applied where land is severely restricted. Here continuous cropping of an agricultural holding is practised.

The Hariq type of cultivation has been almost replaced by mechanized farming. In this mechanized farming system the farmer is given an area of 1,000 - 1,500 fd. to grow sorghum as a main crop in a rotation with cotton and sesame or fallow. In fact it is rare that private mechanized scheme owners stick to these conditions, where sorghum is always dominant and fallow is rarely considered (International Development Association, 1972; Mahmoud, 1977).

6.1.3 Developments in Sudan Agriculture

Sudan has extensive potential in agricultural land which, if developed, could make the country self-sufficient in agricultural products. With population growth and national interest in mind many efforts have been exerted in recent years to develop agriculture. The type of irrigation plays a substantial role in the location, type and dimension of agriculture in the Sudan. The three main types of agriculture (the irrigated, the rainfed and the flooded) witnessed different phases of development that will be discussed here and the location of the main schemes is shown in Figure 6.1.

Irrigated area

Irrigated agriculture has been known in the Sudan since early times. 'Saqiya' and 'shaduf' cultivation on the Nile shows traces of the ancient Egyptian cultural influence. For a long time little expansion occurred in areas of this type until the beginning of this century, when revolutionary changes began.

In 1904 a project was started at Zeidab, about 290 kilometres north of Khartoum, to experiment with techniques of mixed farming. The project developed into a scheme devoted solely to cotton and necessary food crops under the administration of the Sudan Plantation Syndicate. An area of 40,000 fd. was covered by the scheme (Mackinnon, 1948a).

The second project involved the Gezira. The idea of constructing a dam on the Blue Nile with a linked canalization system to irrigate the Gezira came as early as 1904. In 1912, before the start of the dam construction, a pilot pump scheme in the Gezira, at Tayiba near Wad Medani, was established bringing 610 fd under cultivation. Two years later a similar pilot scheme was established at Barakat, just south of Tayiba, to increase the cultivated area by about 6,000 fd, and to include, together with the Tayiba scheme, an area of 2,962 fd. for cotton growing. Both schemes were administered by the Sudan Plantation Syndicate.

The execution of the building of the dam at Sennar in 1913 was held up by World War 1, and the dam with the accompanied canalization were completed by 1925. Meanwhile two pumping stations at Hagabdalla and Wad en Nau were functioning to extend the cotton area up to 22,483 fd. by 1923.

In 1925 a new era of extensive organized cultivation started in the Sudan by the opening season of irrigated cultivation of the Gezira Scheme. The area allotted to cotton, the main commercial crop, increased quickly to over 80,000 fd, and it continued to increase until it reached 235,000 fd. in 1953 (Mackinnon, 1948a; SGB, 1954). The gross area of the Gezira scheme was 667,000 fd. by 1931, 852,000 by 1938 and 876,000 by 1944 (Allan, 1948).

The administration of the Gezira scheme was handed over by the Sudan Plantation Syndicate to the Sudan Gezira Board (SGB) in 1950, and in the late 1950's the Managil extension of the Gezira scheme, in four equal phases, started with a target of adding some 800,000 fd. to the already cultivated one million fd. (Ministry of Information, 1967). The Gezira cultivated area was 1.35 million fd. by 1960 and 2.07 million fd. by 1970 together with a slight increase in 1975. About 25% of the area is left fallow in the course of rotation (SGB, 1979).

After the development of the Gezira scheme in 1925, the largest expansion of the irrigated land occurred as a result of the development of pumping schemes brought about by the high commercial reputation of cotton. The area of pumping schemes enlarged from 38,000 fd. in 1925 to 180,000 fd. in 1944 (Osman 1958). The availability of water, the high prices of cotton, and government encouragement were among the factors which accentuated that rapid growth. By 1956 more than 1,500 schemes were in existence irrigating over 625,000 fd. (Osman, 1958).

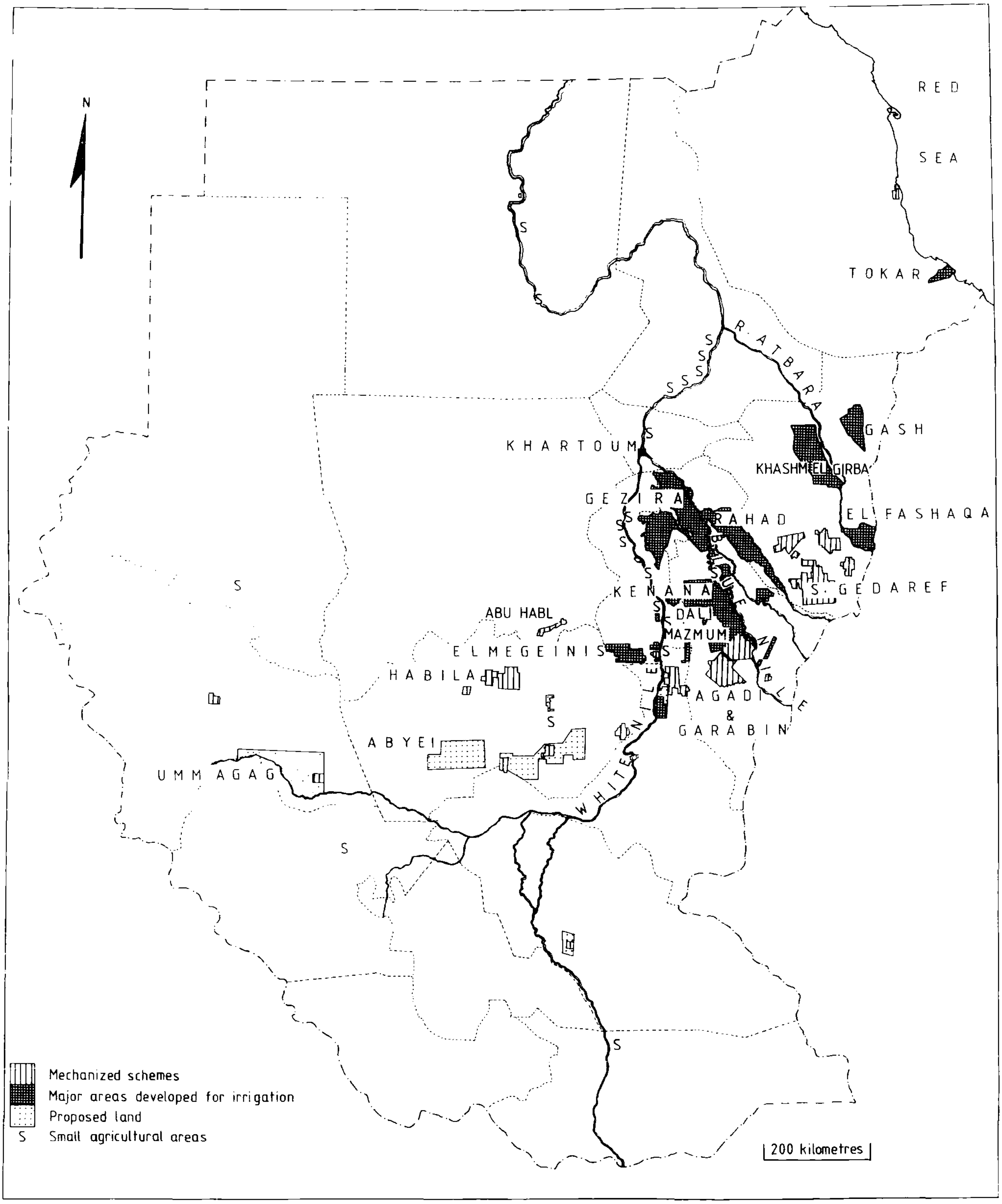
The incidence of establishing schemes after World War 2 was higher in the White Nile than in the Blue Nile area. Lifting water by pumps is much easier from the former than from the latter because of the raised water level by the construction of the Jebel Aulia dam beside the relatively low banks of the White Nile.

The Blue Nile schemes developed later, and on a smaller scale. The first large scheme in this area was established in 1948 at El Busata (just above the Sennar dam). No big scheme was developed after that until 1955, when the Guneid scheme, on the eastern bank of the Blue Nile north of Rufaa, which was established to irrigate 30,000 fd. to grow cotton (Lebon, 1965). This area changed in the early 1960's to growing sugar cane. The development of El Suki, below the Sennar dam on the eastern bank of the Blue Nile, extended the irrigated area by 70,000 fd. in 1970 to be cropped by cotton, wheat and groundnuts. The Rahad project east of Sennar, is planned to add about 285,700 fd. to the irrigated lands for growing cotton and groundnuts in a rotation system. Another characteristic of the Rahad scheme is that it is partly irrigated by pumps from the Blue Nile and partly through a dam on the River Rahad, a Blue Nile tributary (see Fig. 6.1). This scheme, whose first phase was completed in the late 1970's came to be the most mechanized irrigated agricultural area in the country.

The development of the Khashm el Girba scheme, depending on irrigation from a dam built on the River Atbara, an important branch of the Nile, in the early 1960's added considerably to the area of irrigated agriculture. The plan was to include 150,000 fd. for growing cotton, wheat and groundnuts as well as adding 40,000 for growing sugar cane (Shaw, 1970).

In general, the development of organized irrigated agriculture has been designed to effect a shift away from the subsistence economy. This task is not an easy one, and many problems have arisen from it, but in general the result is an enhancement of economic development at both national and local levels.

Fig. 6.1 AGRICULTURAL SCHEMES IN THE SUDAN



Source: Sudan Surveys (1976)

Rainfed area

Since 1924 the Nuba Mountains have become an area of commercial interest. The government was sharing the growing of American-type of cotton with two companies. Cotton has been introduced since that time together with some ginneries in the area. The area of 20,000 fd. in 1942 was enlarged to 117,000 fd in 1950 and reached 228,000 fd in 1960 (March, 1948; Ministry of Agriculture, 1970). Other small schemes for growing cotton such as those in north Kordofan (Abu Habil) and Equatoria developed within the era of cotton expansion.

Gedaref was the first rainfed area to witness the initiation of state mechanization in 1944. Twelve thousand feddans were cultivated in the Wad el Huri scheme in 1945 and 21,000 fd. in the next year. The failure of rainfall in some seasons in this area caused the planners to direct their attention to the southern Gedaref area where rainfall is more reliable. In 1950 two schemes at Umm Sugura and Umm Bileil appeared in this area with about 7,800 fd. of mechanized agriculture between them, mainly under sorghum cultivation. This area underwent cotton and sesame trials aided by the provision of a water supply from earth tanks ('Hafirs') and better mechanical equipment. At this stage the northern and southern areas of the Gedaref region totalled 27,600 fd. of mainly sorghum, followed by cotton and sesame (Ministry of Agriculture, 1954).

These pilot schemes, together with the establishment of the Rainland Farming Research station at Tozi in the

Blue Nile province in 1952, encouraged the private entrepreneurs to enter this sector of agriculture (Ministry of Agriculture, 1954). The growing interest in mechanized farming caused significant change in the middle 1950's and the area cropped was enlarged to reach 210,000 fd. by the season 1954/55 (Rep. Sudan, 1957).

The Blue Nile province, south of the Sennar-Kosti railway line, was the region which followed the Gedaref area in the development of mechanized rainfed schemes. Dali and Mazmum have been the most famous areas of production in the region since the early 1960's. In the late 1970's some mechanized schemes were established away from those major areas; one in southern Kordofan with 227,000 fd. and another in Upper Nile with 85,000 fd.

However, of the total mechanized area, Gedaref had 32% and the Blue Nile 12% (Ministry of Agriculture, 1976). Towards 1978 about 1400 mechanized crop production schemes were functioning, of which 90% were private. International investments especially from other Arab countries are expected to be used in this sector in the western and the southern parts of the country (Hendry, 1978).

Flooded area

The interest in commercial cotton grown in the Sudan came from Egypt in the latter half of the nineteenth century (Ahmed, 1970). Cotton production probably began in 1860 in the Gash delta and in 1867 in the Baraka delta by the Egyptian governors (Mackinnon, 1948b). During the Condominium period cotton growing entered a new phase of development, and in 1924 a canalization system was set up to control the Gash river for irrigation. The Baraka river, because of its torrential and seasonal flow has always been difficult to control. The total cultivated area in the flooded lands has always fluctuated due to variability of the rainfall (Mackinnon, 1948b; Ministry of Planning, 1969). The cotton area ranged between 70,000 and 13,000 in each delta during the period 1920-1960 (Davie, 1924; Mackinnon, 1948b; Rep. Sudan, 1957; Ministry of Agriculture, 1970). For the period 1960-1974 an average area of 120,000 fd. was cropped yearly (Ministry of Agriculture, 1977).

General agricultural development

Concerning the general aspects of agriculture in the Sudan it can be seen from Tables 6.1 and Figure 6.2 that an average area of 7.7 million fd. was cropped between 1960/61 and 1968/69, with an exceptional year in 1967/68 where over 9 million fd. were cultivated. An increase of land by about 77% over the 1960's average occurred in 1969/70, followed by successive expansions through the following years. The resultant aggregate of cultivated lands was 15 million fd. by 1975/76, which was more than double the area cropped yearly in the early 1960's. About 95% of that area was occupied by cotton, sorghum, millet, sesame, groundnuts and wheat. In 1975/76 sorghum occupied about 42% of the cultivated lands, followed by millet (16%), sesame (15%), and groundnuts (14%). Cotton, which is the most important in the government revenue, occupies only 6.4% of cultivated land.

The expansion in recent years has been greater for other crops than for cotton, which maintained an average of about one million fd, even dropping slightly in 1975/76. The decline of the percentage of land occupied by cotton from 14.4% to only 6.4% does not mean a sharp drop in the actual size of the cotton area. The reasons for this can be seen from two factors :

(1) The huge extension of the sorghum and sesame areas because of the extensive mechanization taking place in the rainfed areas (see Fig. 6.1); and

(2) The growing interest in diversifying crops instead of depending on cotton alone. This development took place in the irrigated areas where groundnuts, wheat, sugar cane and other crops have been recommended to be grown affecting cotton areas (Table 6.1).

Between 1960 and 1975 the wheat cropped area increased almost twenty fold to reach 714,000 fd, and that increase mainly occurred in the Gezira area. By 1975 groundnut cultivation had increased to five times its area in 1960 (see Fig.6.2). In the Gash area cotton has been totally replaced by castor oil and in Guneid sugar cane has developed causing a shrinkage in the cotton area.

From Table 6.2, which shows the average areas, production and yields of the main crops by type of irrigation for the period 1960-1975, it can be observed that the most important crops from the area viewpoint were cotton in the irrigated (760,000 fd) and flooded (60,000 fd) areas and sorghum (3.5 million fd) in the rainfed area. In terms of

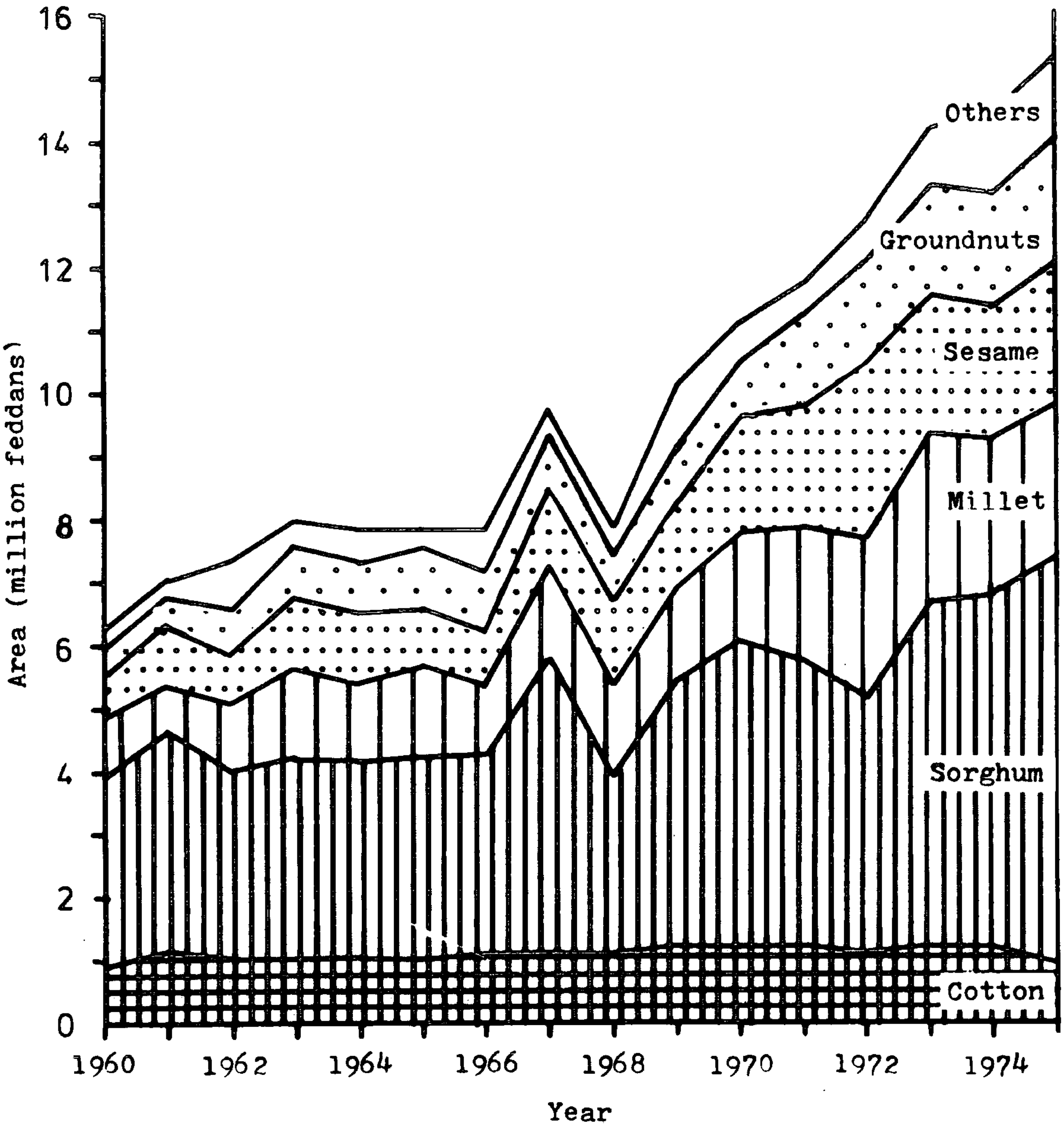
Table 6.1 — Total area of main crops in thousand feddans

	Cotton	%	Sorghum	%	Millet	%	Sesame	%	Groundnuts	%	Wheat	%	Others	%	Total
1960/61	906	14.4	3,067	48.8	932	14.8	694	11.0	470	7.5	39	0.6	179	2.9	6,287
61/62	1,133	16.2	3,516	50.2	759	10.8	981	14.0	472	6.7	41	0.6	107	1.5	7,009
62/63	1,066	14.5	3,517	48.0	1,066	14.5	776	10.6	695	9.5	54	0.7	159	2.2	7,333
63/64	1,049	13.1	3,277	41.0	1,411	17.7	1,184	14.8	847	10.6	56	0.7	164	2.1	7,988
64/65	1,068	13.6	3,158	40.3	1,427	18.2	1,116	14.3	779	10.0	136	1.7	145	1.9	7,829
65/66	1,050	13.4	3,199	40.9	1,447	18.5	948	12.1	935	11.9	137	1.8	112	1.4	7,828
66/67	1,158	14.9	3,182	40.8	1,297	16.6	924	11.9	926	11.9	172	2.2	137	1.7	7,797
67/68	1,149	11.7	4,700	48.1	1,452	14.8	1,234	12.6	847	8.7	213	2.2	186	1.9	9,781
68/69	1,118	14.3	2,823	36.0	1,436	18.3	1,321	16.9	719	9.2	263	3.4	158	1.9	7,838
69/70	1,256	12.4	4,229	41.8	1,502	14.8	1,359	13.4	1,073	10.6	290	2.9	419	4.1	10,128
70/71	1,210	10.9	4,894	44.0	1,735	15.6	1,857	16.7	914	8.2	290	2.6	230	2.0	11,130
71/72	1,219	10.3	4,555	38.7	2,100	17.8	1,921	16.3	1,511	12.8	288	2.4	188	1.7	11,782
72/73	1,141	9.0	4,095	32.2	2,548	20.0	2,847	22.7	1,642	12.9	248	2.0	195	1.5	12,716
73/74	1,215	8.6	5,446	38.4	2,713	19.1	2,265	16.0	1,748	12.3	424	3.0	369	2.6	14,180
74/75	1,219	8.5	5,577	38.3	2,584	17.9	2,178	15.1	1,792	12.4	591	4.1	475	3.3	14,416
75/76	987	6.4	6,374	41.6	2,513	16.4	2,292	15.0	2,067	13.5	714	4.7	383	2.4	15,330

Source : (1) Ministry of Agriculture (1970) Bull. Agricultural statistics of the Sudan No.10, Khartoum.

(2) Ministry of Agriculture (1977) Sudan yearbook of Agricultural statistics, Khartoum.

Fig. 6.2 TOTAL AREA OF MAIN CROPS IN THE SUDAN (1960/61-75/76)



Source: (1) Ministry of Agriculture (1970) Bull. Agricultural statistics of the Sudan, No. 1, Khartoum

(2) Ministry of Agriculture (1977) Sudan yearbook of agricultural statistics, Khartoum

Table 6.2 Average area, production and yield of crops by type of irrigation; 1960/61 - 1974/75*

Area in 1000 fd.
Production in 1000 tonnes
Average yield in kg/fd

	Irrigated			Rainfed			Flooded			Total		
	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.	Yield
Cotton(Egyptian)	695	423	608	-	-	-	28	5	170	724	428	591
Cotton (Others)	65	35	539	215	28	131	32	5	140	312	68	217
Sorghum	434	223	513	3,521	1,127	320	57	24	421	4,012	1,374	342
Millet	-	-	-	1,667	330	198	10	3	35	1,677	333	198
Sesame	-	-	-	1,493	212	141	-	-	-	1,493	212	141
Groundnuts	161	130	807	903	241	266	-	-	-	1,064	371	348
Wheat	227	111	486	-	-	-	2	1	500	229	112	489

* Cotton figures are averages of the period : 1955/56 - 1974/75

Source : Ministry of Agriculture (1977) Sudan yearbook of agricultural statistics, Khartoum, Sudan.

exports cotton has always occupied the first rank in earning foreign currency; about £133 million in 1977. The second rank has recently been taken by groundnuts (£26 million), followed by sesame (£17 million). Both the latter crops caused gum arabic to drop to the fourth place in the rank of earning foreign currency (O'Neill, 1980; Suliman, 1980).

Considering the regional balance in irrigated agriculture, it can be seen that about half of the area of cotton grown in the Sudan lies with Gezira (Table 6.3). The Gezira, Blue Nile and White Nile (old Blue Nile province) together included about 73% of the Sudan's cotton area. Sorghum, the main food crop in the Sudan, is cropped in all the provinces, principally in Kassala (30% of total area) and the Blue Nile (20%). In northern Kordofan and Darfur where millet replaces sorghum as a food crop, the percentages of areas occupied by this crop are 48% and 43% respectively. Forty two per cent of the sesame area is in northern Kordofan. This latter crop is also important in the Blue Nile and Kassala provinces where 34% of Sudan's sesame growing areas are shared by both those provinces. Groundnut areas are mainly in northern Kordofan (32%) followed by Darfur (20%). It is noted that the status of this crop has been growing in the irrigated areas in recent years, and by 1975 the Gezira scheme shared 15% of the country's total groundnuts area. Wheat, which is the least significant in area, has been developing in recent years. The Gezira area included 72% of the total area of wheat in the Sudan, followed by the Khashm el Girba scheme of Kassala with 20% of the Sudan wheat area.

Table 6.3 Areas of main crops by province in 1974/75 in thousand feddans

Province	Cotton		Sorghum		Millet		Sesame		Groundnuts		Wheat	
	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%
Northern	-	-	2	0.3	-	-	-	-	-	-	23	3.9
Nile	7	0.5	68	1.2	1	*	-	-	2	0.1	7	1.1
Khartoum	-	-	24	0.4	-	-	-	-	1	0.1	1	0.3
Gezira	603	49.4	253	4.5	2	0.1	-	-	261	14.6	428	72.4
Blue Nile	140	11.5	1,111	20.0	40	1.5	374	17.1	66	3.7	7	1.1
White Nile	151	12.4	250	4.5	41	1.6	88	4.1	64	3.5	7	1.2
Kassala	117	9.6	1,678	30.1	2	0.1	374	17.2	68	3.8	118	20.0
Red Sea	57	4.7	40	0.7	7	0.3	-	-	-	-	-	-
N.Kordofan	-	-	347	6.2	1,250	48.4	924	42.4	579	32.3	-	-
S.Kordofan	104	8.6	631	11.3	74	2.9	167	7.7	127	7.1	-	-
N.Darfur	-	-	50	0.9	570	22.0	23	1.1	85	4.7	-	-
S.Darfur	-	-	256	4.7	530	20.5	69	3.2	360	20.1	-	-
Bahr el Ghazal	-	-	196	3.5	63	2.4	70	3.2	51	2.8	-	-
Upper Nile	25	2.0	435	7.8	-	-	51	2.3	1	0.1	-	-
Equatoria	16	1.3	219	3.9	4	0.2	38	1.7	128	7.1	-	-
Sudan	1,219		5,577		2,584		2,178		1,792		591	

* neglected fraction

Source : Ministry of Agriculture (1977) Sudan yearbook of agricultural statistics, Khartoum, Sudan.

6.1.4 Variations in crop yield

Table 6.4 shows the contribution of each of the most important crops to the total agricultural crop production in the Sudan. But those figures, though quite useful, should be considered carefully because an increase or decrease in production does not always mean a rise or fall in productivity. The figures may just be due to enlargement or shrinkage of agricultural lands. Variation in crop yields, which is the productivity (unit per fd), is an important indicator of variation in cultivation, physical and socio-economic conditions.

From a comparison between Tables 6.4 and 6.5 (crop yields), it can be observed that cotton production in the season 1969/70 (675,000 tonnes) was higher than the production in the previous season (655,000 tonnes) while its productivity was lower by 49 kg/fd. A similar situation is noticed for the year 1973/74 and 4 year before it. In the case of sorghum, where both variation in production and yield were greatly affected by rainfall, coinciding rises and falls of the two can be seen in many cases. However, increase of production here may still be misleading. It can be observed that although in 1970/71 an increase was seen in sorghum production of 83,000 tonnes over the previous year, a drop in yield of 30 kg/fd was recorded. The production at the end of the period was over 2 mi. tonnes yet the productivity (318 kg/fd) was even less than for instance that of 1964/65 (360 kg/fd), where the production was only 1.3 million tonnes the same could be said about millet where comparison between production and yield of 1971/72 441,000 tonnes; 210 kg/fd) with those of

Table 6.4 Production of main crops; 1960/61-1974/75
in thousand tonnes

Year	cotton	Sorghum	Millet	Sesame	Ground-nuts	Wheat
1960/61	341	1,051	226	127	192	26
1961/62	612	1,434	204	233	148	28
1962/63	476	1,266	291	142	228	31
1963/64	310	1,349	374	174	289	37
1964/65	442	1,138	354	184	280	56
1965/66	449	1,094	353	160	305	69
1966/67	537	850	252	134	313	79
1967/68	527	1,980	269	187	298	87
1968/69	655	870	267	154	164	123
1969/70	675	1,452	385	175	385	115
1970/71	731	1,535	439	297	339	163
1971/72	685	1,591	441	296	387	124
1972/73	556	1,300	355	340	568	152
1973/74	671	1,691	284	244	553	235
1974/75	641	1,681	402	234	928	269
1975/76	322	2,027	404	239	932	264
Average	539	1,394	331	207	394	116

Source : (1) Ministry of Agriculture (1970) Bull.Agr. Statistics of the Sudan, Khartoum.
(2) Ministry of Agriculture (1977) Sudan Yearbook of Agricultural Statistics, Khartoum.

Table 6.5 Average yield of main crops; 1960/61-1974/75

(kg/fd)

Year	Cotton	Sorghum	Millet	Sesame	Ground-nuts	Wheat
1960/61	376	343	243	183	409	667
1961/62	540	408	269	238	314	683
1962/63	446	360	273	183	371	574
1963/64	295	412	265	147	341	667
1964/65	414	360	248	165	359	421
1965/66	427	342	244	169	326	504
1966/67	463	267	194	145	338	459
1967/68	458	421	185	152	352	408
1968/69	586	308	186	117	228	469
1969/70	537	344	256	129	359	397
1970/71	604	314	253	160	371	562
1971/72	561	349	210	154	256	431
1972/73	487	317	139	119	346	613
1973/74	552	311	105	108	317	554
1974/75	530	301	155	107	518	455
1975/76	325	318	160	104	451	370

Source : Ministry of Agriculture (1977), Sudan yearbook of agricultural statistics, Khartoum, Sudan.

1962/63 (291,000 tonnes; 273 kg/fd) gives a good example that horizontal expansion does not mean, by definition, expansion in yield. Sesame production and yield trends were compatible with each other throughout most of the study period. Groundnuts showed contradicting trends through most of the period and in spite of the rise in production(1975) of 40 00 tonnes over the previous season, a big drop of 67 kg/fd in the yield occurred. These contradictions were also noticed in wheat. Thus it can be seen that wheat production increased ten-fold since the beginning of the period, yet the yield dropped by 297 kg/fd in 1975/76.

Figure 6.3 gives the pattern of variations in yields of the main crops considered in this study for the whole country. It should be kept in mind that this yield averaging is adopted for the sake of generalization. This averaging has levelled out the variations in yields. The observed yield of different areas if obtained can reveal the masked differences in production and yield trends through time and spatial comparison can be obtained.

Yields of all crops here showed variations from year to year with different degrees and trends. Cotton showed a trend of rising yield between 1964 and 1971 to reach a peak of 600 kg/fd in 1970/71, and a tendency for the yield to drop since then with a lowest value of 325 kg/fd in 1975/76. Sorghum had a gentler trend of drop in yield with some sharper variation, between 267 and 421 kg/fd, during the first half of the period, i.e. 1960-1968. The behaviour shown by groundnut yields, though similarly sharp, had an opposite trend to that of cotton; a trend of dropping yield in the first half and of rising yield in the second half of the period with a maximum of 518 kg/fd in 1974/75. Sesame showed a general drop of yield from about 198 kg/fd in the early 1960's to about 100 kg/fd in 1975/76.

Comparing four of the main cotton producing regions (Fig. 6.4) it is observed that in the period 1960-1975 although yields in the irrigated areas (Gezira and White Nile) were always far higher, they display sharper fluctuations than in the rainfed areas (Gedaref and Kordofan). The yield of the Gezira reached 840 kg/fd and never dropped below 320 kg/fd during this period. The White Nile area, although never reaching the highest score of yields at Gezira during the same period (highest 690 kg/fd), still kept the same level of the minimum yield as the Gezira. On the other hand the rainfed cotton yields of Kordofan and Gedaref, being similar to each other, ranged between 60 kg/fd and 220 kg/fd.

This yield variation and the failure of securing a steady high level of yield raises many questions about the factors affecting those crop yields, and the degrees of those effects. And this, as mentioned in the introduction, is one of the reasons for this study, where solely climatic factors have been selected to explore the relationships between climate and crop yields. The effect of climate, particularly rainfall, can best be seen through the expansion or shrinkage of areas in rainfed areas rather than directly reflected in crop yields. However, the relationship between climate and crop yields, as will be seen in the following three chapters,

Fig.6.3 AVERAGE YIELDS OF THE MAIN CROPS IN THE SUDAN

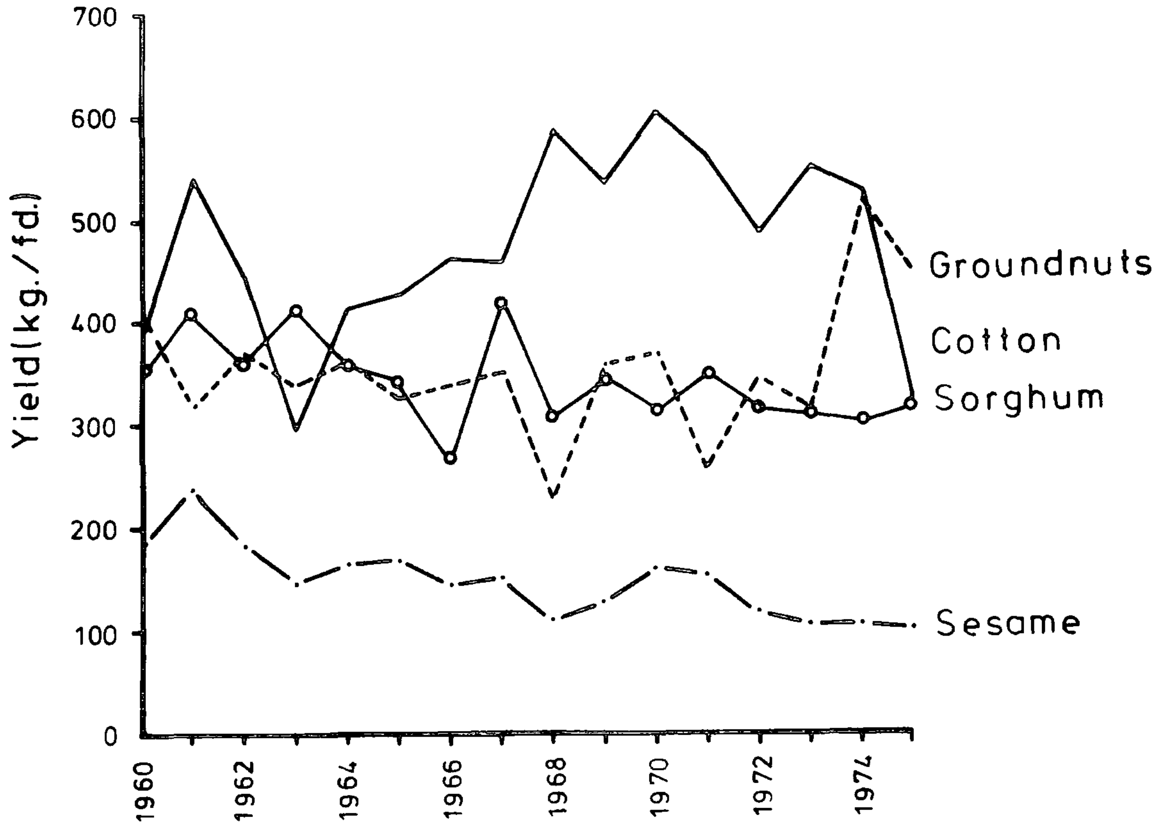
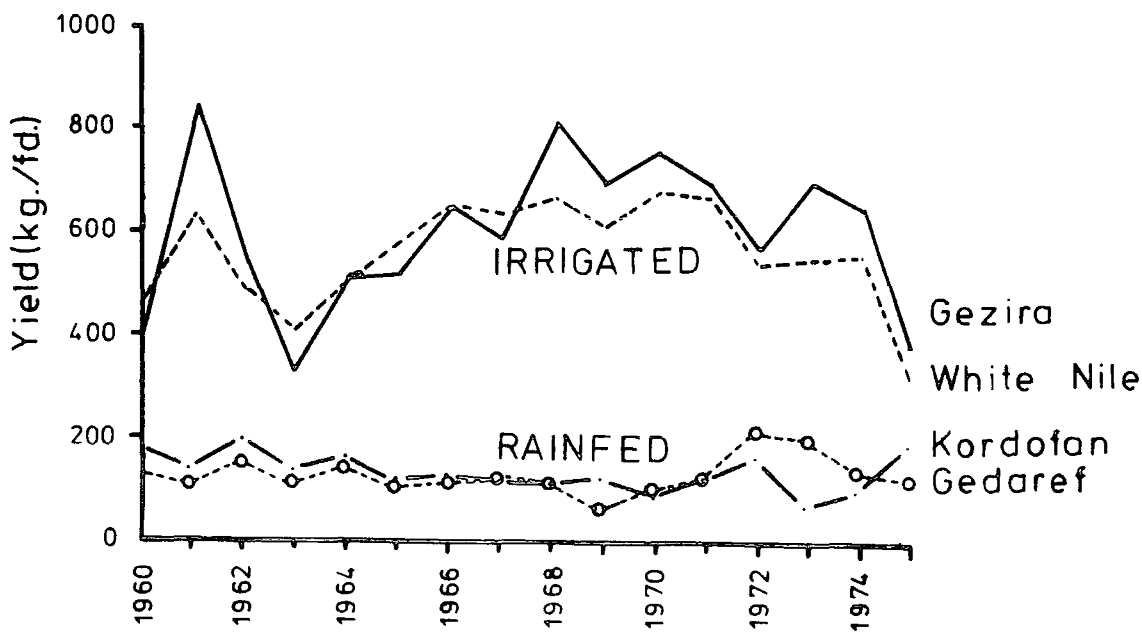


Fig.6.4 AVERAGE COTTON YIELDS IN 4 PRODUCTION AREAS



is not a simple and easily distinguishable one.

Understanding crop yield variability is closely related to the agricultural land use identification. This knowledge has been obscured by practical problems of accessibility and the skills of the assessors. Techniques using Landsat satellite imagery in agricultural land use evaluation are adopted in this study and discussed in the following section, and it is hoped they will help to solve these problems.

6.2 Monitoring agricultural land use from Landsat satellite imagery

6.2.1 General

The use of satellite imagery as mentioned in chapter 5 has contributed a great deal of knowledge to different scientific fields. The application of methods dependent on satellite imagery are complementary to, rather than replacements of conventional methods (Barrett, 1974; Lee et al., 1975). It is stated by Myers et al. (1975) that "remote sensing offers the feasibility of monitoring agricultural areas for rapid and continuous assessment of plant, soil and water resources and interrelated problems". Besides the usefulness of giving quick information repeated at short interval, satellite imagery also prove invaluable in giving comprehensive views of large areas. Satellite imagery give a summary of the relationships between climate, physical and cultural phenomena at a given time in a way that is helpful to the planners in many different fields. Satellite imagery also saves the high costs and the long time otherwise spent through conventional survey techniques (Schwarz and Gaydos, 1975). Comparisons of images of an area for different time periods give an opportunity to assess changes occurring in a phenomenon.

In the Middle East remote sensing can be used to monitor changes in environmental conditions and to provide fresh penetration into geographical problems in areas of difficult accessibility (Harris, 1981). Sudan is one of the largest countries in the Middle East, with a limited capability of financing the well established infrastructure needed to cover its vast regions. Also, as will be mentioned in some detail in this chapter, there have always been problems of monitoring physical features, economic activities or potentialities in a way conducive to efficient development. The usefulness and feasibility of applying Landsat imagery to the Sudan was discussed by Beaumont and Beaven (1977), Helldén (1978), Parry (1978), and Petrie (1979) on the basis of their examinations of Landsat imagery in different parts of the country for terrain mapping and inventory.

Landsat satellite orbits at a height of about 912 kms. in a trajectory that passes close to the poles. The images here are made by the Multi-Spectral Scanner (Sheffield, 1981). The Landsat data can be obtained from visual study of films or their prints, or by means of a computer from magnetic tapes, or by combining both methods. Beaumont and Beaven (1977) stated that the study of digital data is preferable for their accuracy, their minimal loss of information compared with visual method, and their advantage of removing errors of image distortion. Beaumont and Beaven (1977) maintain that "At present most systems using magnetic tapes are in a search phase of development and very few can be considered fully operational." Because of the problems of manipulating digital data efficiently, this study has concentrated on the visual interpretation of the Landsat imagery.

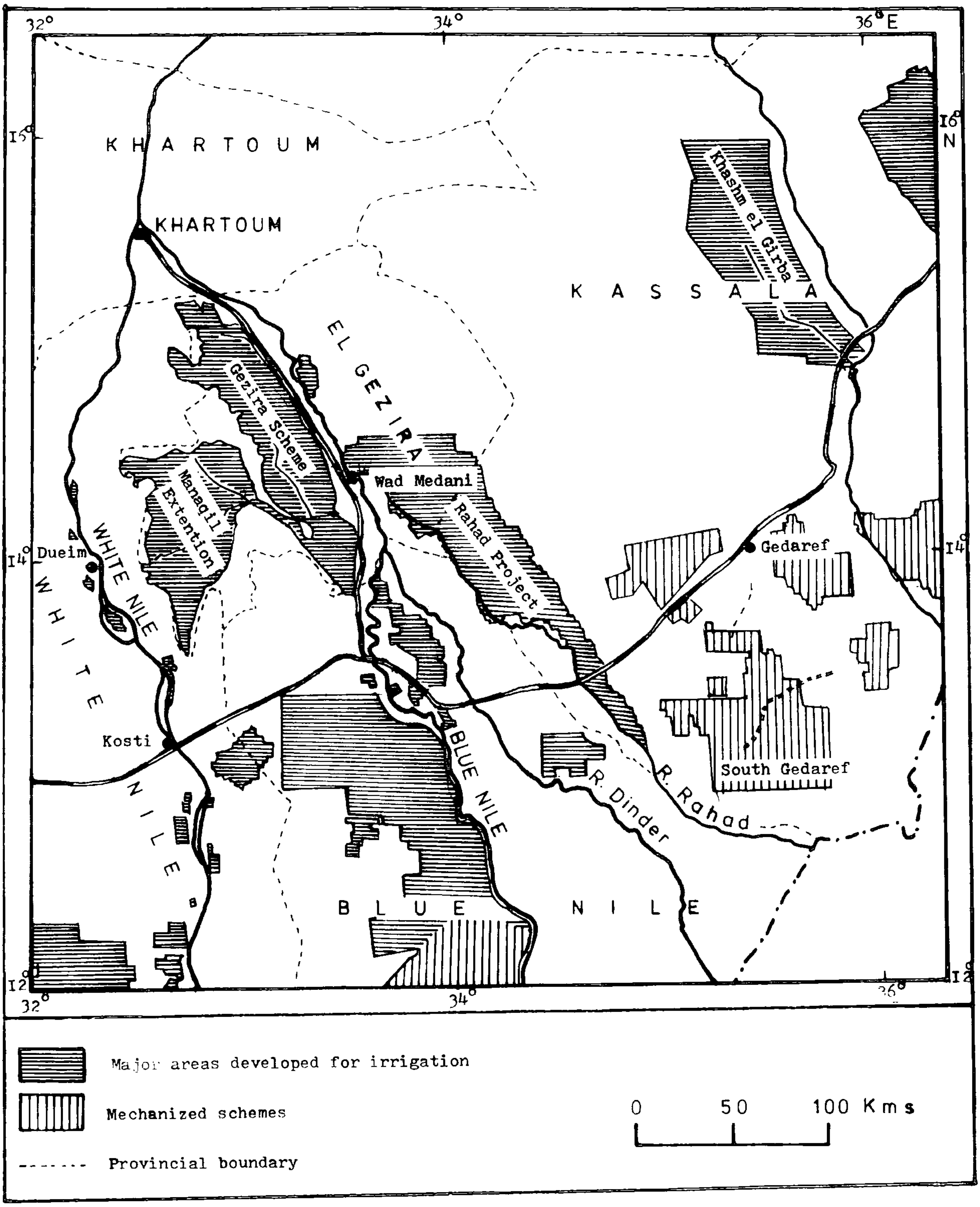
Many workers confirmed the usefulness of the visual study of Landsat imagery. Among them are Wilson(1967), Aldrich (1971), Krishnamurti and Vrinivasan (1973) and Bunnik (1981). Everrett and Simonett (1976) state that satellite imagery gives an opportunity to partition aggregate natural and social data. An example of this is the rich detail given by Landsat images of the study area in relation to drainage systems, small private schemes and the plans of irrigated schemes with their detailed canalization. These features are not expected to appear in the same detail on maps covering areas under consideration at the same scale of the satellite images.

From the archive of American Landsat data, it was found that the 1972/73 season was the best to fulfil the purposes of this study. The specified areas were all covered with satellite images free of, or with minimal, cloud cover. Five sets of satellite imagery produced for Gezira, Kassala and the Blue Nile (Fig. 6.5) were selected for inspection fo fulfil the following purposes:

(1) To examine the feasibility of demarcating, visually, the agricultural regions, and to identify some other physical and cultural land uses from the spectral signatures they have on the satellite image; and

(2) To show some of the relationships between phenomena such as climate and agriculture.

Fig.6.5 AREA CHOSEN FOR LANDSAT SATELLITE IMAGERY STUDY



Source: Sudan Surveys(1976)

Two steps were followed in this study of which the first was to obtain the information given by the black-and-white positive film transparencies through an ordinary projector or by studying prints from them. The second step was to study the enhanced Landsat images and the densities given by different features on those images. The sets of positive film transparencies used in the present study were composed of bands 4, 5 and 7. Bands 4 and 5 lie in the visible spectrum (0.5-0.6 μm and 0.6-0.7 μm) while band 7 lies in the near infrared spectrum (0.8-1.1 μm).

6.2.2 Preliminary study of Landsat imagery

Landsat imagery, with a resolution as small as an acre (Sheffield, 1981) is known to identify easily general patterns and agricultural areas, and they are unexpected to be quite useful in identifying features such as villages and urban areas (Johnson and Johannsen, 1975; Petrie, 1979). Leatherdale (1978), quoted by Petrie (1979), summarized those features difficult to identify from satellite imagery as "man-made infrastructure".

From the study of the two sets of Landsat imagery of Gezira and Kassala (Plates 2 and 3), the previous statements have generally been found to be true. Agricultural lands, rivers, dams, canalization, rocks and hills and drainage systems were clearly identified. On the other hand many features could not be identified. These were the rural and urban settlements, roads and railways. Sparse vegetation and traditional agriculture also could not be identified at this state of inspection. However, Parry (1978) from his

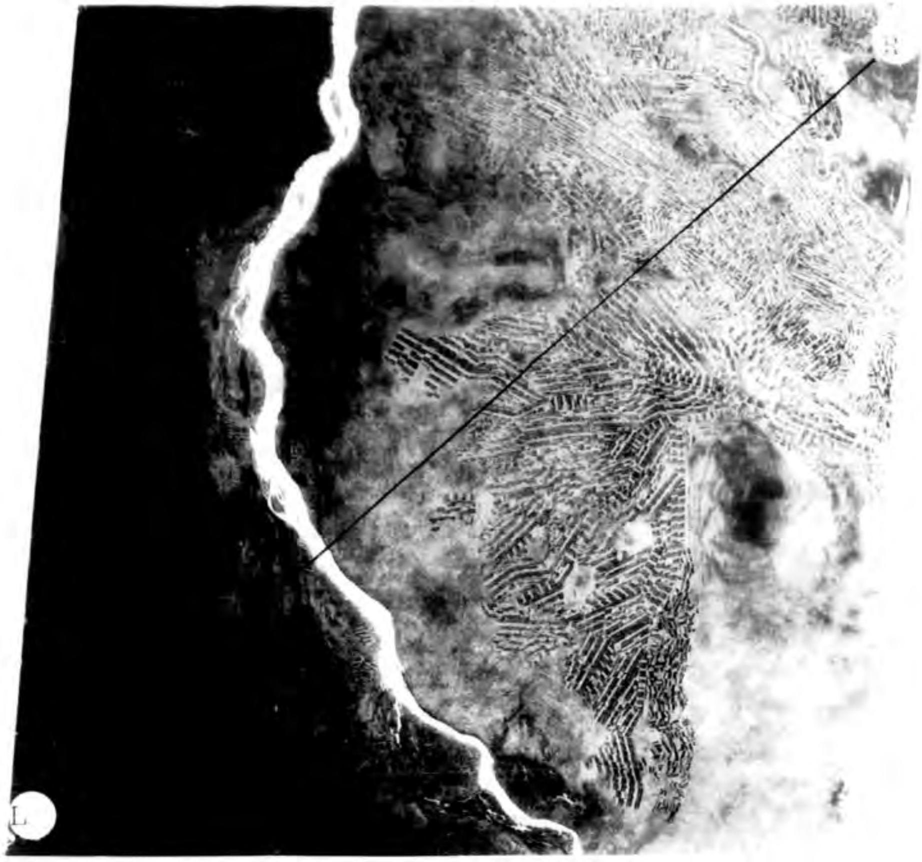


Plate 2 : Landsat band 7 image of the El Gezira and White Nile provinces. The transect line relates to the density trace in Fig.6.8, Left (L) to Right (R).

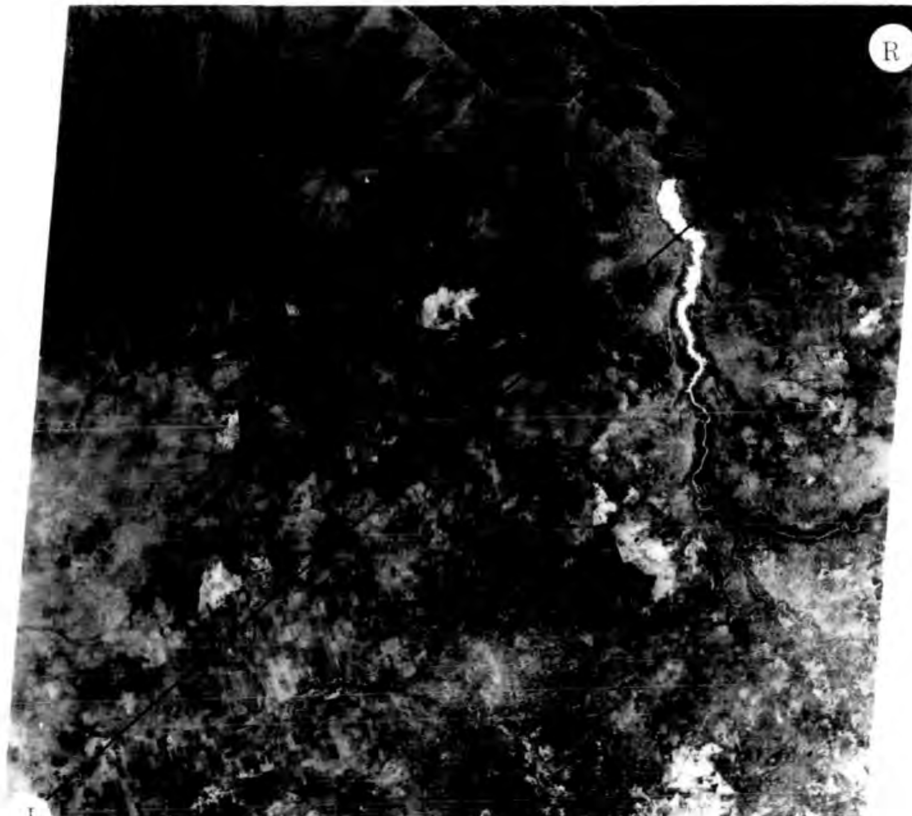


Plate 3 : Landsat band 7 image of the Kassala province. The transect line relates to the density trace in Fig 6.[illegible], Left (L) to Right (R).

study of Landsat imagery of western Sudan, could identify features such as railraods, Similarly,two parts of the railway, one west of the junction of the River Atbara's two branches, and the other in the north east at Khashm el Girba, could be identified in this study (Figs. 6.5 and 6.7). Roads could not easily be identified but a great help in demarcating them on the imagery came from the geometrical order of the well planned agricultural schemes. This can be noticed particularly in satellite image of part of the Gezira scheme (see Plate 2) where a major road crossing the Gezira scheme and Manaqil Extension can be followed between Wad Medani and El Manaqil and westwards to the boundary of the scheme. This identification must be examined against 'ground truth' knowledge. Because such features could not explicitly be distinguished, and away from their associate features (here, schemes) they become totally unidentifiable.

The image for Gezira and Kassala also showed two different patterns of agriculture. The plan of the Gezira scheme with its well planned canalization and its well organized agricultural plots is displayed in great detail on the satellite image (Plate 2). The Gezira area image showed also the intensive cultivation on different parts of the eastern and western banks of the White Nile as well as on its islands. The image of the Kassala province (Plate 3) showed two agricultural practices - the irrigated cultivation in the Khashm el Girba scheme in the northern part, and the mechanized, rainfed type of agriculture which is concentrated in the southern part of the study area.

Table 6.6 Colour on false Colour Landsat imagery

Feature	Colour	Pattern
Irrigated agriculture	Red	Geometrical rectangular areas
Traditional agriculture	Red	Mosaic of small irregular fields
Natural vegetation	Red	
Red soil	Yellow green/ White	Mottled
Sandy soils	Yellow green/ White	Mottled
Black soil	Black	Mottled
Rivers	Black	

Source: (1) Beaumont and Beaven (1977)
(2) Sheffield (1981)

6.2.3 Enhanced Landsat imagery

A step forward in the study of the Landsat imagery can be taken by using enhancement techniques which give a better chance of inspecting their multispectral nature. The predominant technique used is to superimpose one image on another to enhance certain phenomena. The enhancement method adopted in this study is the use of an additive colour viewer which is a projector system that permits several images to be projected simultaneously onto a viewing screen. The system enables the production of colour composites with different degrees of brightness. The advantages of these composites over the black-and-white images is because it is easier for the eye to pick up the differences in colour than in grey tones.

The colour composites of the Gezira, Kassala and Blue Nile areas were produced on a Fairey Surveys (MK2) additive colour viewer by projecting film positives of band 4 images through a blue filter, with band 5 images through a green filter and band 7 images through a red filter. The colours obtained for physical, agricultural and vegetation features on this order of filter colours is shown in Table 6.6. Agriculture and living vegetation are always red. The use of the additive colour viewer is particularly helpful in the study area for it permits us to distinguish between bare soil and vegetation cover. This could be applied particularly to the area west of the Gezira scheme and to different parts of the Kassala and Blue Nile areas (see Plates 2,3,4 and 5). Irrigated agriculture was shown having a strong red appearance. It became possible to pick out the cropped land within the agricultural

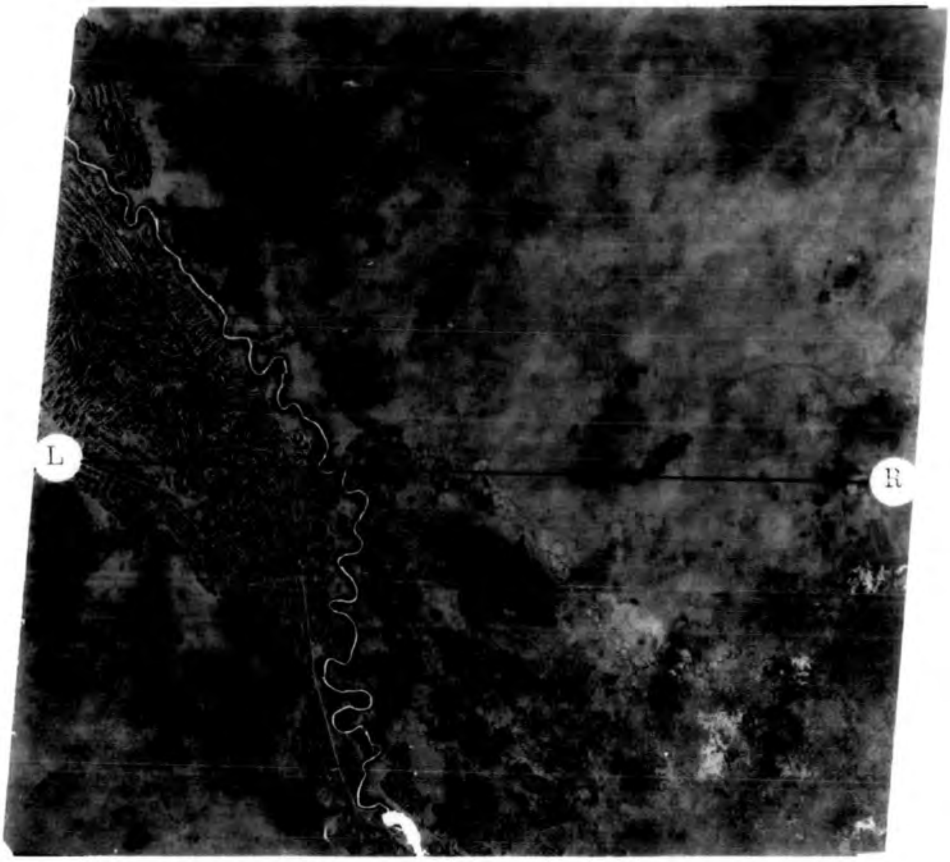


Plate 4 Landsat band 7 image of the western Kassala and southern El Gezira. The transect line relates to the density trace in Fig. 6.9, Left (L) to Right (R)

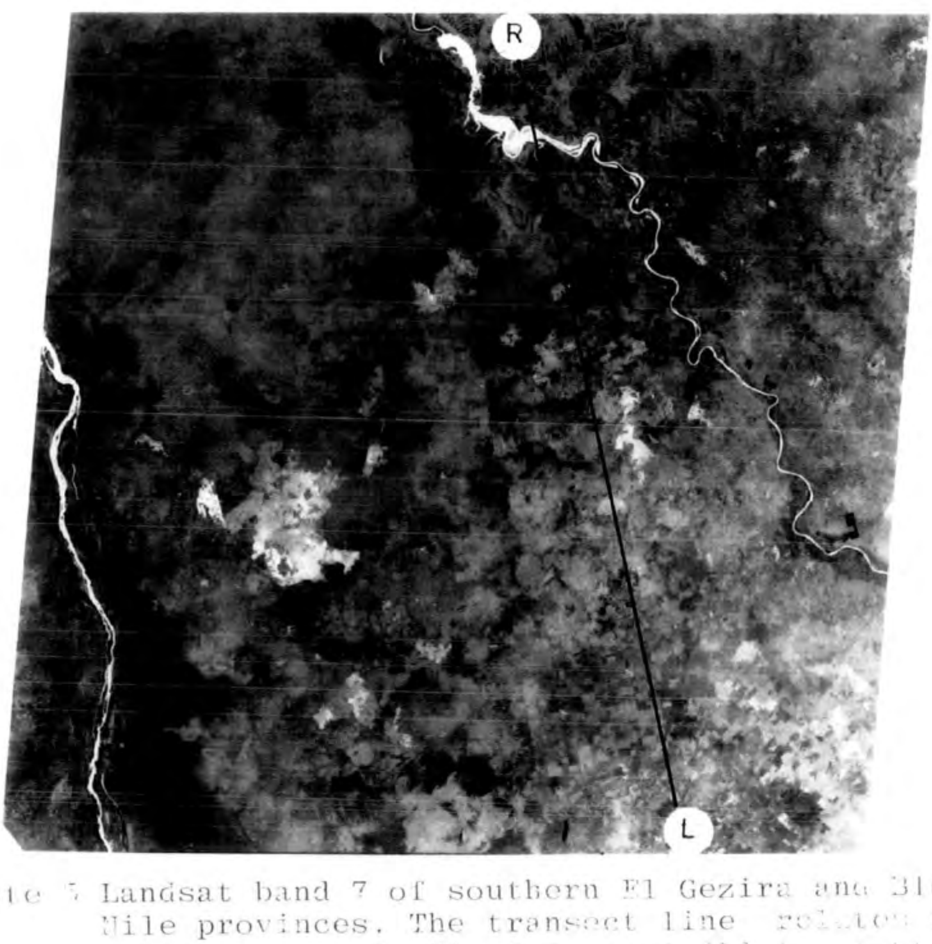


Plate 5 Landsat band 7 of southern El Gezira and Blue Nile provinces. The transect line relates to the density trace in Fig.6.[illegible], Left (L) to Right (R).

schemes. A good example of that is the mechanized scheme in the southern part of the Blue Nile (see Plate 5). Different soils become easier to identify. An example of this is found in the soils of the Gezira area where the black alluvial soil east of the White Nile, with a dark tone, could be distinguished from the light soil with yellow green signature, to the west of the White Nile.

One of the problems needing further investigation through 'ground truth' is the distinction between the natural vegetation and the non-organized agriculture. The geometric order and the planned agriculture practices of both the irrigated and mechanized schemes that helped in their identification are absent in the case of traditional cultivation. Woods and large trees alongside rivers, e.g. the rivers Dinder and Rahad in the Kassala and Gezira areas (Plate 4), could be identified through using the additive colour viewer, but grass and other plants away from the rivers and streams were harder to distinguish from crops.

Clues to the effect of climate on, or its relationship with agriculture, are given by :

1) The concentration of mechanized agricultural schemes in the southern areas of Kassala and the Blue Nile areas, where rainfall is heavier and more reliable.

2) The comparison of successive agricultural season's images to monitor the size of agriculture in mechanized schemes where rainfall is the major factor.

3) The examination of different Landsat images of different parts of the year to inspect the pattern

of the rainy season. The relatively wet south and dry north in the study area are suggested through the relatively richer vegetation and more streams and water courses in the south when compared with the north.

6.2.4 Density investigations

The enhanced satellite imagery was further investigated by tracing spectral signatures of features along a line or at different spots on the satellite film transparencies. This was made in this study by using a spot densitometer. The aim of such investigation is to improve the interpretability of the image (Beaumont and Beaven, 1977). Using this method it is possible to discriminate between parts of areas having similar tones which are harder for the eye to identify.

An X-Rite (301) black-and-white spot densitometer was used to measure spot densities along straight trace lines or at different spots on the film positive transparencies of the three study areas. The densitometer computes density comparisons and subtractions. The film area in question is centred directly over the bright green light spot under the reading head, then the reading head is lowered until it touches the film surface. At this stage a density value will appear in the screen of the instrument which basically uses a black film for density = 0.

Average densities

Landsat film densities in the Gezira, Kassala and Blue Nile provinces were studied in two steps as follows :

1) The average density for each phenomenon;
2) The detailed densities along certain trace lines

The mean density values given for each land use type in each band were graphically displayed labelling their characteristic densities. These densities are either shown in temporal sequence of the same type of land use, as in the case of the Gezira agriculture, or they are compared with other types in the same area (see Figs. 6.6 and 6.7). In this latter way spatial comparison can also be made.

Considering first the temporal change in signature of the Gezira agriculture based on three periods in 1972/73 seaon (20 Oct., 13 Dec., 17 Jan.), it can be seen that signatures in bands 4 and 7 were generally of higher densities than in band 5 (Fig. 6.6). It can also be seen in the bands of the visible spectra, i.e. bands 4 and 5, that there is regular decrease in density with time through the three periods of study. There is also a need for further tests, for this change might be caused by differences in film processing. In band 7, in the first period, agricultural density was remarkably higher than in the next two periods, where the expected sequence of density was not fulfilled.

In relation to the Blue Nile and White Nile waters in the Gezira, the same order of temporal drop in density was preserved but with band 7 taking the place of band 4 , and showing the highest density values. In conclusion here, bands 4 and 5 are of more use for the temporal study of agriculture, and band 7 is best for the study of water.

In the context of studying different types of land use within a region compared with other regions in the study area, and looking at Figure 6.7, it can be observed that the order of decreasing density from agriculture to fallow

Fig. 6.6 MEAN TEMPORAL DENSITIES OF AGRICULTURE AND WATER IN EL GEZIRA LANDSAT IMAGERY

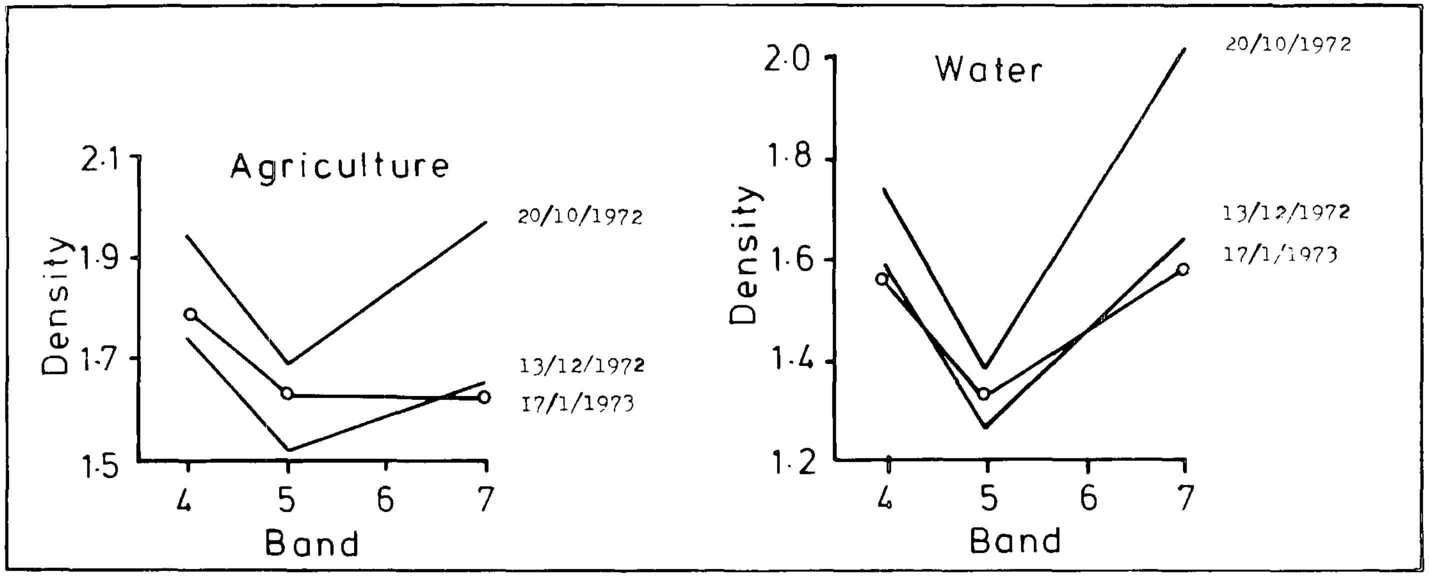
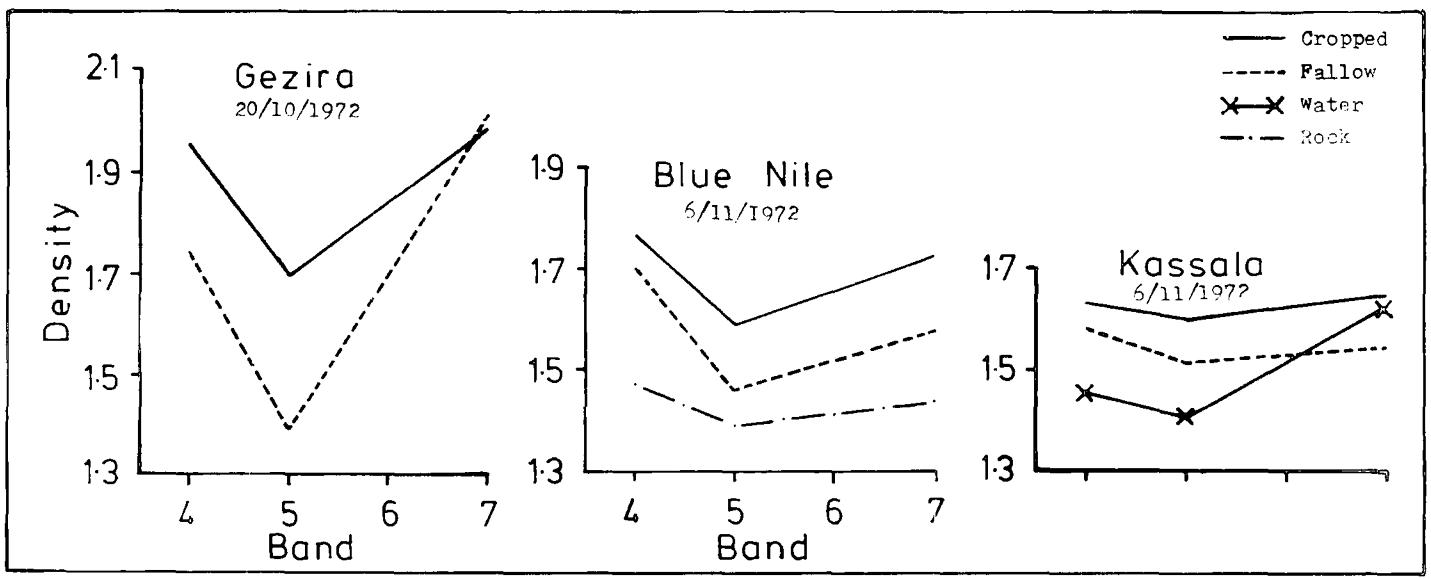


Fig. 6.7 MEAN DENSITIES OF DIFFERENT TYPES OF LAND USE FROM LANDSAT IMAGERY



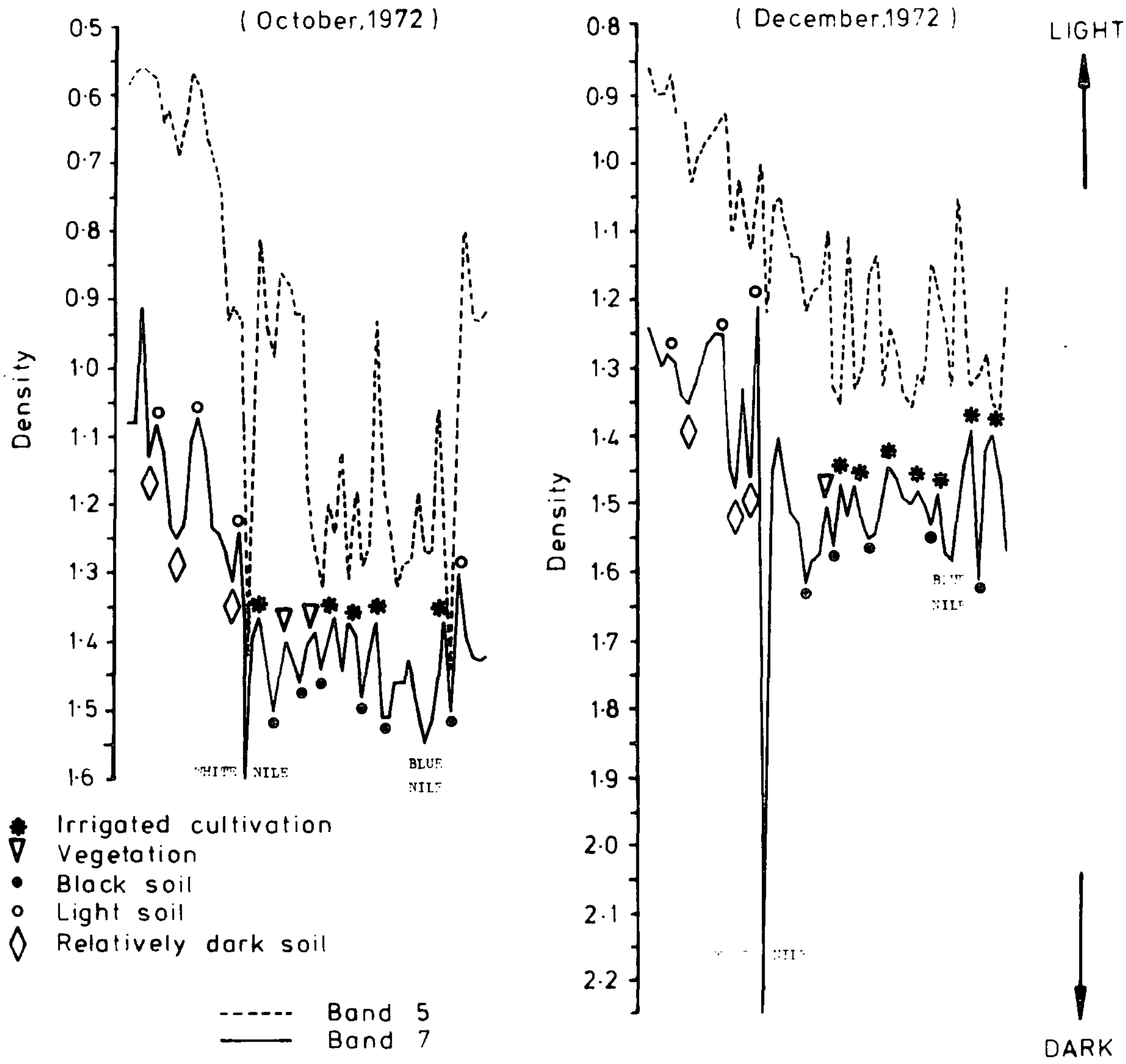
fields was always preserved for all bands in all regions. Hills had the lowest densities as shown in the Blue Nile province. Agriculture in the Gezira, though similar to the other regions, had a higher density. The water signatures were lower in the visible spectra and were clearly distinguishable from agriculture in both the Gezira and Kassala areas, where as in band 7 that distinction was not as clear, because both types had very similar average densities.

Averaging of densities described in the previous discussion has the advantage of giving a crude basis for generalization. Because densities were based on values collected from the different parts of the image, they might be representative of the whole area considered. However, averaging naturally masks the true differences and sometimes causes much loss of information, and, as will be seen later in this section, in some cases caused considerable contradiction with absolute values obtained from the same image but on a trace line. Thus it became necessary to get an idea of the absolute densities obtained for each of the study regions, along a trace line, in detail. Trace lines from A to B on both bands 5 and 7 for each region were followed by the spot densitometer.

Absolute densities along trace lines

In the Gezira trace line densities of band 5 and 7 during October were compared (Fig. 6.8). It can be observed that band 7 showed a very clear contrast between the black soils of the Gezira and the sands to the west of the White Nile. Band 5 preserved that contrast, and also had the

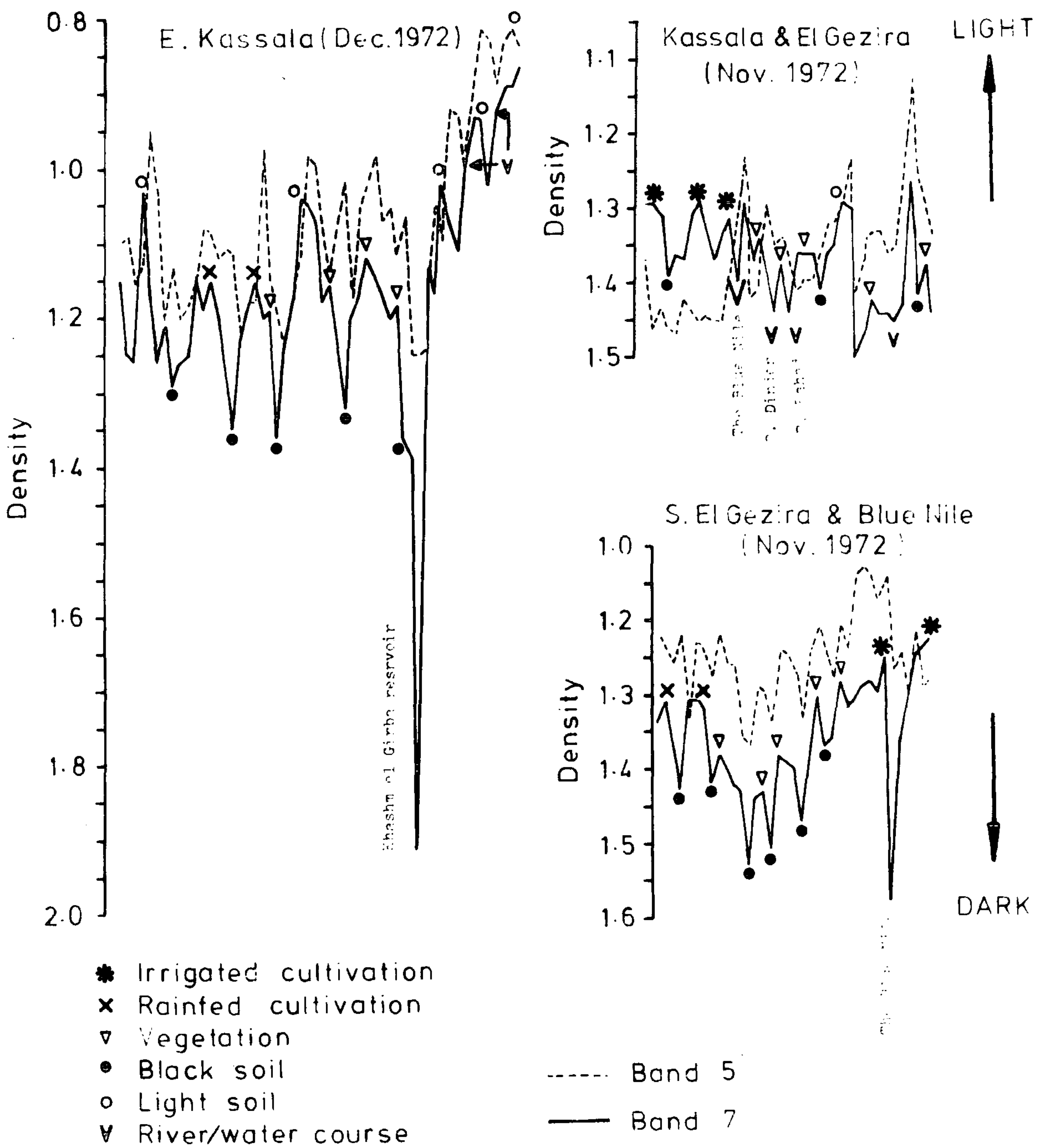
Fig. 6.8 SPOT DENSITOMETER TRACES OF LANDSAT SATELLITE IMAGERY ACROSS THE EL GEZIRA AND WHITE NILE PROVINCES



advantage of showing contrasts between the black soils of the irrigated Gezira scheme (denser) and the black bare soil with sparse vegetation to the west of the scheme (relatively lighter). The contrast between agriculture and bare soil within the Gezira scheme was consistently preserved by band 7, while in band 5 it was obscured for other land use types. The Blue Nile and the White Nile waters were better distinguished by band 7 than by band 5 although the White Nile was always easier to identify by its characteristically high density. In December, the late phase of the growing season in the Gezira scheme (Fig. 5.8), band 7 densities generally remained the same as in October, keeping almost the same pattern, with particular intensification ofthe density of the White Nile water. Band 5 densities, on the other hand, although preserving the general trend of lighter densities when moving westward, showed irregular and different behaviour when representing different features. Band 7 seems to be advantageous in this season over band 5 for its discriminating power towards different cultural and physical features.

In the eastern Kassala province, and from the trace line of Plate 3 densities obtained from bands 5 and 7 (Fig. 6.9) at the end of December, it can be observed that the River Atbara water at the Khashm el Girba reservoir was more distinctively identified by band 7 than by band 5. The relatively light soils to the east of it were shown by both bands as having lower densities, although band 5 seemed to be better at distinguishing them from the valleys dissecting them. At this time of the year living vegetation is mostly confined to woods and water courses. The mechanized

Fig 6.9 SPOT DENSITOMETER TRACES OF LANDSAT SATELLITE IMAGERY OF THE KASSALA, EL GEZIRA AND BLUE NILE PROVINCES



scheme's crops are harvested, and there are vast areas of bare soil. Both bands had similar powers of discriminating different soils and cultivated lands and each is assumed to be of value in the study of the area.

Another trace line was selected across west Kassala and east Gezira in November (Plate 4) for both band 5 and 7, and the densities obtained are shown in Figure 6.9. In this area the contrast between the two bands was not great but this is the only image where band 5 densities became greater than band 7 in the western part of the trace line (south Gezira). The densities of rivers and water courses were less easily distinguishable from other features than in other images. The image differentiated between the intensive irrigated cultivation in the Gezira and the area to the east of it. The Gezira agriculture was shown with a lighter density in band 7, and with a darker density in band 5, than the area to the east of it.

A density trace line from the southern Gezira southwards into the Blue Nile province (Plate 5 and Fig.6.9) showed that the lighter density of irrigated cultivation in band 7 was replaced by a darker density through the partially vegetation-covered black soil. The rainfed cultivation in the southern part of the region also contrasted with the black soil by showing lighter densities. Band 5 showed the general trend of light-dark-light densities from north to south across the area, although the category densities were different from that of band 7.

From the previous discussion it can be concluded that Landsat imagery are useful for distinguishing vegetation from bare soil and other features. They can be used for checking and monitoring agricultural areas covered. This step should be accompanied by ground truth checking for the satellite imagery at the satellite pass, or at least by detailed conventional study of the agriculture and land use of the part of the area covered in the time of, or as near as possible to, the satellite pass. An example of such a need is to discriminate non-organized agriculture from natural vegetation. Because of the absence of such information, comparison between satellite imagery and conventionally observed agricultural phenomena is not done here.

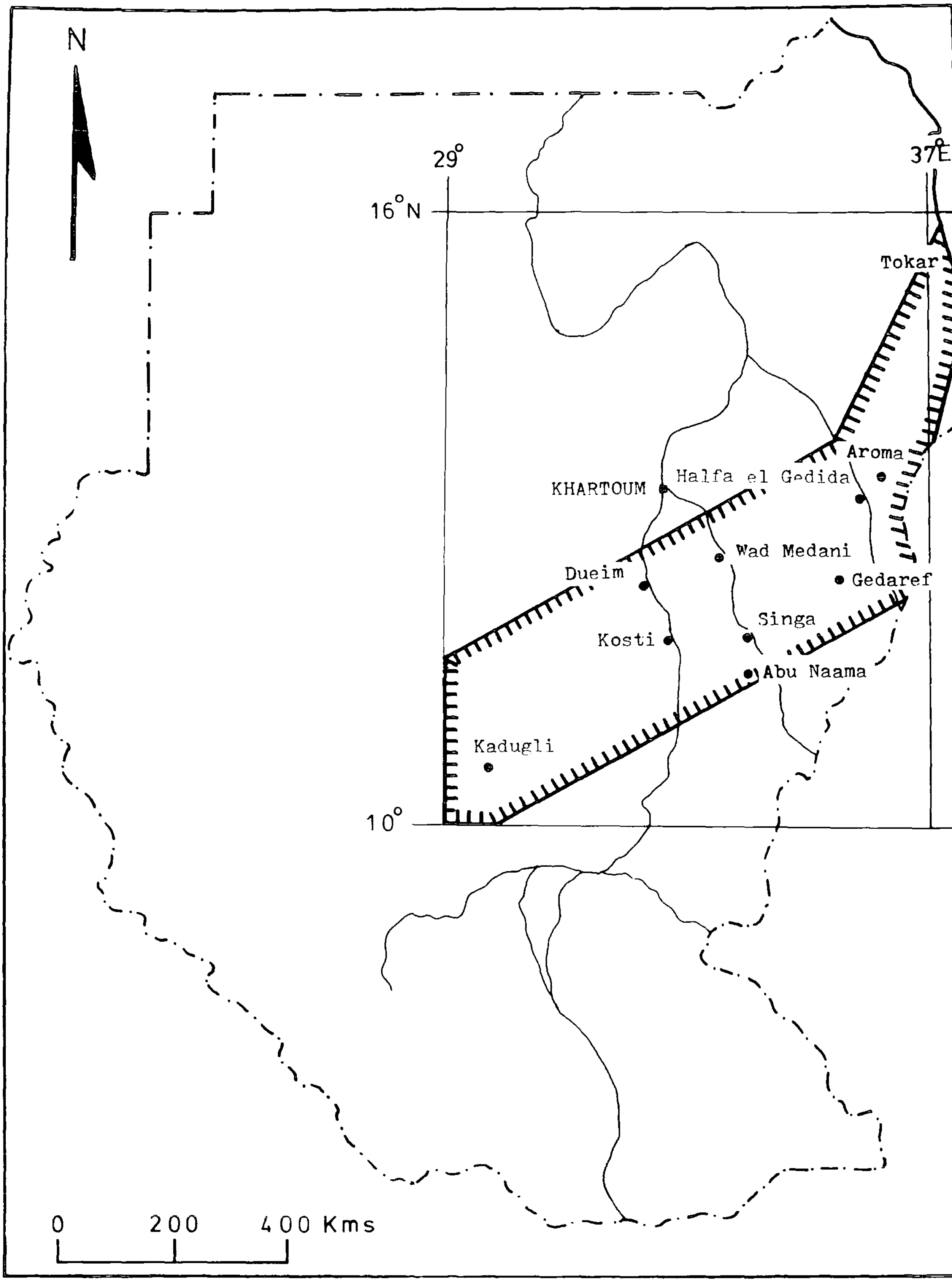
6.3 Climate-agriculture relationship

6.3.1 Area selected for the study

The area selected for this study lies roughly between latitude $10^{o}N - 16^{o}N$ and longitudes $29^{o}E - 37^{o}E$. It is in fact a strip within the Central Rainland belt with a northeast - southwest orientation (see Fig. 6.10). The northern boundary of the study area is a line running from north of Aroma through northern Gezira to El Obeid added to Tokar area near the Red Sea coast. The southern boundary originates south of Gedaref and runs through Er Renk to south of Kadugli. This area includes the Gezira, the White Nile and Blue Nile, the Gash scheme and the Nuba mountain agricultural areas.

The selection of this area was a result of many

Fig. 6.10 AREA SELECTED FOR CLIMATE - AGRICULTURE RELATIONSHIP STUDY



factors, one of which was, as shown earlier in this chapter, that it witnessed the biggest advance in agriculture in the recent history of the country. Extensive and intensive agriculture with considerable diversification and mechanization of cropping took place in this area. This area is also richer in the relatively well established meteorological stations.

6.3.2 Data and period of the study

It is stated by the Ministry of Agriculture (1972 - translated) that

> "The absence of complete and reliable data in the past, led to a blurred vision by the planners and in spite of the appreciable efforts exerted by the authorities in the areas of the Rainfed agriculture..., the lack of technical, human and material capabilities caused those efforts to lag behind the goals".

This situation of unreliable data is confirmed by the same body (Ministry of Agriculture, 1977) mentioning that the state corporations keep good records of cotton in particular, unlike the situation in the private sector where agricultural inspectors, not trained, produce purely subjective estimations of crop yields.

The Sudan Gezira Board (SGB) is the most notable in the Sudan for keeping the most accurate agricultural records, particularly of cotton. However, many other crops in the Gezira do not have the same status as cotton. It is stated by SGB (1972) that there was a difficulty in keeping the true production of groundnuts, and only an estimation of the 1971/72 season was made.

On many occasions, complete absence of agricultural data from the records, pure estimations, or giving the averages for large areas - like provinces - caused fragmentation of the data and deprived us of long systematic sequences of agricultural data. Other kinds of data problems are those such as the replacement of some crops by others, as happed in the Gash delta where cotton has been totally replaced by castor oil cultivation. The degradation of some crops' status, in addition to their being considered to be entirely owned by the tenant, mean that the authorities neglected to keep accurate records of them. An example of this occurred with the sorghum crop in the Gezira scheme. A third kind of problem is the conflicting figures encountered sometimes when consulting different sources, and even the same source of data an authority occasionally revises its earlier figures. Special care was taken in such situations by comparison with the mean and by ranking the sources of data according to their relatively higher degree of reliability. A fourth sort of problem stems from the inclusion of some schemes into other larger ones, where it becomes difficult to distinguish the figures after the unification. A good example of this occurred when the White Nile private schemes were grouped in what came to be known as Agrarian Reform schemes.

On the subject of climatic data, although the meteorological records are more accurate and more consistent than the agricultural data, some problems are still found. Some stations are relatively new, and some stations differ in their offical status. The reliability of data may be affected by their status. Systematic records of sunshine were lacking from most of the stations in the study region, and radiation records were only consistent since 1958 for Wad Medani.

In trying to match the agricultural with the climatic data, the area of overlap shrinks. And after the trimming and the removal of data with large gaps, the period from 1960 on is considered to be the best period for the study. The data for recent years, i.e. the late 1970's in many cases were not yet available to the author. In the case of the Gezira cotton, longer records of yield and climatic elements exist than elsewhere, matching as far back as 1950, and they are treated in a special way as will be seen in Chapter 7.

6.3.3 Climate-crop relationship problems

The variation of crop yield from year to year is a significant problem in agricultural production. Although there may be almost uniform conditions, such as those in the Sudan Gezira where irrigation agriculture practices are scheduled, this variation may be considerable. The yields of crops in equatorial and tropical regions are low in comparison with those in temperate regions. One of the main factors in equatorial and tropical regions is the interaction of climate with crop growth (Russel, 1976), the detailed study of which has been rather neglected.

The effect of climate on agricultural products is generally recognized. Wiesner (1970) classified the effect of weather on the crop as biological, physical and chemical. Germination, flowering, fruit formation and development of a plant are biological and movement of water and water vapour in the soil are physical. The year to year variation in crop yields is largely dependent on changing weather conditions. Sanderson (1954), Hogg (1964), Baier (1974) and Thorne (1979a) stated that in spite of the trials to eliminate or at least reduce that effect, agriculture continued to a large extent to be affected by weather and climate. Laur (1976) notes an unfortunate tendency to consider the climate as a stable factor in agriculture, and he quotes Thompson (1966) who stated that record yields were achieved only under favourable weather conditions.

Basic knowledge furnished about climatic conditions and the extent of their control of crop growth and development is the essence of agrometeorology (Frisby, 1951; Monteith, 1965; Webster and Wilson, 1980; Seguim, 1981). There is, however, a special need for this knowledge to be improved in developing countries. A well established understanding of agrometoerology through examining the physics of the atmosphere and the physiology of crops and farm animals would clarify the poorly understood crop variation. This knowledge can be utilized in farm management, assessment and preservation of the physical environment and increasing agricultural production (Baier, 1974). But the use of this growing knowledge for the assessment of yield from weather has not progressed to the extent that might be expected (Baier, 1977). By and large agrometeorological knowledge is a tool for short term tactics whereas agroclimatological knowledge is used in long term strategy (Bourke, 1968; Waggoner, 1968). The ability to be sure about the profitability of the cultivation of various crops can be achieved through statistical analysis of meteorological data and regional agrometeorological surveys (Wallén, 1968).

While recognizing the need for agroclimatic study, and taking practical steps in that direction, it must be understood that the relationships between yields of farm crops and the weather that controls them are complex. This complexity is partly due to the complexity of the problem of specifying the weather itself (Fisher, 1924) and partly due to the fact that the crop surface itself exerts an important modifying effect on the general climatic conditions (Smith, 1968; Stanhill and Fuchs, 1968). Hendricks and Scholl (1943) stated that

> "... any attempt to express these relationships in terms of mathematical formulas is beset by difficulties. Not only does the final yield of a crop depend upon a large number of such factors (weather factors) but also upon the particular combinations in which they occur."

In the Sudan and elsewhere, detailed data of the micro-environment of crops as well as other factors' effects are not yet available. In spite of the inadequacy of standard meteorological data in explaining weather-crop relationships, those standard data can be used for the purpose of generalization through a statistical approach. In fact frequent attempts have been made in the direction of the statistical approach (Stacy et al., 1957). Sanderson (1954) stated that "correlation techniques can be successfully applied to weather-crop research. Some of the results have been equal or even superior to those obtained by the traditional methods of crop reporting." In this study the techniques of linear correlation and multiple regression previously described in sections 5.3.2 and 5.3.3, as well as second degree regression (Fisher's model), were used to analyse the relationships between climatic variables and crop yields in different areas in the Sudan. In this context Sanderson (1954) does not believe that a linear relationship is the rule; Hendricks and Scholl (1943) mentioned that a linear relationship can be justified when the weather factors do not fluctuate over too wide a range. However, in this study, by preliminary examinations through scattergrams, no non-linear tendency relationships between variables were found.

When considering the simple linear correlation in this study, the final yield of a crop was correlated with a single climatic variable such as monthly rainfall, temperature or relative humidity. Details will be given in the following chapters. Large numbers of such studies were conducted with various degrees of success. The disappointingly low correlations found in some of those studies were as commented on by Hendricks and Scholl (1943) as being : "... because a single variable is rarely the principal factor that determines the final yield of a crop".

However, one of the most important reasons for the correlation study is to show the relationships of most of the climatic variables with crop yield, in isolation. From this study it can be observed that many climatic variables which were highly correlated with crop yield did not appear in the regression formulae. And as will be shown later the regression formulae were considered as a special step, which cuts out many significantly correlated variables.

A more comprehensive analysis, ahead of simple correlation, of weather-crop relationships adopted in this study was made through the multiple regression method. This method is characterized by fitting the following form of equation:

$$y = a + b_1 x_1 + b_2 X_2 + \ldots b_n x_n$$

where y = crop yield

$x_1, x_2 \ldots x_n$ = controlling variables (climatic)

a, b_1, $b_2 \ldots b_n$ = constants

The application of multiple regression in this field has been widely recognized, and Baier (1977) gives examples from the USA, Brazil, Turkey, Iran,Israel, India, the USSR and Australia.

Models based on stepwise linear regressions were developed in this study for the purposes both of explaining and of predicting crop yield. This approach does not easily explain cause-and-effect, but it is a practical approach for the assessment or prediction of yield (Baier, 1977). The reason for the selection of this type of multiple regression is to limit the number of independent variables, in case they should exceed the sample size. In this type of regression the predictor variables are entered on the bases of the partial correlation coefficients. The selection of the variables next in the regression is due to the order of their contribution to the residual variance, though they may be of weak significance in the linear correlation matrix (Dyer and Gillooly, 1977). Mather (1976) refers to the wide use of the linear model because of its ease of computation and comprehension. He mentions the difficulty of interpreting multivariate relationships, especially in the early stages of investigations and suggests that it is wiser to build up a theory, then later non linear relationships may be postulated and alternative regression models may be employed. The linear regression coefficients for weather variables are useful in estimating the effects of small deviations from averages, but are not suitable over a wider range of conditions (Thompson, 1963).

Those using regression techniques generally approach the work with several assumptions, one of which is the normal distribution of the data. The monthly averages and totals seem to satisfy this assumption, but shorter period data may not necessarily do so. Also the controlling variables used in the regression are assumed to be independent while in fact this rarely occurs (Sakamoto, 1981).

Added to the problems of the linear regression, it is noted that, in spite of the fact that a greater number of climatic variables included in the explanation of crop yield will give more information (Hanus, 1980), their number should be limited. The inclusion of many variables may cause the problem of multicollinearity. This situation occurs when one explanatory variable is a linear function of one or more of the other explanatory variables in a multiple regression. The problem of multicollinearity, as mentioned in section 5.3.3, is that it reduces the degree of reliability of the equations. It is stated by Sakamoto (1981) that "The real problem in multiple regression analysis is to find variables that reduce inter-correlation among them. This problem could lead to unstable coefficients as well as to incorrect signs."

Bearing in mind the properties and the limitations of the regression technique, it has been used in this study as a tool for general, basic knowledge about climate-crop yield relationships. It can be seen from comparing correlation matrices with regression equations that many of the climatic variables which showed strong correlations with crop yield declined from appearing in these equations. Regression equations were used to estimate different crop yields which were correlated with the observed yields.

Extrapolations for two years outside the original period from which the equations were derived were made in many instances. There is a great need by national and private interest for forecasting for administration, farm management or trade purposes. The expected results from the predictive functions of the regression equations are always less successful than its explanatory functions.

Second degree multiple regression models were also used in this study as another aspect of the statistical approach to the weather/climate-crop relationship. The characteristics of the crop response to each biometeorological variable are not known. It is believed that the response changes gradually over the season and shorter period of each variable can be fitted by a second degree polynomial as a function of biometeorological time (Baier, 1973). The idea was first developed by Fisher (1924), who suggested that the growing season should be split into shorter intervals and a measurement of the effect of precipitation during each interval on the final yield should be performed. The advantage of such a split is that it makes a time identi-ification possible while not increasing the number of the independent variables in the multiple regression equation (Runge and Odel, 1958). Fisher suggested that a smooth curve could be produced because any change in the net effect of an inch of precipitation through short intervals would not be abrupt or erratic but an orderly one that followed some mathematical law. It is stated by Hendricks and Scholl (1943) that "... However, an analysis based on weekly weather data enables one to determine the seasonal variation in the effects of weather factors more accurately."

The Fisher (1924) polynomial technique, as adapted by Hendricks and Scholl (1943), and as adopted by Runge (1968) and Huda et al. (1975) was used here in solving the equations to estimate crop changes due to increase (or decrease) in rainfall. The second degree multiple regression equation is

$$y = a + b_1 \sum_{i=1}^{n} (t_i^0 x) + b_2 \sum_{i=1}^{n} (t_i^1 x) + b_3 \sum_{i=1}^{n} (t_i^2 x) + cT$$

where y = deviation of crop yield

a, b_1, b_2, b_3 and c = constants

x = any climatic variable within any given 5-day period

t_i = the number of 5-day periods (from July 1st to Oct. 3rd)

n = number of 5-day periods in a given season of the year (19)

T = year number (beginning with one in the first year 1960 - and ending with eighteen in 1977) which was included to correct for the long term upward or downward trend in yield.

The statistical methods used in searching for climate-crop relationships are believed to be useful. The lack of long-term intensive and extensive agrometeorological experiments made it necessary to use published data collected from meteorological stations, and agricultural data (crop yields) collected from the nearest fields to them. As the laboratory experiments on plants are suspected not to be representative of the true field conditions, the statistical approaches, as described, can be continued until more accurate data are obtained for better modelling. In support of this it is stated by Dyer and Gillooly (1977) that "although controlled experiments are necessary for a greater understanding of crop and weather relationships, there is a need to investigate techniques that will provide useful information in the field. These techniques must be capable of using readily available and commonly recorded data". This does not mean the exclusion of controlled experiments where they are to be found, but better analysis can be obtained by comparing results coming from them with meteorological and crop yield results. Statistical science helps us to judge whether the differences between experimental units are because of unaccounted for variability or real treatment effect (Little and Hills, 1972). The present models help in closing the data gap as well as sketching the general climate-crop relationship, by way of opening avenues for further studies.

Based on the previous discussion, a detailed climate-crop relationships study for selected areas (Fig. 6.10) will be presented in the following three chapters. The main crops selected for the study are cotton, sorghum, sesame and groundnuts.

CHAPTER SEVEN

THE RELATIONSHIP BETWEEN CLIMATE AND COTTON YIELD IN THE SUDAN

7.1 General

Cotton in the Sudan occupies the highest status in the commercial sector of the government budget. This status is reflected by strong emphases on cotton growing. However, these emphases differ from place to place as they differ between the state and the private sector. One of the problems always concerning the agricultural planner is the variation in cotton yield and the way in which stable or increased productivity can be achieved. The year-to-year variation in crop yield, according to McQuigg (1975, noted in Baier, 1977), can generally be related to three factors:

1. Technological change;
2. Meteorological variability; and
3. Random noise

The objective of the study in this chapter is to inspect the relationships between climate and cotton yield in the Sudan, and to examine how accurately climatic elements alone can explain variations in cotton yield. The data series for the study areas were not long enough to study the time trend reflecting technological change. In the case of the Wad Medani-Dueim area where the data series were relatively longer, the effect of technological change on climate-cotton relationship was considered through splitting the period into two shorter periods. The relationship between several climatic variables and cotton yields at different centres and areas of production are studied. The three statistical methods, correlations, multiple regressions and second degree regressions (Fisher's model), described in sections 5.2.2, 5.2.3 and 6.3.3, were adopted in this study in the search for relationships between climate and cotton yield. The properties and the limitations of each of these methods are discussed in those sections. The data of cotton yield used in this study are shown in Table A.9.

Four spatial and temporal scales are considered in this study, as follows:

1. The whole area (areal integration);
2. Smaller tracts of regions;
3. Temporal study of a part of the study area;
4. Local areas (centres of production)

The integration of the whole area is believed to have the advantage of enabling generalizations to be made, besides providing a large set of data which is expected to reflect more stable results than the smaller data sets. This integration may contribute to a better view of both spatial and time dimensions which may help in further investigation of climate-cotton relationships. However, as will be seen later, this integration has the disadvantage of bringing together areas of different weather and climatic conditions as well as a diversity of cotton growing methods. These conditions are expected to bring poor results as the cotton crop in each region may have different reactions towards climatic variables from those of other areas. It is for this reason that different scales of spatial dimensions from large regions and long tracts of land, down to production localities, were considered. As has been mentioned earlier in this section, the changes in methods of agriculture and technology, such as mechanization, soil fertilization, and pest and weed control, may affect the crop yield and the performance of climatic elements. To inspect the effect of such changes on climate-crop yield relationships, the Wad Medani-Dueim area was studied. The period 1951-1970 was split into the two decades it includes. This period is the best covered by the available data and the later decade (1961-1970) saw advances in mechanization, intensification of agricultural and technological development.

The climatic elements studied in chapter 3, such as temperature, relative humidity, sunshine and evaporation, as measured for annual and monthly averages or totals, were considered in this study. Added to these elements, pentad rainfall totals during the growing season (described in section 7.2.1) were calculated Wang (1972) and Baier (1973) mentioned the importance of including such short interval data in agroclimatic studies. The cotton growing season in the Sudan generally extends from July of one year to April of the next year except at Kadugli and Gedaref where it starts and ends earlier (see Table 7.1).

The first step of the statistical method adopted here is to study bivariate correlations (in the following section); this is followed by studies of multiple correlation and regression analysis and cotton yield estimations.

7.2 Correlations between climatic variables and cotton yield

7.2.1 The whole study area

The area selected for this study is large. It covers an area of approximately 7^{o} of latitude by more than 6^{o} of longitude (see Fig.6.10). It includes a variety of climatic conditions, as was shown in chapter 3. It is believed that these differences in climatic conditions are reflected in crops and hence in the crop yield differences in different places in the area. This area also displays differences in types of cultivated cotton, agricultural practices, methods of irrigation and levels of governmental and private sector emphases. The water supply provides a good example of this diversity in cotton growing in different parts of the area. The supply of water varies from secured irrigation to changeable flooding and rain watering systems (Table 7.1). These methods are amongst the factors influencing the choice of different varieties of cotton in different areas. The differences between schemes in the rate of technological change through time are another dimension adding to the heterogenity within this large area.

The data were collected over the study area from 8 meteorological and agricultural centres (see Fig.6.10) for the period 1950-1977. It can be observed that the data had both temporal and spatial characteristics. From the annual and monthly climatic variables, 19 pentad's rainfall variables were also calculated in the study. The numbering of these pentads differed from the conventional system, starting with pentad 1 (1-5 July) and ending with pentad 19

Table 7.1 Cotton crop calendar

Centre	Area	Watering method	Sowing period	Picking period
Wad Medani Dueim Kosti	Gezira	Irrigation	Early August	January to April
Aroma	Kassala	Flood	late August to late September	Mid January to April
Tokar	Red Sea	Flood	late September to mid October	January to May
Kadugli	Kordofan	Rain	Mid June to mid August	Mid October to February

Source : (1) Rep.Sudan (1966) Progress report for the season 1965/66, Khartoum.

(2) Mackinnon (1948b) Kassala Province, in Agriculture in the Sudan, Tothill (ed.), Oxford University Press, London.

(29 September - 3 October). At best only 137 cases from the annual, monthly and pentad data were obtained as most of the records only partially covered the whole period. This number was in many cases reduced further to less than 100 cases because either one or both figures for the climatic and crop yield variables were missing in the pair. This was particularly true in the case of sunshine where there was no long and consistent record.

The results of the correlations between cotton yield and climatic variables obtained from the data series considered in this study will be discussed below. The climatic variables discussed in this study are : rainfall, temperature, sunshine, relative humidity and evaporation.

Rainfall

From Table 7.2 and 7.7 it can be observed that no obvious correlations occurred between any of the rainy month's total rainfall and cotton yield, and the correlation coefficient approached zero during June and October (early and late rainy months). This result supports what was assumed by Dayal (1965), that it would be unrealistic to determine the rainfall-crop relationship in a single analysis for the country as a whole "... unless the entire country constitutes a homogeneous region from the point of view of precipitation."

Temperature

From the agronomic point of view temperature is of vital importance for plant growth, development and yield (Bierhuizen, 1973), particularly in tropical Africa

Table 7.2 Correlations between climatic variables and cotton yield (Kantar/fd) for the whole study area

	Rainfall mm	Average temperature °C	Temperature >35°C (No. days)	Max. temperature °C	Min. temperature °C	Sunshine %	Relative humidity %	Evaporation mm	Windspeed 4-7 (Beaufort)
July	0.16	-0.26**	-0.13	-0.24*	-0.30**	-0.44**	0.18	-0.20	-
August	0.16	-0.31**	-0.24*	-0.29**	-0.32**	-0.44**	0.28**	-0.32**	-
September	0.11	-0.32**	-0.15	-0.29**	-0.34**	-0.44**	0.23*	-0.31**	-
October	0.00	-0.10	0.02	0.10	-0.25*	-0.44**	-0.22*	0.13	-
November	-	-0.37**	0.09	0.09	-0.44**	-0.44**	-0.40**	0.36**	-
December	-	-0.33**	-0.07	0.01	-0.47**	-0.44**	-0.42**	0.32**	-
January	-	-0.37**	-0.15	0.06	-0.46**	-0.39**	-0.45**	0.34**	0.07
February	-	0.01	0.15	0.22**	-0.29**	-0.39**	-0.46**	0.42**	0.05
March	-	0.17	0.28**	0.33**	-0.15	-0.39**	-0.46**	0.44**	0.00
Year	0.12	-0.09	-	-0.07	-0.20*	-0.46**	-0.42**	-	-

N = 137
* significant at α = 0.05
** significant at α = 0.01

(Russel, 1976). Plants, when exposed to adverse temperature conditions when flowering and fruit setting, may give a greatly reduced yield (McMichael and Powell, 1971). An example of this is stated by Chang (1968) : "The photosynthesis rates (of plant) increase with temperature reaching a maximum at 30^{0} - 37^{0}C and then drop sharply at high temperatures. For most plants in temperate and tropical regions optimum temperatures are > 25^{0}C .

The average monthly temperatures gave negative correlations with cotton yields almost throughout the pre-harvest period of the growing season. The highest correlations were for November and January, with a coefficient -0.37 each. The annual and February average temperatures were hardly above the zero level. The maximum temperature - cotton yield correlations were significantly negative in the early period, insignificant in the middle period, and significantly positive in the harvest period of the growing season. The insignificant relationships during October-January, inclusive, may be related to the fact that temperature normally drops as winter progresses. The minimum temperature - cotton yield correlations were notably negative throughout the growing season. They were stronger during October-January inclusive, as opposed to those of maximum temperature-yield correlations for the same period. The highest coefficients here were those of November, December and January with values of -0.44, -0.47 and -0.46, respectively (all significant at α = 0.01).

The reduction of temperature and humidity, especially during November-January inclusive, is known to be preferable for yield as this reduction helps to reduce insect development.

This is supported by Jackson (1969a quoting Cowland (1947) and Corbett and Bedford (1948) from their experiments in the Sudan Gezira, saying that "...the incubation period of the egg and larval stage of thrips were shortened by a rise, in temperature, and that Jassids were much less prolific and had longer immature stages during cold dry weather...". It is also maintained by many workers with different experience that boll production and maturity are inversely related to mean daily temperature (Eaton, 1955), inversely related to both day and night temperatures (Gipson and Joham, 1968) or inversely related to night temperatures (Powell, 1969). The optimum temperature for boll production, as maintained by Hesketh and Low (1968), was lower than that for vegetative growth.

Towards the end of the growing season the picture changes. As the minimum temperature - cotton yield correlation became progressively lower, the maximum temperature-yield correlation acquired progressively higher positive correlations. The correlation coefficients for February and March were -0.29 and -0.15 for minimum temperatures, and 0.22 and 0.33 for maximum temperatures respectively.

Sunshine

Sunshine records were unavailable at many stations in the study area. The data were inconsistent in many parts of the study period. From the available data, in general, relatively strong negative correlations between sunshine and cotton yield were shown throughout the growing season. July and December have correlation coefficients with values of -0.44 each, and January and March, -0.39 each. The highest correlations were obtained with the average annual sunshine (r =-0.46, significant at α = 0.01). These results match generally the negative relationship of cotton yield with temperature.

Relative humidity and evaporation

The relative humidity and evaporation figures were negatively correlated with each other throughout the growing season of cotton, and they behaved differently in relation to cotton yield. While the relative humidity showed a positive correlation with cotton for the first three months of the growing season (July-August-September) and then negative values for the rest of the season; evaporation on the other hand gave negative correlations for the first three months and positive values for the rest of the season.

High humidity is believed to be preferred by plants, for either direct absorption of moisture or photosynthesis, since this increased with the increase of relative humidity (Chang, 1968; Nieuwolt, 1977). This was found to agree only with the first period of the growing season where the highest coefficient is found in August with a value of 0.28. Evaporation showed stronger negative correlations for this latter period particularly August (r =-0.32, significant at α = 0.01).

Cotton, as is the case with many tropical crops, needs a dry period to ripen (Nieuwolt, 1977), and a linear relationship between transpiration and dry matter production exists (Chang, 1968). From this positive correlation of evaporation at the later stages of plant development with cotton yield were expected. In all the months from November to the end of the season positive correlations with values ranging between 0.32 in December and 0.44 in March were found. This, as mentioned earlier, implies the existence of negative correlations between relative humidity and cotton yield for the same period, with a value of -0.4 in November, becoming progressively higher towards the end of the season reaching -0.46 in March.

Wind speed

Wind speed variables are taken as the number of occasions of surface wind incidence with force 4-7 on the Beaufort scale at three fixed hours : 8 a.m, 2 p.m. and 6 p.m. Z. The records of wind of this specification for January, February and March were considered in this study to examine whether any relationship existed with cotton yield and to test the assumption that wind in this particular period (harvest) had direct adverse physical effects on cotton. Because of regional differences in the timing of the harvest (Table 7.1) and the local differences in wind forces no correlations are shown to be of any significance. The wind factor, as will be seen later, was better illustrated on a local basis rather than in this integrated area study.

It can be concluded from the integrated area study that the results obtained are poor in terms of the values of correlation coefficients where none reached a value of 0.50. As will be seen in section 7.4.1, this situation made it unlikely that it would be possible to erect a successful model for estimating cotton yield for the whole area. Nonetheless, this study provided general statements about the general trends of climate-cotton yield relationship. Those trends are the negative correlations of yield with temperature, sunshine, early season evaporation and late season relative humidity as compared with the positive values with rainfall, early season relative humidity and late season evaporation. However, the unexpectedly poor results with variables such as rainfall and temperature do not imply that these variables have no effect on the crop. It may suggest that variations within the optimum limits of rainfall or temperature are of insignificant influence. The poor results also necessitate further study of the climate-cotton yield relationships based on dividing this large area into smaller regions or centres for closer inspection in the way described in the following sections.

7.2.2 Regional studies

The study of climate-cotton relationships in this section is made for two groups of regions. The first one is the irrigated Gezira - the White Nile area represented by Wad Medani, Dueim and Kosti, while the second is the rainfed cotton area represented by Gedaref and Kadugli. This grouping separates the irrigated and drier areas from the rainfed and wetter areas.

Irrigated agriculture : Wad Medani - Dueim - Kosti

The inclusion of these three centres in one area was made on the assumption that similar agricultural practices without great climatic contract are existing between them. Dueim and Kosti on the west bank of the White Nile are taken here to represent the western and the southwestern parts of the Gezira scheme which lie not far from them. The period 1960-1970 was chosen for this triangular area of the Gezira (Fig. 7.3) in which to examine the relationship between climatic variables and cotton yield (Table 7.3). This short period serves the purpose of reducing the effect of the change in technology through time. In addition to that this period is the best covered by consistent data for the area of the study. The paired sets of data for each station and each year were amalgamated and they were all analysed together. From the 33 cases expected (11 cases for each station), 31 cases were actually obtained. The advantage of this method is that a larger set of data was obtained than by using the individual centres.

Although one must admit that differences in climatic and other factors will result in different relationships, the benefits of generalization, similar to those from the integrated whole area (section 7.2.1), could be gained from such grouping.

Rainfall

It can be seen from Table 7.3 that rainfall variables, in general, had weak correlations with cotton yields, and in some cases they approach the value of zero. It was only for the annual total rainfall that correlation rose to 0.34 and even here it failed to be significant at $\alpha = 0.05$. This result is not surprising as this area is an irrigated area and does not rely on rainfall directly. It was only in the pre-sowing (July) and the flowering period (October)

Table 7.3 Correlations between climatic variables and cotton yield (Kantar/fd) for Wad Medani - Dueim - Kosti area

	Rainfall mm	Average temperature °C	Temperature >35°C (No.days)	Max. temperature °C	Min. temperature °C	Relative humidity %	Evaporation mm	Windspeed 4-7 (Beaufort)
July	0.23	0.23	-0.33	-0.29	-0.07	0.37	-0.30	-
August	0.04	-0.21	-0.19	-0.15	-0.15	0.24	-0.19	-
September	0.09	-0.15	-0.19	-0.20	-0.16	0.06	-0.27	-
October	0.23	0.01	0.03	0.02	-0.18	0.07	-0.31	-
November	-	-0.03	0.04	0.24	-0.13	-0.20	-0.24	-
December	-	-0.41*	-0.07	-0.18	-0.56**	-0.20	-0.26	-
January	-	-0.30	0.09	0.01	-0.57**	-0.39*	-0.25	-0.04
February	-	0.56**	0.69**	0.72**	0.02	-0.22	-0.02	-0.39*
March		0.32	0.51**	0.60**	0.26	-0.22	-0.10	-0.40*
Year	0.34	-0.34	-	-0.12	-0.35	0.00	-	-

N = 31
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

that the correlations rose considerably above zero level, although neither reaches any significance, with r = 0.23 each.

Temperature

Generally weak relationships between temperature and cotton yield were obtained for the period from July to November. In December and Jan. strong negative correlations were noticed for minimum temperatures with r = 0.56 and -0.57 respectively, which are both significant at α = 0.01. The reason is the same as that mentioned in section 7.2.1; that cooler conditions will be preferable for both production as well as for insect control. In February and March the picture was totally reversed as strong positive correlations for maximum temperatures occurred with r = 0.72 and 0.60 respectively (significant at α = 0.01). As mentioned in the previous section the crop presumably needs hot conditions towards the end of the season to help ripening and harvesting (Lomas et al., 1977).

Relative humidity and evaporation

The climatic variables of monthly average relative humidity and evaporation both acted as less important factors compared with that of temperature. They also showed weaker relationships with yield than in the whole integrated area of section 7.2.1. Relative humidity was generally positively correlated with cotton yield in the early months and negatively in the majority of the growing season. The highest values of correlation were for July and January, with 0.37 and -0.39 respectively (both significant at α = 0.05). Evaporation was always negatively correlated with yield except for February and March where no significant relationships were noticed. The highest values were in July ($r = -0.30$) and October ($r = -0.31$) which both failed to reach the $\alpha = 0.05$ significance level.

Wind speed

In the same way as in section 7.21 wind speeds of January, February and March were considered. It can be seen from Table 7.3 that negative correlations, particularly in February and March, were obtained with $r = -0.39$ and $r = -0.40$ respectively. Investigating this result in the light of the stage of plant development at this period (picking stage) it can be said that wind speed had an adverse effect on yield. This was particularly true in the middle and the late part of the cotton picking phase. Mechanical destruction of the plant, particularly its leaves and bolls, or blowing off of cotton takes place (Webster and Wilson, 1980; Griffiths, 1966). When cotton is blown off, the situation will be even worse if the occurrence of strong winds coincides with field watering. Here the falling cotton will be ruined for it will be mixed with water and mud. The situation will be even more severe towards the end of the picking period because drier cotton hanging from the dried bolls will easily be blown off.

Rainfed area : Gedaref - Kadugli

The Gedaref and Kadugli areas are quite distant from each other. The line joining these centres runs from north east to south west, south of the Gezira area (Fig. 6.10). The reason for including both these centres in one group is that both centres receive relatively high rainfall (649 mm p.a.) and the cotton grown in both centres is totally dependent on rainfall. In addition to that, the cotton grown in both areas is of the American type and the cotton growing methods are generally similar. These factors justified this grouping as distinct from the Gezira area (Wad Medani - Dueim - Kosti) where methods of cultivation, as well as climatic conditions, are different. From the period 1960-1975, 31 cases were found which were consistent from the point of view of both the dependent and controlling variables for climate-cotton yield relationships, and the correlation coefficient results are shown in Tables 7.4 and 7.7

Rainfall

From Tables 7.4 and 7.7 the pre-July total rainfall showed a positive correlation with crop yield ($r = 0.36$, significant at $\alpha = 0.05$). This period of rainfall seemed to be needed for an early sowing so that the cotton may have ample water for a longer period of development. In July the negative correlation suggests a period free of added rainfall to permit germination and emergence of the plant as well as to escape water-logging. Ample water is needed in the vegetative and flowering stages in September and October. The total rainfall of each of these months showed a significant correlation with yield individually. The correlation between the yield and the total rainfall of the two months together was stronger ($r = 0.55$, significant at $\alpha = 0.01$). The total annual rainfall also showed a

Table 7.4 Correlations between climatic variables and cotton yield (Kantar/fd) for Gedaref - Kadugli

	Rainfall mm	Average temperature	Temperature > 35°C (No.days)	Max. Temperature °C	Min. Temperature °C	Relative humidity %	Evaporation mm
July	-0.32	0.08	-0.01	0.04	0.32	0.16	-0.57**
August	0.05	0.14	-0.03	0.06	0.41*	0.11	-0.52**
September	0.46**	-0.24	-0.38*	-0.27	-0.11	0.38*	-0.59**
October	0.48**	-0.40*	-0.68**	-0.23	-0.53**	0.61**	-0.76**
November	-	-0.70**	-0.49**	-0.45*	-0.74**	0.08	-0.40*
December	-	-0.16	-0.06	0.01	-0.30	-0.28	0.28
January	-	-0.13	0.13	0.05	-0.25	0.31	0.28
Year	0.43*	-0.35*	-	-0.25	-0.38*	0.17	-

N = 31
* significant at α = 0.05
* significant at α = 0.01

positive correlation with cotton yield (r = 0.43, significant at $\alpha = 0.05$).

Temperature

In most cases temperatures (annual and monthly averages) were negatively correlated with crop yields and correlation became very strong in the period of flowering and bolling (October and November). The values of r for November minimum and average temperatures, and October number of days with temperature $>35^{o}C$, were -0.74, -0.70 and -0.68 (all significant at $\alpha = 0.01$). This result matches the previously noted observation (section 7.2.1), that the bolling period prefers a drop in the minimum temperature. At the beginning of the season and towards its end no significant correlation was observed except for the minimum temperatures of July and August. Here positive correlations were noticed which rise to a value 0.41 (significant at $\alpha = 0.05$). This result remains unexplained as it contradicted the general trends of negative relationships in this period. During the pre-season (April to June), negative relationships were shown, the strongest in May (r = -0.53, significant at $\alpha = 0.01$).

Relative humidity and evaporation

The rise in relative humidity seemed to be beneficial to cotton in these areas as in the flowering and bolling period (September and October), and in the late harvest (January) period, with r = 0.38, 0.61 and 0.31 for September, October and January respectively. Because this area is totally dependent on rainfall, very strong negative correlations between evaporation and cotton yield were shown throughout most of the growing season, the reverse of the relative humidity-cotton yield relationships. The strongest correlations were at the late vegetative, flowering and bolling stages, September and October with r = -0.59 and r = -0.76 respectively. At the ripening stage (December and January) a weak positive correlation occurred (r = 0.28).

In general terms this rainfed area showed responses of cotton yield to climatic elements which were different from those of the whole integrated area, although in many instances they both displayed compatible results. From the correlation matrix for this area, October and November seemed to be of extreme importance to cotton where high correlations with climatic elements occurred. It seems on the other hand that the crop is almost indifferent to these elements towards the harvest period.

7.2.3 Temporal base of analysis

Many agricultural practices that affect cotton yield and cotton's response to climate have changed through time. Amongst these practices are the changes in varieties, insect pests, plant disease, exhaustion of soil fertility, changes in the type of lands under crop, changes in the amount of fertilizer and changes in crop rotation. Also changes in the efficiency of picking, transportation and ginning of cotton occurred, as well as other cultural changes, or what might be related to what is described by Thomson (1962) as a time trend for technology. Show (1964) maintains that the assumption of the independence of the technology variable from meteorological variables is a serious problem. He gives an example from Lowa where the deficiency of rainfall of two inches in 1930 may have cut the corn yields by 25% while the same deficiency in 1960 may have cut yields by only 10%.

As has been mentioned in section 7.2, the period of study is not large enough to follow a time trend analysis. However, as Wad Medani and Dueim, in the Gezira-White Nile area had a relatively long period of records (1951-1970), a study was made by splitting that period into two periods (1951-1960 and 1961-1970). This study is assumed to give a crude idea about the change in cotton yield response to climatic elements through time. Similar small sampling was used by Lomas (1972) in the north Negev of Israel to check the error that might result from the adjustment of any time trend. The purpose was to eliminate or reduce the time effect for better inspection of climatic-cotton yield relationship.

Wad Medani - Dueim (1951-1960)

For the twenty cases available, correlations between climatic elements and cotton yields are shown in Table 7.5 It can be observed that rainfall totals always showed positive correlations with yield, the strongest of these being the annual, September - October and July rainfalls with r = 0.65, 0.60 and 0.56 respectively. In this period of study the crop seemed to respond positively in the presowing period, June and July, as well as to the vegetative period rainfall (September). This positive response was weak during the sowing and emerging period (August). This result is in keeping with the requirements of the plant and the necessary agricultural processes during its development.

The average temperature generally had the strongest negative correlations with yield. October mean and minimum temperatures, and summer mean temperatures (July - August - September), presented the strongest correlation coefficients, $r = -0.75$, -0.72, and -0.70 respectively. Relative humidity had weaker correlations but it can generally be said that it was almost positive throughout the season except for January and February where noticeable negative correlations occurred.

Wad Medani - Dueim (1961-1970)

It is found that a difference in the results obtained for this period from those of the previous one occurred in relation to the annual and monthly rainfall (see Tables 7.5 and 7.6). In this later period, rainfall ceased to show any direct significant correlation with cotton yield, although the pre-sowing (July) and the flowering period (October) and the annual total showed some tendency for rainfall to be beneficial to cotton yield.

Temperature in most cases, as in the earlier period (1951-60), showed a general negative correlation with yield, yet the peak of this behaviour differed from that of the earlier period. The stronger correlations were those of December and January ($r = -0.65$ and -0.68, both significant at $\alpha = 0.01$). One of the notable differences is that the

Table 7.5 Correlations between climatic variables and cotton yield (Kantar/fd) for Wad Medani-Dueim area (1951-60)

	Rainfall mm	Average temperature °C	Temperature > 35°C (no. days)	Max. temperature °C	Min. temperature °C	Relative humidity %
July	0.56*	-0.57*	-0.64**	-0.47*	-0.55*	0.37
August	0.23	-0.55*	-0.48*	-0.44	-0.43	0.44
September	0.53*	-0.48*	-0.65**	-0.60**	-0.57*	0.40
October	0.18	-0.75**	-0.47*	-0.60**	-0.72**	0.09
November	-	-0.23	0.26	0.18	-0.27	0.10
December	-	-0.07	0.07	0.10	0.34	0.16
January	-	-0.47*	-0.18	-0.13	-0.64**	-0.45
February	-	-0.12	0.23	0.14	-0.32	-0.20
March	-	0.03	0.17	0.10	-0.04	0.05
Year	0.65**	-0.31	-	0.05	-0.43	0.26

N = 19
* significant at α = 0.05
** significant at α = 0.01

Table 7.6 Correlations between climatic variables and cotton yield (Kantar/fd) for Wad Medani - Dueim (1961-70)

	Rainfall mm	Average Temperature ^{o}C	Temperature > $35^{o}C$ (No. days)	Max. temperature ^{o}C	Min. temperature ^{o}C	Relative humidity %	Evaporation mm	Windspeed 4-7 (Beaufort)
July	0.35	-0.32	-0.39	-0.36	-0.19	0.48*	-0.25	-
August	-0.07	-0.20	-0.24	-0.05	-0.11	0.22	-0.06	-
September	0.07	-0.21	-0.24	-0.25	-0.19	-0.02	-0.23	-
October	0.31	-0.07	0.07	-0.08	-0.28	-0.18	-0.29	-
November	-	-0.15	0.08	0.20	-0.28	-0.53*	-0.12	-
December	-	-0.51*	-0.02	-0.14	-0.65**	-0.48*	-0.12	-
January	-	-0.30	0.19	0.08	-0.68**	-0.52*	-0.12	0.09
February	-	0.50*	0.70**	0.71**	-0.14	-0.41	0.17	-0.28
March	-	0.24	0.50*	0.59**	0.14	-0.34	0.46*	-0.38
Year	0.40	-0.50*	-	-0.14	-0.44	-0.28	-	-

N = 20
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

Table 7.7 Correlations between climatic variables of the pre-growing and early growing season and cotton yield (Kantar/fd) for different areas (1)

Climatic element	Calendar period	Region				
		Whole area	Wad Medani-Dueim - Kosti	Gedaref - Kadugli	Wad Medani-Dueim (1951-60)	Wad Medani-Dueim (1961-70)
Rainfall (mm)	June	0.00	0.34	0.11	0.52*	0.37
	Pre-July	0.00	0.26	0.36*	0.46*	0.24
	Jul.+ Aug.	0.21*	0.20	-0.18	0.45*	0.24
	Sep.+ Oct.	0.08	-0.01	0.55**	0.60**	-0.08
	Jul.to Sep.	0.20*	0.25	0.15	0.56*	0.29
Average temperature (°C)	Jul.to Sep.	-0.31**	-0.27	-0.03	-0.70**	-0.35
Temperature >35°C (No.days)	Jul.to Sep.	-0.16	-0.29	-0.21	-0.70**	-0.38
Max.temp. (°C)	April	0.40**	0.03	-0.19	0.37	0.10
	May	0.32**	0.36*	-0.44*	0.37	0.29
	June	-0.13	-0.16	-0.31	-0.55*	-0.07
Min.temp. (°C)	April	-0.10	-0.29	-0.30	0.24	-0.14
	May	0.04	0.06	-0.53**	-0.17	0.25
	June	-0.03	-0.24	-0.18	-0.26	-0.12
Relative humidity (%)	May	-0.22	0.07	0.45*	-0.36	-0.16
	June	0.00	0.30	0.20		
No.of cases		137	31	31	19	20

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

(1) The early growing season = July - September, inclusive

stronger correlations of temperature with yield were concentrated in the earlier part of the season in 1951-60, and concentrated in the later part of the season in 1961-70. December and January night temperatures reflected a negative relationship with cotton, r = -0.65 and -0.68 respectively. During the harvest period, February and March, strong positive correlations with day temperature occurred, with r = 0.71 and 0.59 respectively. This result is compatible with Thomson and Basinski's statement (1962) that high temperatures promoted rapid ripening and boll opening. Temperature elements in general were again the most effective ones on cotton yield, as they had been in the earlier period (1951-60).

Relative humidity also showed a different behaviour : where the 1951-60 period showed weaker and in most cases positive correlations, the 1961-70 period showed correlations with generally negative values except for the first two months of the growing season. The strongest correlations here were those of November and January with r =-0.53 and -0.52 (significant at $\alpha = 0.05$) respectively.

Sunshine data were missing for both periods and evaporation data were available for the later period only. Although comparison is not possible, evaporation yield correlations of the 1961-70 period were negative throughout the growing season. However, this relationship was generally weak and it rises to a significant level at $\alpha = 0.05$ only in March (r = 0.46) where dryness was preferable for ripening and harvest.

From the different results of the climate-cotton yield relationships obtained for the two areas of the Gezira in the two decades studied here, factors other than the climatic one are thought to have an effect on cotton yield as well as on the climate-cotton yield relationships themselves. It can be seen from Table A.10 that rainfall variability for July (c.v. = 70%) and September (c.v. = 70%) are higher, and mean annual rainfall are lower, in decade 1961-1970 than the preceding decade (293 mm compared with 369 mm). In spite of this the rainfall-cotton yield relationship showed weak or no correlations in the 1961-1970 decade when compared with the preceding decade. The other climatic variables also showed weaker relationships with cotton yields in the early months of the growing season in the 1961-1970 decade than in the preceding decade. In this context many factors may be taken into consideration. These factors are :

(1) The application of wide scale irrigation of fallow in March and April or May before cotton sowing, since 1965, in the Gezira and Managil (SGB, 1966). This pre-watering method was recommended in 1952 but the water was not sufficient till the opening of the Roseires dam (Taha and Musa, 1971). It may also be suggested, here, that there had been an improvement of irrigation efficiency through the season with a decrease of dependency on rainfall watering in the 1961-1970 decade if compared with the preceding decade.

(2) The introduction of new methods of pest control and spraying (SGB, 1963).

(3) The adoption of a new commercial intra-row spacing of cotton plants.

(4) The change in the method of applying soil fertilizers (SGB, 1967).

7.2.4 Locally based study

Following to the argument proposed earlier in this chapter a need to inspect the effect of local climate on crop yield became necessary. The advantage of such a study, besides showing the local differences in the response of cotton yield to climatic elements is that it also gives a chance to compare the different treatments of the available data and helps to assess the best way to handle the weather-crop relationship problem in this area of the Sudan.

In this section four centres are studied separately. Two represent the irrigated cotton of the Gezira (Wad Medani, Kosti), one represents the rainfed cotton (Kadugli) and one represents the flooded cultivated cotton (Aroma). This selection also has the advantage of covering all types of cultivation. Generally the period 1950-1975 was considered in this study, with variations in the lengths and coverage of the available data among these centres.

Wad Medani

In this irrigated locality rainfall acts as an additional source of cotton watering, so that sometimes, it exerts an adverse influence on the crop development and yield. Thus it is not surprising that at Wad Medani rainfall showed no significant correlation with cotton yield (see Table 7.8). June totals and the distribution of pentad rainfall suggest

Table 7.8 Correlations between climatic variables and cotton yield (Kantar/fd) for Wad Medani

	Rainfall mm	Average temperature ^{o}C	Temperature >35^{o}C (No. days)	Max. temperature ^{o}C	Min. temperature ^{o}C	Relative humidity %	Evaporation mm	Wind speed (4-7) Beaufort	Radiation Cal./sq.cm. N = 16
July	0.19	-0.30	-0.39*	-0.29	-0.30	0.27	-0.33	-	0.25
August	-0.10	-0.10	-0.09	-0.06	-0.20	0.21	-0.15	-	0.42
September	0.29	0.07	-0.07	-0.09	-0.39*	0.13	-0.02	-	0.51*
October	0.11	-0.05	-0.42*	-0.39*	-0.39*	0.22	-0.13	-	0.26
November	-	-0.19	-0.07	-0.14	-0.16	0.20	-0.20	-	0.52*
December	-	-0.11	0.02	-0.17	-0.13	0.23	-0.38*	-	0.50*
January	-	-0.37	-0.31	-0.32	-0.44*	0.09	-0.36	-0.27	0.50*
February	-	0.11	0.17	0.12	0.10	0.12	-0.44*	-0.39*	0.25
March	-	0.09	0.06	-0.40*	-0.24	0.27	-0.37	-0.40*	-
Year	0.16	-0.26	-	-0.32	-0.14	0.18	-	-	-

N = 27
* significant at $\alpha = 0.05$

that early pre-sowing rainfall may be beneficial to cotton, though none of the correlation coefficients were significant at $\alpha = 0.05$. The correlation coefficients of June and pentad 1 were 0.33 and 0.44 respectively (see Tables 7.13, 7.14). The suggested benefits to the crop from rainfall at that time are that it increases soil moisture after the very dry conditions and gives the opportunity of pre-sowing weeding that remarkably reduced the weeding problem. Also, as maintained by Crowther (1945) quoted by Taha and Musa (1971), heavy rains in the pre-sowing period allowed increased availability of soil nitrogen and increased its distribution in depth. Crowther found that heavy rains in July and August increased the yield of cotton in the Gezira, though this generalization cannot be applied here. August rainfall generally had a non significant correlation with cotton yield and the early pentads of the month (Table 7.14) were characterized by a negative, though weak, correlation ($r = -0.25$).

Excessive rains in August might result in inundation of the soil for a long period, having an adverse effect on the sown cotton, or it might physically delay sowing. Experiments in the Gezira scheme suggested that cotton sown early in August grows much more rapidly in its early stages than does cotton sown later in the year (Razoux et al., 1967; Jackson, 1969b). Rain is preferable in vegetative period (September) rather than in the sowing period. The dangers of inundation and the other problems mentioned become insignificant, but because rainfall here is a complementary factor in cotton watering, this relationship never develops to be significant at $\alpha = 0.05$.

The relationship between temperatures and cotton yields at Wad Medani, although generally showing results compatible with those of the whole Gezira area (Wad Medani - Dueim - Kosti), did display different emphases. One of the reasons, besides the removal of spatial differences, is that results from this centre covered a longer period (1951 - 1977, 27 cases) than they did when it was included in the whole Gezira (11 cases). There were general negative temperature-yield correlations almost throughout the growing season. October day and night temperatures reflected negative relationships with cotton yield with a correlation coefficient of -0.39 each. The number of days with temperature $>35^{o}C$ had a stronger negative correlation with cotton yield ($r = -0.42$). All these correlation coefficients are significant at $\alpha = 0.05$. The reasons mentioned in section 7.2.1, that a rise in temperature is harmful to cotton, as it encourages insect pest reproduction and discourages boll production, are generally applicable here.

Relative humidity showed an insignificant relationship with cotton yield in this area for the study period. It can be seen from Table 7.8 that although positive correlations occurred, they never reached a value of 0.3 .

There were, in general, negative correlations between evaporation and cotton yield. Evaporation relation in this locality with cotton yield is compatible with the whole area of the Gezira (Tables 7.3, 7.4). The emphases here were at the pre-sowing and the later half of the growing seasons with special stress on the relationships in December and February ($r = -0.38$ and -0.44, both significant at $\alpha = 0.05$).

The reason for the noticeable negative correlations through the second half, towards the end of the season, may be attributed to the fact that this period is the driest in the growing season and any lack of watering efficiency occurs in this part. The differences in evaporation rates from place to place and from one part of the season to another led Hudson (1964), from his experiment on evaporation in the Sudan Gezira, to criticize what he called "the rather inflexible method of dispensing water" and to suggest the start of a search for a new approach to cotton irrigation in the Gezira. In this search a detailed study of evapotranspiration, spatially and temporally, is important for the agriculturalist to estimate the water need of a crop and to avoid any damage that might happen because of the lack of water at a certain stage of growth (Griffiths, 1966). However, the Piche evaporation used here, as mentioned in section 3.8.2, is not the ideal representative of evaporation. With the availability of data, more reliable and probably clearer relationships may be discovered.

The adverse effect of wind speed is shown through physical damage to the plant, as mentioned in section 7.2.2; in addition wind accelerates evaporation (Penman, 1948), and may result in a reduction in the growth and the yield of the crop through water removal from the plant (Webster and Nelson, 1980). This adverse effect was clearly shown in negative correlations of yield with February and March wind force (4-7, Beaufort scale) with values of -0.39 and -0.40 respectively (both significant at $\alpha = 0.05$).

On the subject of the radiation-cotton yield relationship, it is mentioned by Chang (1968) that "in the absence of water deficit, mineral deficiencies and other limiting factors, a good relationship can be expected between radiation and photosynthesis. This is of course reflected on the yield". The results from Wad Medani, the only station which recorded radiation in the study area for a period of 16 years (since 1960), confirm that good positive correlations were obtained for most of the vegetative and boll formation period (Table 7.8). The r values were around 0.5 for September and November to January monthly averages. Table 7.9 shows that even stronger correlations occurred within some of the shorter periods (pentads) with emphases on different parts of the whole period. Towards the end of August (pentad 11) and at the end of September (pentad 18) high correlations were obtained with r values of -0.67 (significant at $\alpha = 0.01$) and -0.60 (significant at $\alpha = 0.05$).

Kosti

In the Kosti area, which represents the south western corner of the irrigated Gezira scheme, and from the study period (1960-1974), a similar generalization to that of Wad Medani can be made, that is rainfall acts as a complementary factor. It may sometimes reflect an adverse effect on cotton yield, for the same reasons mentioned earlier in this section that it may delay agricultural processes. From here, it can be seen that that monthly and annual rainfall totals displayed very weak correlations, negative for July (r = -0.24). Table 7.14 shows that the distribution of rainfall within

Table 7.9 Correlations between pentad radiation and cotton yield (Kantar/fd)for Wad Medani(1)

Pen-tad	Calendar period	Radiation Cal/sq.cm	Pen-tad	Calendar period	Radiation Cal/sq.cm
1	1 - 5 July	0.26	19	29 Sep.-3 Oct.	0.27
2	6 - 10	0.41	20	4 - 8	0.41
3	11 - 15	-0.11	21	9 - 13	0.08
4	16 - 20	0.05	22	14 - 18	0.27
5	21 - 25	0.16	23	19 - 23	-0.05
6	26 - 30	0.02	24	24 - 28	0.15
7	31 Jul- 4 Aug.	0.05	25	29 Oct.- 2 Nov.	0.50*
8	5 - 9	0.07	26	3 - 7	0.41
9	10 - 14	0.20	27	8 - 12	0.49
10	15 - 19	0.22	28	13 - 17	0.38
11	20 - 24	0.67**	29	18 - 22	0.16
12	25 - 29	0.45	30	23 - 27	0.20
13	30 Aug.- 3 Sept.	0.12	31	28 Nov.- 2 Dec.	0.18
14	4 - 8	0.28	32	3 - 7	0.37
15	9 - 13	0.29	33	8 - 12	0.52*
16	14 - 18	0.47	34	13 - 17	0.39
17	19 - 23	0.53*	35	18 - 22	0.38
18	24 - 28	0.60*	36	23 - 27	0.51*

N = 16

* significant at α = 0.05
** significant at α = 0.01

(1) The numbering of pentads here is different from the conventional system

shorter periods (pentads) in most cases reflected weak or negative correlations. Rainfall in the later part of September (pentad 17) in particular showed a strong negative correlation with cotton yield (r = -0.62, significant at α = 0.05).

The effect of temperature in this area is presumed to be stronger in the winter portion of the season (December - March, inclusive). December and January temperatures were always negatively correlated with yield. Their minimum temperatures in particular had the highest correlations with r values of -0.54 and -0.59 respectively (both significant at α = 0.05). February and March temperatures showed positive correlations with values of 0.57 (significant at α = 0.05) and 0.42 respectively. The behaviour of winter (December - March inclusive), displayed earlier negative, and later positive, correlations with yield, as obtained at Wad Medani (see Table 7.10).

Relative humidity and evaporation in this area acted in almost opposite directions in relation to cotton yield. While relative humidity monthly averages had positive correlations with cotton yield for most of the growing season, evaporation averages were always negatively correlated. The values of correlation coefficients with evaporation were always higher than those of relative humidity. November and December were the only months when relative humidity correlations rose to a significant level at α = 0.05 (r = 0.56 and 0.53). Except for February, evaporation was always strongly correlated with yield, strongest in December, January and March with r values of -0.79, -0.66 and -0.61 respectively.

Table 7.10 Correlations between climatic variables and cotton yield (Kantar/fd) for Kosti

	Rainfall mm	Average temperature ^{o}C	Temperature >$35^{o}C$ (No.days)	Max. temperature ^{o}C	Min. temperature ^{o}C	Relative humidity %	Evaporation mm	Windspeed 4-7 (Beaufort)
July	-0.24	0.17	-0.02	0.10	0.29	0.03	-0.22	-
August	0.12	-0.01	0.22	0.02	-0.10	0.13	-0.19	-
September	0.14	-0.10	-0.12	-0.06	-0.18	0.20	-0.24	-
October	-0.09	0.23	-0.02	0.25	0.14	0.23	-0.25	-
November	-	-0.06	0.22	0.12	-0.10	0.56*	-0.52*	-
December	-	-0.40	-0.16	-0.32	-0.54*	0.53*	-0.79**	-
January	-	-0.46	-0.32	-0.28	-0.59*	-0.08	-0.66**	-0.42
February	-	0.48	0.47	0.57*	0.25	-0.36	-0.36	-0.68**
March	-	0.31	0.42	0.42	0.18	0.16	-0.61*	0.31
Year	0.12	0.01	-	0.11	0.21	0.31	-	-

N = 15
* significant at α = 0.05
** significant at α = 0.01

The harvest period wind speed, as at Wad Medani, was negatively correlated with cotton yield. The strongest value of correlation coefficients occurred in February ($r = -0.68$, significant at $\alpha = 0.01$). The positive correlation between March wind speed and yield, though weak ($r = 0.31$) remains unexplained as it contradicts the general concept of adverse relationships at the harvest period.

Sunshine showed no significant correlations with cotton in this area. Only in November the value of r reached -0.38, and this is still far below being significant at $\alpha = 0.05$.

Kadugli

In this area the data obtained covered the period 1960-1974. The rainy season starts earlier with heavier rainfall so the growing season also starts earlier, and since cotton is totally dependent on rainfall the growing season ends earlier than in the irrigated area.

Table 7.11 shows that although July and August total rainfall appeared to act in opposition to one another in relation to cotton yield, with r values of -0.36 and 0.39 respectively, neither of them rose to a significant level at $\alpha = 0.05$. The annual, September and October rainfall totals showed no relationships with cotton yield. The shorter period (pentad) rainfall totals showed the general behaviour displayed by the monthly values (see Table 7.14). This seems to be because rainfall is more reliable for the period of study and it is likely to satisfy the water requirements of the American cotton grown here, so that no strong relationships were obtained. However, there is a general tendency

Table 7.11 Correlations between climatic variables and cotton yield (Kantar/fd) for Kadugli

	Rainfall mm	Average temperature °C	Temperature >35°C (No. days)	Max. temperature °C	Min. temperature °C	Relative humidity %	Evaporation mm
July	-0.36	0.51*	0.24	0.46	0.37	-0.37	0.26
August	0.39	0.25	-0.08	0.27	0.23	-0.31	-0.04
September	-0.01	0.30	0.04	0.29	0.30	-0.24	-0.10
October	-0.03	-0.14	-0.25	-0.18	0.44	0.23	-0.27
November	-	-0.37	-0.41	-0.52*	0.02	0.11	-0.08
December	-	0.00	0.09	0.23	-0.24	-0.10	-0.16
January	-	-0.30	0.08	0.18	-0.49	0.03	-0.27
Year	-0.04	0.35	-	0.50	0.06	-0.40	-

N = 15
* significant at $\alpha = 0.05$

of negative relationships with early germination and emergence period (July) and positive one in the following period (August).

As can be seen from Table 7.11, this area showed positive correlations between temperatures and cotton yield in the early part of the growing season (June - October, inclusive), with the strongest in July ($r = 0.51$). Negative correlations, on the other hand, were seen during the later part of the season, with the strongest in November ($r = -0.52$, significant at $\alpha = 0.05$). This difference in the behaviour of cotton in relation to temperature, especially at the early part of the growing season, from that of Wad Medani may have some relation to the fact that temperature averages here are lower than those of Wad Medani. In addition, the response of the American type of cotton grown here may also be different from that of long staple cotton. Although the results shown here in many cases matched those obtained from the grouping of Kadugli with Gedaref, there were some contradictions. This needs further investigations with a large set of data to test which are the most meaningful, results from the integrated Gedaref-Kadugli or the local area.

In this area, where cotton is sown earlier, (June) and rainfall is heavier than anywhere else in the study area, there were generally negative correlations between cotton yield and relative humidity averages for sowing and early part of the growing season (June to September), with the strongest in June ($r = -0.60$).

Evaporation, as can be observed from Table 7.11 always showed negative, though weak, correlations with crop yield except for July where a positive one is obtained ($r = 0.26$). This insignificant relationship may be thought of in the light of the fact that this area has relatively heavier rainfall with milder temperatures which are assumed to help in restoring more moisture which reduces the danger of water stress on the plant.

Aroma

Aroma, which lies in the Gash delta, and where cotton is grown by means of controlled flush irrigation described in section 6.1.1, is unique amongst the study centres in its agricultural methods and its lighter soil. This situation is assumed to affect the climate-cotton yield relationship. Nineteen cases within the period 1950-1972 were obtained for the testing of such relationships.

The pre-sowing rainfalls, June and July, were negatively, though weakly, correlated with cotton yield, $r = -0.36$ each, (see Tables 7.12 and 7.13). From the nature of this area it might be said that early heavy rainfall may add to the problems of water percolation in the soil as the flood will bring a huge amount of water and inundate the delta. The increase of water may also add to the problem of weeds. August and September monthly rainfall showed no significant relationship with cotton, but their pentad periods showed alternate positive/negative correlations (see Table 7.14). In some cases the correlations of these shorter periods rose above 0.40 and to a significant level at $\alpha = 0.05$, in for example pentad 17 ($r = 0.49$) of September 19th to 23rd.

Table 7.12 Correlations between climatic variables and cotton yield (Kantar/fd) for Aroma

	Rainfall mm	Average temperature °C	Temperature > 35°C (No. days)	Max. temperature °C	Min. temperature °C	Relative humidity %	Evaporation mm	Windspeed (4-7) Beaufort
July	-0.36	0.12	-0.16	0.10	0.03	-0.22	0.25	-
August	-0.15	0.21	0.14	0.21	-0.03	-0.39	0.41	-
September	0.14	-0.02	0.00	0.05	-0.11	-0.25	0.38	-
October	0.23	-0.05	0.18	-0.02	-0.03	0.11	0.69**	-
November	-	0.05	0.41	0.05	0.03	-0.16	0.40	-
December	-	0.07	-0.13	-0.02	0.16	-0.14	0.07	-
January	-	-0.07	-0.07	-0.21	-0.06	-0.18	0.36	-0.02
February	-	-0.07	-0.15	-0.17	-0.04	-0.10	0.38	0.20
March	-	-0.20	-0.15	-0.09	-0.21	-0.33	0.40	0.21
Year	-0.26	-0.13	-	-0.16	-0.09	-0.16	-	-

N = 18
** significant at $\alpha = 0.01$

Table 7.13 Correlations between climatic variables of the pre-growing and early growing season and cotton yield (Kantar/fd) for 4 centres (1)

Climatic element	Calendar	Centre			
		Wad Medani	Kosti	Kadugli	Aroma
Rainfall (mm)	June	0.33	-0.01	-0.20	-0.36
	Pre-July	0.10	0.13	-0.16	-0.23
	Jul.+ Aug.	0.02	-0.05	0.12	-0.35
	Sep.+ Oct.	0.07	0.12	-0.02	0.22
	Jul.to Sep.	0.11	0.06	0.07	-0.23
Average temperature (^{o}C)	Jul.to Sep.	-0.16	0.06	0.41	0.15
Temperature > 35^{o} C (No.days)	Jul.to Sep.	-0.21	0.03	0.12	0.32
Max.temp. (^{o} C)	April	-0.02	0.20	-0.08	-0.13
	May	0.23	0.39	0.15	-0.54*
	June	-0.30	0.10	0.49	-0.41
Min.temp.	April	0.18	-0.19	0.06	0.11
	May	-0.08	0.24	-0.18	-0.07
	June	-0.32	-0.09	0.23	-0.29
Relative humidity (%)	May	-0.01	0.25	-0.07	0.23
	June	0.18	0.24	-0.60*	-0.10
	Jul.to Sep.	0.23	0.15	-0.33	-0.33
No. of cases		27	15	15	18

* significant at α = 0.05

(1) The early growing season = July - September, inclusive

Table 7.14 Correlations between pentad rainfall (mm) and cotton yield (Kantar/fd) for 4 Centres (1)

Pentad	Calendar	Wad Medani	Kosti	Kadugli	Aroma
1	1 - 5 July	0.44	0.24	-0.20	-0.01
2	6 - 10	-0.26	-0.17	-0.28	-0.14
3	11 - 15	0.05	-0.13	-0.22	-0.22
4	16 - 20	0.33	-0.13	0.12	0.37
5	21 - 25	0.29	0.01	-0.31	0.20
6	26 - 30	-0.05	0.00	-0.18	-0.09
7	31 Jul. - 4 August	-0.22	-0.05	0.05	-0.16
8	5 - 9	-0.25	0.10	0.22	-0.28
9	10 - 14	0.07	-0.20	0.15	0.46
10	15 - 19	0.11	0.16	-0.04	-0.42
11	20 - 24	0.24	-0.07	0.28	-0.08
12	25 - 29	-0.06	-0.32	0.34	-0.23
13	30 Aug. - 3 September	-0.05	-0.07	-0.08	0.17
14	4 - 8	-0.03	0.44	-0.02	0.14
15	9 - 13	0.16	0.21	0.10	0.09
16	14 - 18	-0.09	-0.27	0.08	-0.38
17	19 - 23	-0.12	-0.62**	0.24	0.49*
18	24 - 28	0.04	-0.21	-0.36	0.07
19	29 Sept. - 3 October	0.02	-0.24	-0.05	-
No. of cases		16	15	15	15

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

(1) The numbering of pentads here is different from the conventional system.

As can be observed from Tables 7.12 and 7.13, temperature displayed a different behaviour here from all the other stations. It showed noticeable negative correlations with cotton yield only in May (r = -0.50, significant at α = 0.05) and June (r = -0.44) which are considerably ahead of the growing season. Relative humidity also showed an insignificant relationship with yield as it only rose to r = -0.39 in August which failed to reach significance at α = 0.05. However, relative humidity always reflected a negative correlation with yield almost throughout the growing season. It is also observed that no significant relationship was shown between wind speed and cotton yield in this area.

Evaporation was the main climatic variable where this area showed a considerable difference. Because of the high availability of moisture in the soil evaporation showed positive correlations with cotton yield in this area. It was positively correlated with cotton yield throughout the growing season. The correlation coefficients were in most cases above 0.36 and were exceptionally strong in October (r = 0.69, significant at α = 0.01).

In general, correlation coefficients resulting from the whole area studied as one region were generally lower than from the smaller regions and localities. In many cases there is a general confirmation of patterns of climate-cotton yield relationships whereas in some other cases they were contradicting. One of the reasons for such contradictions was the inclusion of all the centres with all their climatic and technological differences. In the study of the integrated whole area, consideration was made only of variables common to all centres, whereas at the local level there were opportunities to include in the statistical analysis more climatic elements which were measured at those localities only.

Of the climatic data obtained for different areas, pentad rainfall data were taken forward to another form of statistical analysis, Fisher's second degree polynomial regression, to inspect more closely the effect of rainfall, the vital climatic element in the Sudan, with the readily available data on cotton yield.

7.3 Effect of pentad rainfall changes on cotton yield

The Fisher's 1924 polynomial regression technique adapted by Hendricks and Scholl (1943) as described in section 6.3.3 was used here to describe the effect of pentad rainfall through the growing season on the final cotton yield. The advantage of this method is that the season can be divided into as many intervals as desired without increasing the number of variables as might happen in the other types of regression. The result at any place can be displayed in a form of a continuous curve which represents the increase (or decrease) of yield resulting from an additional 1 or 2 millimetres of rainfall at any particular date. The expected effect of the observed rainfall can be calibrated from this curve.

From their work on corn, Hendricks and Scholl (1943) concluded that crop yields cannot be predicted much more accurately from weekly weather data than from monthly weather data, but an analysis based on weekly data enables one to determine the seasonal variation in the effects of weather factors more accurately. Similar results are found to be true in the case of pentad rainfall in relation to cotton yields in this study.

Two assumptions adopted in this study were -

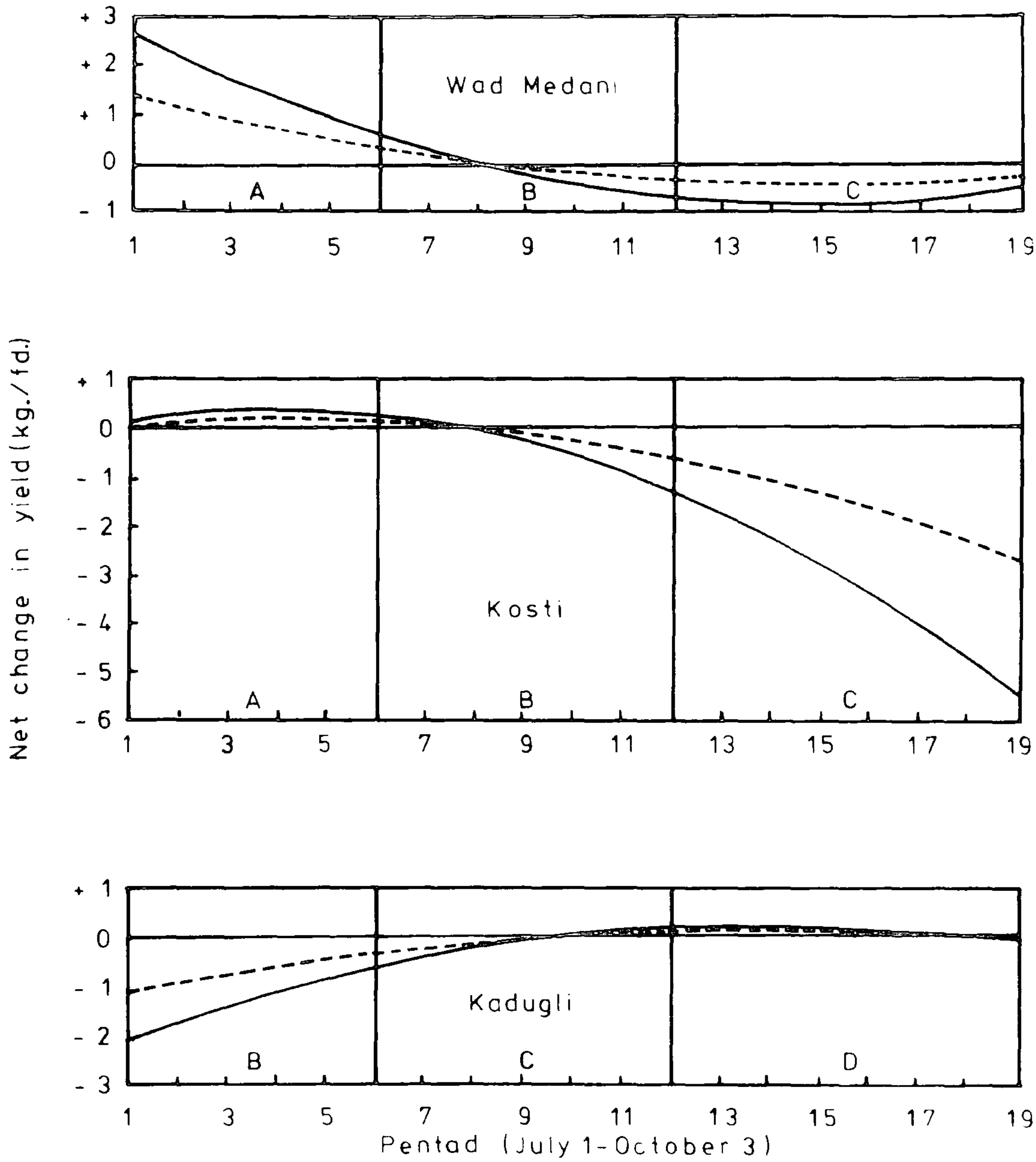
(1) One millimetre of rainfall has the same effect on cotton yield whether the rain total for each pentad period is above or below average;

(2) The total effect is directly proportional to the number of millimetres of rainfall above or below average.

The effects of the increase of one or two millimetres over the average pentad rainfall on the change in the final cotton yield in the way described here, were considered for the Wad Medani, Kosti and Kadugli cotton production centres. The pentad rainfall data collected for the period 1960-1974 were divided approximately into pre-sowing and early sowing (July), sowing, germination and emergence (August), and vegetative and early flowering (September) stages. Those were identical for Wad Medani and Kosti, but they were shifted to earlier calendar phases at Kadugli where the growing season starts and ends earlier (see Fig. 7.1).

The curves shown in Figure 7.1 have been drawn using Fisher's technique on which approximate season's phases have been superimposed. According to the assumption previously mentioned, that the effect of rainfall is proportional to the number of millimetres, the more comprehensive effect of 2 mm rainfall above average will be discussed. The clear

Fig. 7.1 EFFECT OF 1 AND 2MM ABOVE AVERAGE PENTAD RAINFALL ON COTTON YIELDS IN 3 AREAS



—— +2 mm rainfall

---- +1 mm rainfall

A pre-season & early sowing

B sowing, germination & emergency

C vegetative & early flowering

D flowering & early bolling

Pentad calendar is shown in Table 7.14

relationship between the effects of the two levels of rainfall increase, 1 and 2 mm, can be observed from Figure 7.1. This procedure is a hypothetical one and it indicates that a potential increase (or decrease) in yield is likely to result from the change in rainfall.

Pre-sowing and early sowing

At Wad Medani the increase of rainfall by 2 mm above the average rainfall of the early pentads of this phase was marked by an increase of 2.6 kg/fd of cotton. That increase in yield drops to +0.6 kg/fd at the end of the phase. Kosti showed an insignificant change in yield in a way that suggests indifference to rainfall increase at this stage. Here the increase in yield was assumed to be only +0.2kg/fd at the beginning, +0.4 kg/fd in the middle and +0.3 kg/fd at the end of the phase. At Kadugli the pre-sowing and early sowing phase occurs before the period under consideration here (1st July) and the lack of data for the earlier period made it impossible to investigate cotton performance at a similar phase.

Comparing these results with correlations between monthly or pentad total rainfall, traces of similarity can be found. The start of the period in both Wad Medani and Kosti was marked by positive relationships, stronger at Wad Medani. These curves are more practical in showing the trend of change in cotton yield than the unexplained erratic correlation coefficients of the pentads.

Sowing, Germination and emergence

In this case the net changes in cotton yield according to an increase of 2 mm above average pentad rainfall at both Wad Medani and Kosti followed similar patterns. A drop from a positive contribution at the beginning of the phase to an adverse effect towards the end of the phase occurred. However, the adverse effect of rainfall increases at Wad Medani at the end of the phase (-0.7 kg/fd), was smaller than that at Kosti (-1.3 kg/fd). At Kadugli the increase of rainfall at this level had a more pronounced effect on cotton yield as it seemed to result in a decrease of 2.1 kg/fd at the beginning of the phase. This negative effect reduces as time passes until it reaches only 0.5 kg/fd at the end of the phase.

Vegetative and early flowering

This phase at Wad Medani showed unremarkable changes in cotton yield in response to an increase of 2 mm of rainfall above the average. The effect ranged only between -0.5 and -0.9 kg/fd. Kosti showed the most profound change occurred in any phase at any of the three centres. The increase of 2 mm rainfall here resulted in an increasing negative effect on cotton yield from -1.3 kg/fd at the beginning to -5.5 kg/fd at the end of the phase. Kadugli showed a very slight effect of rainfall at the beginning of this phase (-0.7 kg/fd). This was followed by slight effects on yield throughout this phase where the curve of net change remained around zero. This indifferent behaviour of cotton yield to the increase of rainfall at Kadugli extended throughout the bolling phase.

The results obtained in this phase showed some similarity with the correlation coefficients obtained for pentad rainfall with cotton yield. The strong negative correlations at Kosti towards the end of September, and the insignificant relationships in many of the pentads at Wad Medani and Kadugli can roughly be related to the curves.

The results from Fisher's model are assumed to establish relationships useful in assessing the effect of rainfall change through the growing season on the change in cotton yield. It should be noted here that such curves are only useful at the localities where they were developed.

The general climate-cotton yield relationships, so far discussed, were entered into a further step, where regression analysis and regression models based on climatic factors were built for cotton yield estimation. This step is discussed in the following section.

7.4 Regression analysis and cotton yield estimation

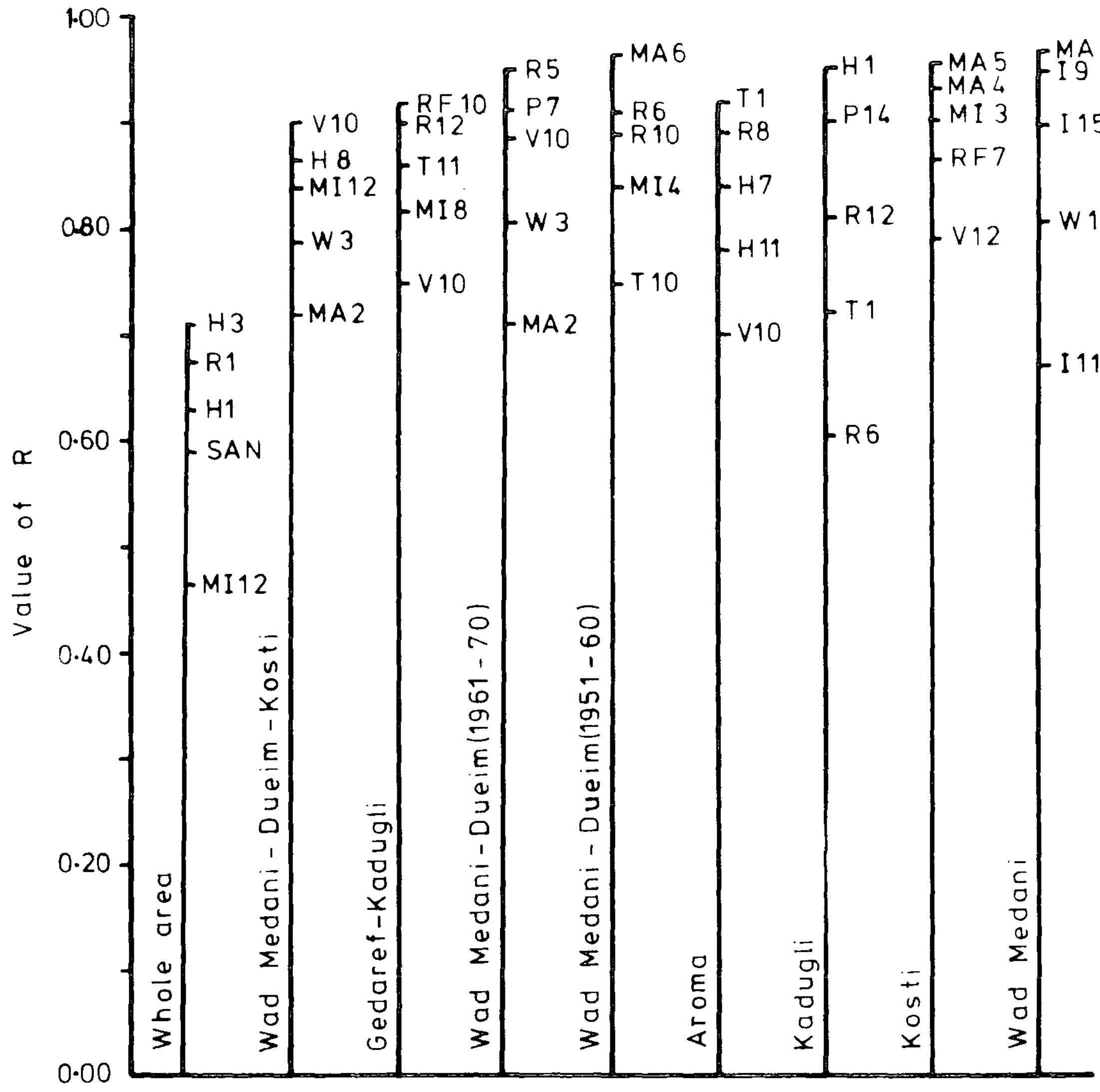
7.4.1 Regression analysis

In this section there is a discussion of the stepwise regression built up by different climatic variables for each of the previously defined regions or localities for the same periods between 1950 and 1978. The advantages and limitations of the regression model have been discussed in sections 5.2.3 and 6.3.3. The formulae derived from those regressions were used to compute cotton yields. It is stated by Thompson (1963) and Maunder (1968) that it is not advisable to restrict the prediction to the period of the record and ignore the period beyond that. Therefore the computation of cotton yields was done in two steps. The first step was restricted to the estimation of cotton yield for the same period from which the formulae were derived, whereas the second step, which was considered for local areas only, was an extrapolation for two or three years beyond the basic period.

The whole area

From Figure 7.2 and Table 7.1[5] where a summary of multiple correlation coefficient (R) sets are displayed, it can be seen that treating the whole study area as a single region will result in low values of multiple correlation coefficients. The most important variable here was December minimum temperature ($r = -0.47$). At step 2 the average annual sunshine (taken as a percentage of the possible) caused the value of R to reach 0.59. January number of days with temperatures $>35^{o}C$ came in the third place in the regression hierarchy ($R = 0.63$). At step 4 the value of R rose to 0.68 by the inclusion of January relative humidity. The final step considered in this study showed March number of days with temperatures $>35^{o}C$ to be important in cotton yield estimation in the area. The value of R at this stage was 0.71 ($R^2 = 0.5$). It can be observed that after the first two variables entered in the stepwise regression the contribution dropped to only 4% and then maintained almost equal values through the final steps considered in the study. After the five variables identified, only negligible additional contributions occurred. The value of R rose to only 0.75 after including a total number of 10 variables. It is noted that all the variables identified by the regression procedure

Fig.7.2 COEFFICIENTS OF MULTIPLE CORRELATIONS FOR COTTON CROP IN DIFFERENT AREAS



For the interpretation of symbols see Table 7·15

Table 7.15 Regression analysis of cotton yield in different areas in the Sudan

	No.of Cases	Average yield (Kantar/fd)	R	R^2	S.E.
The Whole area	137	2.97	0.71	0.50	1.44
Wad Medani-Dueim-Kosti	31	4.48	0.90	0.81	0.51
Gedaref-Kadugli	31	1.83	0.92	0.85	0.47
Wad Medani-Dueim (1951-60)	19	4.37	0.97	0.93	0.51
Wad Medani-Dueim (1961-70)	20	4.27	0.95	0.90	0.59
Wad Medani	16	5.29	0.96	0.92	0.49
Kosti	15	5.18	0.96	0.91	0.50
Kadugli	15	2.83	0.95	0.90	0.32
Aroma	18	1.19	0.92	0.85	0.28

Table 7.16 Regression Formulae used for cotton yield estimation (Y)

A-Areas

1. The Whole Region
   Y = 14.4019-0.2539MI12-0.0126SAN-0.0691H1-0.1016R1-0.1147H3

2. Wad Medani-Dueim-Kosti
   Y =-2.5008+0.4587MA2-0.0628W3-0.3833MI12+0.0723H8-0.2111V10

3. Gedaref-Kadugli
   Y = 2.7248-0.2165V10+0.8324MI8-0.5407T11-0.0641R12-0.0073RF10

4. Wad Medani-Dueim
   Y = 72.6509-1.047T10+0.387MI+0.1079R10-0.088R6-1.1519MA6

5. Wad Medani-Dueim (1961-1970)
   Y =-11.2558+0.658MA2-0.0084W3-0.2883V10-0.0261P7-0.0893R5

B-Centres

1. Wad Medani
   Y =-25.8747+0.0082I11-0.1081W1+0.0031I15-0.001919+0.2148MA2

2. Kosti
   Y =-27.2324-1.7054V12-0.0144RF7+0..343MI3+0.4778MA4+0.5601MA5

3. Kadugli
   Y = 20.4018-0.804R6-0.5012T1-0.067R12-0.0132P14+0.0385H1

4. Aroma
   Y = 2.4016+0.2266V10+0.561H11-0.0354H7-0.0355R8-0.1087T1

Symbols

H1	=	January No.of days with temperature 35°C	
H3	=	March	ditto
H7	=	July	ditto
H8	=	August	ditto
H11	=	November	ditto
I9	=	Pentad 9 (Table 7.9) Radiation (Cal./sq.cm)	
I11	=	Pentad ii	ditto
I15	=	Pentad 15	ditto
MA2	=	February Maximum temperature (°C)	
MA4	=	April	ditto
MA5	=	May	ditto
MA6	=	June	ditto
MI3	=	March Minimum temperature (°C)	
MI4	=	April	ditto
MI8	=	August	ditto
MI12	=	December	ditto
P7	=	Pentad (Table 7.14) Rainfall (mm)	
P14			ditto
R1	=	January afternoon relative humidity (%)	
R5	=	May	ditto
R6	=	June	ditto
R8	=	August	ditto
R10	=	October	ditto
R12	=	December	ditto
RF7	=	July Rainfall (mm)	
RF10	=	October ditto	
SAN	=	Average Annual Sunshine (% of possible)	
T1	=	January Temperature (°C)	
T10	=	October ditto	
T11	=	November ditto	
V10	=	October evaporation (mm)	
V12	=	December ditto	
W1	=	January No.ofDays with wind force 4-7 (Beaufort)	
W2	=	February ditto	
W3	=	March ditto	

Table 7.17 Correlation between observed and estimated cotton yields (Kantar/fd) for regional and local areas

Area	Period			
	N	Original	N	Extended
Wad Medani-Dueim-Kosti	31	0.88	37	0.78
Gedaref-Kadugli	31	0.90	35	0.89
Wad Medani-Dueim (1951-60)	19	0.97	23	0.72
Wad Medani-Dueim (1961-70)	20	0.83	24	0.76
Wad Medani	16	0.97	18	0.95
Kosti	15	0.95	17	0.55
Kadugli	15	0.91	18	0.90
Aroma	18	0.94	20	0.90

All significant at $\alpha = 0.05$

$r > 0.64$ significant at $\alpha = 0.01$

at its 5 steps, where most of them are temperature and sunshine variables, have a negative effect on cotton yield towards the end of the growing season.

The standard error obtained from the multiple regression formula at the fifth step of the regression procedure was as large as 1.44 Kantar/fd compared with a cotton yield average which was 2.97 Kantar/fd. It can be seen from Table 7.15 that this result is the worst amongst those of the study areas. The standard error here, being 48% of the average yield. is almost double the worst percentage obtained in the rest of the regions. This poor result discourages any further computation of cotton yield for this wide area.

<u>Irrigated area : Wad Medani - Dueim - Kosti</u>

Itcan be seen from Figure 7.2 that the first variables entered in the multiple regression in this irrigated area gave R = 0.9 (R^2 = 0.81) with the highest value given by February maximum temperature (r = 0.72). This first inventory is higher than the R value reached in the fifth step of the whole area previously discussed. The inclusion of March's wind speed (force 4-7, Beaufort scale) resulted in an R value of 0.79. The third step which showed December minimum temperature as an important variable in the estimation of cotton yield raised the multiple correlation coefficient to 0.84. Including August number of days with temperatures $> 35^{0}$C in step 4, the result was R = 0.86. The fifth step as mentioned earlier resulted in R = 0.9 (R^2 = 0.81). The resultant standard error of the regression equation at this stage, 0.51 Kantar/fd, seems reasonable as it is only 11%

of the average cotton yield (4.48 Kantar/fd). This result is far better than that obtained for the integrated whole area and it suggests better estimations of cotton yield based on the regression formula obtained here.

Rainfed area : Gedaref - Kadugli

In the Gedaref-Kadugli area, Figure 7.2 shows that within the 5 variables considered, the most important variable was October evaporation ($r = -0.76$). In the second step August minimum temperature raised the value of R to 0.82. Including November average temperature in the third step the result given was $R = 0.86$. Following this step the value of R reached 0.9 after including December relative humidity. The final multiple correlation coefficient value reached by the fifth variable was 0.92 ($R^2 = 0.85$). It is noted that following the evaporation variable, temperature played the most important role in the contribution to the multiple correlation coefficient. The value of the standard error obtained for this area at the fifth step was 0.47 Kantar/fd which is 26% of the average cotton yield (1.83 Kantar/fd). This value which is less than that of the integrated area, is comparatively higher than those of the rest of the areas. The results expected from the further step, considering computation of cotton yield, may not be as good as those of the other areas (see Table 7.15).

Irrigated area segment : Wad Medani - Dueim

In the multiple correlation coefficient and the multiple regression for the first period in this area (1951-1960), October average temperature give $R = 0.75$ (see Fig. 7.2).

In the second step of the regression, April minimum temperature raised R to a value of 0.81. The value of R reached 0.89 in the third step by including October relative humidity. June relative humidity (in the fourth step) caused the R value to reach 0.91. In the final step considered here the regression identified June maximum temperature giving $R = 0.96$ ($R^2 = 0.93$). In this area, as in the previous ones, the temperature variables were the main contributors to the multiple correlation coefficient (see Fig. 7.2). The standard error shown in Table 7.15 was 0.51 Kantar/fd which is only 12% of the average yield of cotton in this area (4.37 Kantar/fd). This value lies within the lowest standard error values amongst the study regions with its inherent suggestion of good cotton yield estimations.

For the second period of study (1961-1970) of this area the highest contribution to R was made by February maximum temperature ($r = 0.71$). March wind speed caused the value of R to reach 0.81 followed by October evaporation raising it to 0.89. In the fourth step of the multiple regression procedure, pentad 7 rainfall (31 July - 4 August) raised the R value to 0.91. Finally, the inclusion of May relative humidity resulted in $R = 0.95$ ($R^2 = 0.9$). Table 7.15 shows that this area had a relatively small standard error, 0.59 Kantar/fd, which is about 14% of the average cotton yield (4.27 Kantar/fd).

From Figure 7.2 it can be observed that the most important variables in the 1961-1970 period were different from those of the earlier period (1951-1960) of the same area. The reason for this is partly because new climatic variables were introduced in the latter period and it is assumed also to be partly because of time, in relation to technological and other cultural factors change, as mentioned in section 7.3.3. Considering the local areas as represented by centres of meteorological and agricultural activities, better results were obtained. The meteorological station is believed to be the best, at present, to represent the local area surrounding it.

At Wad Medani, as can be seen from Figure 7.2, the arrangement of the variables in the multiple correlation coefficients showed pentad 11 (20 - 24 August) radiation, with r = 0.66, as the most important variable in cotton yield assessment. January wind speed which came second in the hierarchy of the multiple correlation resulted in R = 0.81. This value was raised to R = 0.9 by including pentad 15 (9-13 September) radiation. The fourth step also identified a radiation variable, pentad 9 (10-14 August), where the R value was raised to 0.94, and the final step specified in the study showed February maximum temperature to be important when R = 0.96 (R = 0.92). It is noted that all the important variables (i.e. contributive to R and the regression) in this area were of an energy nature, and the radiation effect was the most important of all. This area showed the lowest standard error amongst the study areas (0.49 Kantar/fd) which is only 9% of the average cotton yield (5.29 Kantar/fd).

At Kosti within the 5 variables identified by the stepwise regression, December evaporation was the dominant contributor (r = -0.79). The second most important variable in the multiple correlation hierarchy was July rainfall which resulted in R = 0.86. This variable was followed by March minimum temperature resulting in R = 0.9. At the fourth step April maximum temperature was identified as being important and it raised the R value to 0.93. Step 5 identified May temperature where the total value of R reached 0.96 (R^2 = 0.91). These variables were in general of an energy and moisture nature. The Kosti area also showed a small standard error, 0.5 Kantar/ fd of cotton, 10% of the average yield (5.18 Kantar/fd).

The contribution to R at Kadugli made by the first variable entered in the regression procedure, June relative humidity, was r = -0.6. The second important variable in this procedure was the average January temperature which resulted in R = 0.72. In the third step December relative humidity raised the R value to 0.81. The fourth important value was pentad 14 (4-8 September) rainfall with which the value of R reached 0.9. This value is pushed to 0.95 (R^2 = 0.9) by including January number of days with temperature >35^{o}C. From Figure 7.2 it can be observed that although this area had the lowest value of R amongst the regions when the first variable was entered by the regression procedure, the contributions made by the remaining variables were considerable and they result in one of the highest values of R. In this area the relative humidity and temperature variables were dominant. This area also showed a low value of standard error, 0.32 Kantar/fd when related to an average yield of cotton of 2.83 Kantar/fd (11%).

In the Aroma area the energy variables were the main contributors to R, and the highest was October evaporation ($r = 0.69$). In the second and the third steps the value of R were pushed to 0.78 and 0.84 by the number of days with temperatures $>35^{o}C$ in November and July respectively. This was followed by August relative humidity with $R = 0.89$, and average January temperature to give $R = 0.92$ ($R^2 = 0.85$). It can be observed from Table 7.15 that this area had the highest standard error (24%) in relation to average yield amongst the local areas and the third highest amongst all the areas studied. It is noted also that the most important variables in the cotton yield estimation in this area were of a thermal nature.

The results generally obtained from the regression analysis in many of the study areas with high values of multiple correlation coefficients and low standard errors encouraged computation of cotton yields with a promising degree of success. An exception to this, as mentioned earlier in this section, is the result of treating the whole area as a single region where poor results were obtained. The results obtained from the cotton yield calculations are discussed in the following section.

7.4.2 Cotton yield estimation

The formulae derived from the stepwise regression procedure at step 5 in each area (see Table 7.16) were used to estimate yearly cotton yields for two periods : the original and the extended periods. Alternative formulae using fewer variables can be obtained from Table A.11.

Because of the high coefficients made at step 5, the observed and estimated yields were close to each other (see Figs. 7.3 and 7.4). It can be seen from Table 7.17 that strong correlations between observed and estimated cotton yields were obtained for the original period. Wad Medani-Dueim-Kosti, and Wad Medani-Dueim (1961-1970) were the only areas where those correlation coefficient values dropped below 0.9 (r = 0.88 and 0.83 respectively). Considering the large regions it can be observed from the scattergrams (Fig.7.3) that the best estimation was made for Wad Medani-Dueim for the period 1951-1960 followed by that of Gedaref-Kadugli. Wad Medani-Dueim (1961-70) came in third place showing a large anomaly in one pair of observations. The local areas (see Fig.7.4) had the following descending order according to the power of their regression formulae in estimating cotton yield : Wad Medani, Kosti, Aroma and Kadugli. The correlation coefficient of the estimated and observed in these areas ranged between 0.97 and 0.91.

By adding two years for extrapolation the correlation coefficients of observed and estimated cotton yields dropped slightly in some cases and remarkably in other cases. At the regional level the coefficients were less than 0.8 whereas at the local level they remained above r = 0.9 except at Kosti where the coefficient dropped to its lowest level (r = 0.55).

The sharp drop at Kosti (south western tip of the Gezira scheme) in relation to the extended period needs to be elaborated. Many factors, some of which were mentioned in the SGB (1977) report, are believed to have caused this

Fig.7.3 OBSERVED AND ESTIMATED COTTON YIELDS(KANTAR/FD) FOR DIFFERENT REGIONS

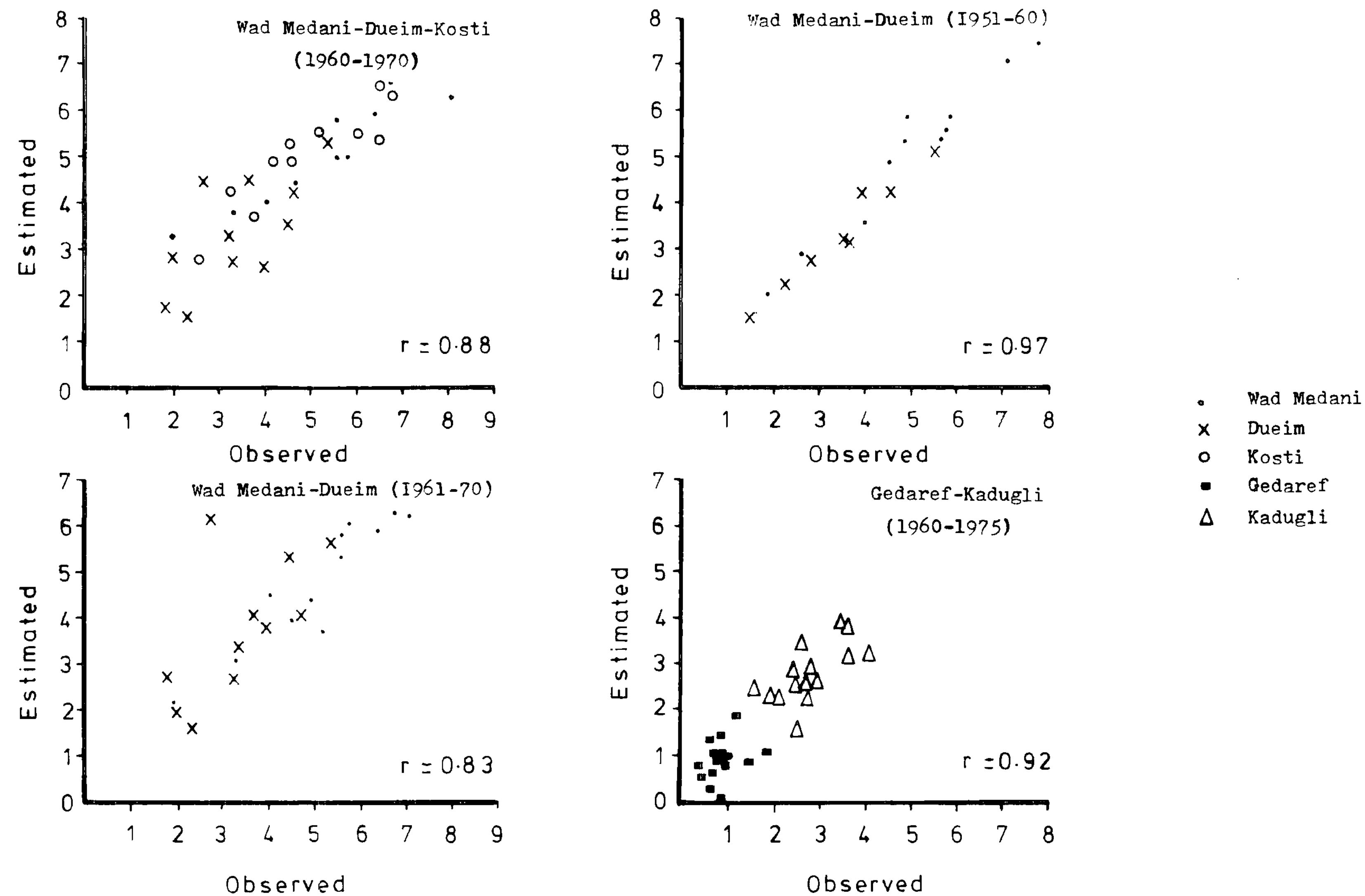
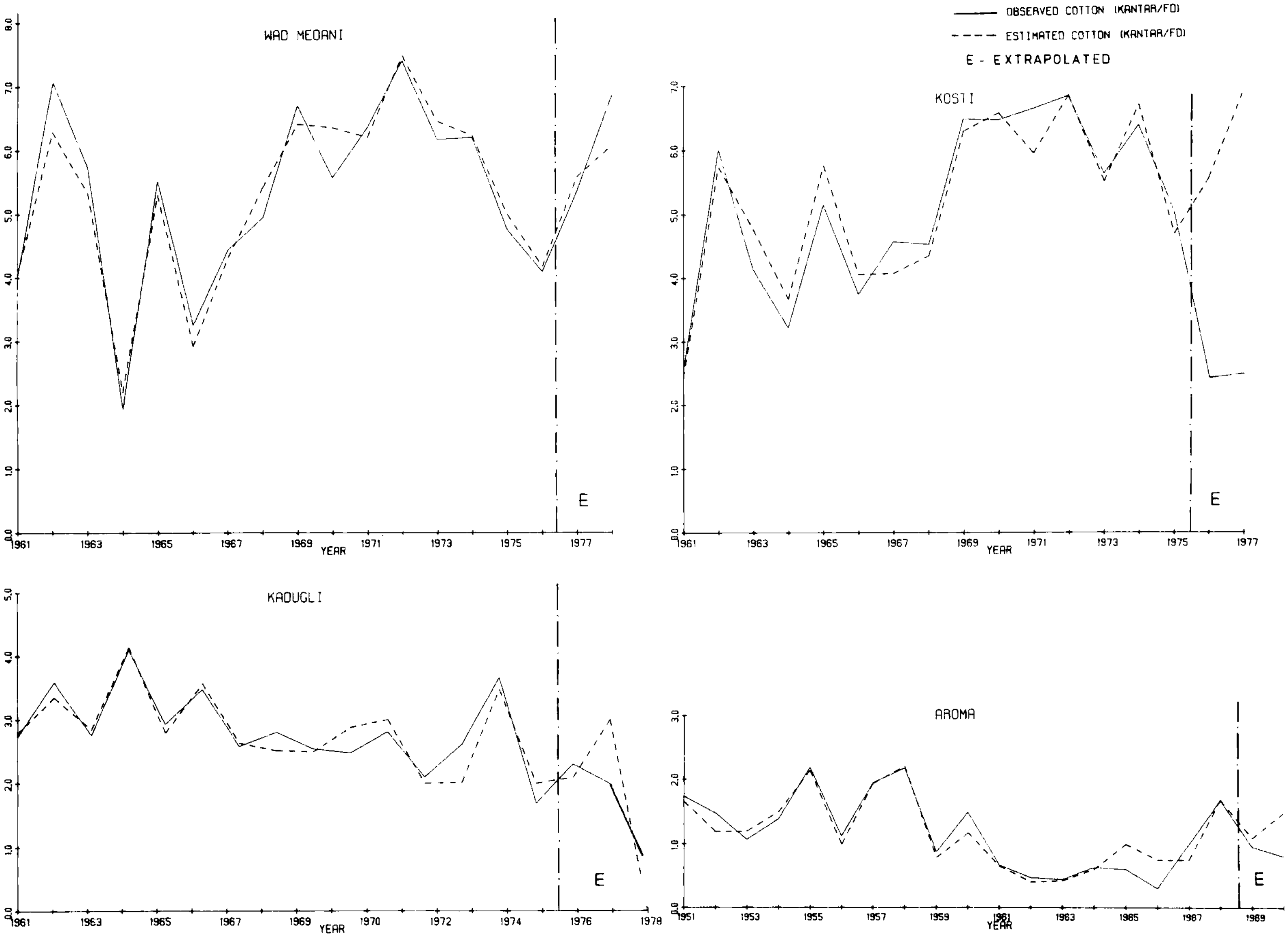


Fig. 7.4 OBSERVED AND ESTIMATED COTTON YIELDS FOR 4 AREAS



deviation from the optimum yield in the seasons 1975/76 and 1976/77. Since 1976 this part of the Gezira scheme entered into a different crop rotation system from the previous one. The fallow phase disappeared completely from the rotation probably adversely affecting the soil fertility or the healthy conditions for the crop. A drop of 0.27 Kantar/fd was calculated here. The new rotation might also have encouraged weed growth due to the successive watering of plots. The introduction of new crops under the tenant's ownership (e.g. wheat) caused tenants to take more care of them than of the cotton. This was especially true in the times of irrigation difficulties. In addition the season 1975/76 was characterized by heavy rainfall and the heaviest August rainfall for 17 years. Beside causing physical damage to some canals, and wash off or inundation of some of the sown cotton, it also delayed the sowing phase and hence affected the consecutive agricultural processes and enlarged the weeding problem. The 1976/77 season, on the other hand, witnessed a significant lack of water. It was reported to be dry in the period following the sowing in that area (SGB, 1977). This problem was aggravated in that season by the operational failure of the pumps which irrigate parts of this area from the White Nile (SGB, 1977). Besides all this the expected shortcomings of such a statistical model made from a small size of data might have contributed to this deivation. However, more data are needed to provide further testing of the models.

In conclusion to this chapter it can be said that the general agreement between different regions and centres in the general negative relationship of cotton yield with temperature and with minimum temperature in particular was recognized. The relationship of rainfall with yield, although sometimes appearing fairly strong, are not as outstanding as,for instance, temperature relationships. Elements like relative humidity and evaporation behaved differently. In many cases the rainfed cotton was positively related to relative humidity and inversely related to evaporation, while in many irrigated areas the opposite occurred. It should be noted that in many cases each group of climatic elements, e.g. rainfall and relative humidity, resulted in similar relationships with cotton yield (positive or negative) as opposed to those resulting from another group, e.g. temperature and evaporation. However, this study revealed that it is not always possible to guarantee the application of the general assumptions about climate-cotton yield relationships.

The climate-cotton yield analysis models proposed in this chapter are believed to be quite useful in providing more reliable cotton yield figures to fill in the historical record of the same period, or even backwards beyond the period of the model, than are available adopting the averages. They also in many cases proved to be useful for extrapolation besides helping to highlight the direction of future experimental study of cause-and-effect relationship between climate and cotton yield. However, these models require further testing or modifications. The paucity of data, the dependence only on climatic data in yield estimation and the statistical methods adopted all suggest such reconsideration of the models proposed in this study.

The next question dealt with is to what degree climate relationships with crops other than cotton are similar to those with cotton. The following chapter will be specialized for similar test of climatic variables relationships with the main subsistence crop in the Sudan, sorghum, followed by similar studies for sesame and groundnuts in Chapter 9.

CHAPTER EIGHT

THE RELATIONSHIP BETWEEN CLIMATE AND SORGHUM YIELD IN THE SUDAN

8.1 General

The study in this chapter is devoted to the relationship between climate and sorghum yield within the area identified in section 6.3.1. The methods used here are correlation, multiple regression and the second degree regression described in sections 5.2.2, 5.2.3 and 6.3.3, and used in the treatment of the climate-cotton relationship. Sorghum yield data used in this study are shown in Table A.12.

The study of this relationship is made as follows:

1) Regional studies (irrigated and rainfed areas)

2) Local studies (centres of production)

As has been mentioned in section 7.2.1 it is not really expected to find significant relationships if an extensive area like the Sudan is treated as one unit. It is not even likely that if the area is split into large regions significant relationships will be found. In fact, a trial like this on sorghum in the Sudan by the author led to this conclusion. From a study of corn yield variability in relation to weather patterns, Mostek and Walsh (1981) reached a similar conclusion. Bunting and Curtis (1968) mentioned that many of the sorghum varieties grown by peasant farmers in developing countries seem to be very closely adapted to their home region. Due to such difficulties, small regions, almost climatically and agriculturally homogeneous and local basis for study has been dealt with as it proved to be more fruitful.

Sorghum is the major cereal of rainfed agriculture in semi-arid tropics (Doggett, 1976). It is the main subsistence crop in the Sudan, and as was mentioned in section 6.1.3 it occupies a high status in the agricultural activities in the country. Different varieties are planted at the beginning of the rainy season (July) flower at the end of the rain (October) and then depend on the residual soil moisture for their ripening. This important crop, like cotton, also suffers from variations in yield from year to year. The same reasons provided in section 7.1 for the importance of climate in such variations, and the study of climate-crop relationships between sorghum yields, which are measured in kilograms per feddan, and different climatic variables in different areas, it might be useful to give a brief idea about the general nature of such relationships.

The availability of water is the most important limiting factor in the growing of sorghum in the Sudan. Rainfall is not only important for the rainfed crops but acts as a supplementary factor in the irrigated area. It is also understandable that harmful effects of rain can be witnessed through physical damage and through encouragement of weeds, pests and diseases. As was shown in Chapter 7, the relationship between rainfall and crops is not always a clear one, positive or negative. That, of course, is understood within the context of the complexity of crop-weather relationship in terms of soil, plant physiology and agricultural practices.

Sorghum is known to have an outstanding ability to withstand dry conditions and it is the only field crop that approaches the true xerophytes (Mansfield, 1949; Skerman, 1956; Wolfe and Kipps, 1959; Klages, 1961; Doggett, 1970; Blum, 1972; Mahmoud, 1977; Hall et al., 1979). It should not be inferred that sorghum can absolutely resist drought conditions. Sorghum may in fact suffer serious loss of yield as a result of a water deficit, through its effect on individual components (Blum, 1972), during floral initiation (Doggett, 1970) and flowering (Klages, 1961; Andrews, 1976; Leakey and Wills, 1977). Kowal and Andrews (1973) recognizing those generalizations added that after flowering the water requirements of sorghum decline sharply and the plant can endure progressively higher moisture deficits. Irvine (1969) also mentioned that the crop likes hot dry weather during the ripening of the grain.

Considering temperature, Skerman (1956), from experience in Queensland, found that three hot days of maximum temperature exceeding 37.7°C within the flowering or the first month of growing would have adverse effects on grain sorghum crops. Another experience of Downes (1972) in the U.S.A. showed that high temperature between germination and initiation resulted in low grain yield of sorghum. Thompson (1963) from his study of sorghum in the U.S.A. concluded that higher than average temperature early in the season appeared to be detrimental to sorghum, while on the other hand the crop appeared to be generally favoured by higher-than average temperature late in the season. The effect of temperature is also apparent through the role it plays in the rate of transpiration (Curtis, 1966) which might lead to plant stress (Pasternak and Wilson, 1969) and because sorghum is most susceptible to drought before or at head emergence (Kowal and Andrews, 1973).

From this generalization, a more detailed examination of the nature of the correlation between climatic variables and sorghum yield in each region or locality is discussed in the following section.

8.2 Correlations between climate and sorghum yield

The study in this section is concentrated on correlation results for the data series of sorghum yield and the main climatic variable (rainfall, temperature, relative humidity, evaporation and radiation). This study which follows the order described in the previous section, concentrates on bivariate correlations. The multiple correlations will be discussed later together with multiple regression.

8.2.1 Regional studies

From the study period 1961-1970 selected here, 26 cases for the irrigated area and 27 cases for the rainfed area were obtained. The selection of this period is based on the fact that it covered best both climatic and sorghum yield data.

This restriction is believed to reduce the time effect on the climate-crop relationship as well as standardizing the period of study for the regions of study, giving better opportunity for comparison.

<u>Irrigated area : Wad Medani - Dueim - Kosti</u>

The treatment of these three areas of the Gezira and White Nile as one, as mentioned in section 7.2.2, is justified by the similarity of the methods of agriculture, besides which there is no great climatic contrast betweeen these areas. Although the study of the localities of this area may provide different results, the idea behind such regionalization is the attainment of some generalization, and the inspection of trends in relationships.

From Tables 8.1, 8.8 and 8.9 it can be said that the sample of data for this area reflected no significant relationships between rainfall and sorghum yield. The monthly rainfall totals and sorghum yield correlation coefficients were very low and never reached 0.3. The pentad rainfall totals reflected erratic results with negative signs at times and the correlation at best was 0.36 which failed to reach the significance level $\alpha = 0.05$. However, the annual, July - to - September and the pre-July rainfall totals reflected better results than the individual month's totals was 0.42, for July - to - September was 0.37, and for the pre-July total was 0.31 (only the $r = 0.42$ is significant at $\alpha = 0.05$). The weak relationship here may be related to the only partial dependency of the crop on rain as it is grown in the irrigated area.

Table 8.1 Correlations between climatic variables and sorghum yield (kg/fd) for Wad Medani - Dueim - Kosti area

	Rainfall (mm)	Average temperature (°C)	Temperature > 35°C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation (mm)
July	0.18	-0.28	-0.32	-0.29	-0.21	0.19	-0.33
August	0.22	-0.39*	-0.34	-0.43*	-0.17	0.42*	-0.54**
September	0.12	-0.23	-0.17	-0.10	-0.31	0.21	-0.29
October	-0.21	-0.05	0.22	-0.08	-0.14	0.29	-0.15
November	-	o.32	o.14	0.27	0.22	0.45*	-0.55**
December	-	0.10	-0.19	-0.24	0.28	0.23	-0.53**
Year	0.42*	-0.06	-	-0.25	0.08	0.34	-

N = 26

* significant at $\alpha = 0.05$

** significant at $\alpha = 0.01$

There is a general negative correlation between temperature and sorghum yield. This was particularly significant in August average and maximum temperatures with coefficients of -o.39 and -0.43 respectively (both significant at $\alpha = 0.05$). In this region which is characterized by high temperatures and dry conditions, excessive heat may be harmful to the plant especially in its floral initiation period (August) by reducing moisture which is crucial at this stage. During this period most of the field crops in the Gezira scheme are established and the demands of water are high in several fields. The priority is given to cotton and there is no guarantee of ample rainfall watering. As mentioned in section 8.1, Skerman (1956) and Downes (1972) maintain that high temperatures at this stage have adverse effects on sorghum. There is no evidence of relationships between the pre-growing season temperature (April, May, June) and sorghum yield (see Table 8.8). At the ripening stage (November) the relationship, though weak, tends to be positive especially between the average temperature and sorghum ($r = 0.32$; below significance level $\alpha = 0.05$). These findings may have support from Thompson's (1963) findings in the U.S.A., mentioned in Section 8.1, that higher temperatures are detrimental early in the growing season and favoured late in the season.

The monthly values of relative humidity and evaporation opposed each other in their relationships with sorghum yield throughout the growing season. Relative humidity always reflected positive correlations while evaporation always reflected negative ones. The need of the plant for humidity and its suffering from very dry conditions reflected these results.

The highest correlation between relative humidity and sorghum yield were obtained at August (r = 0.42) and November (r = 0.45) and both are significant at α = 0.05. The same months, August and November, showed the strongest negative correlations between evaporation and sorghum yield with coefficients values of -0.54 and -0.55 respectively. In December, late crops ripening and harvest month, evaporation showed a relatively strong negative correlation (r = -0.53). These evaporation correlation coefficients are significant at α = 0.01. These results suggest that the increase of evaporation may cause dessication of the plants especially if coincident with shortage of watering.

This area generally showed the highest relationships of sorghum with evaporation followed by those with average and maximum temperatures (negative) and the least with those of rainfall. However, this order does not enforce the order of importance so long as the climate-crop yield relationships are complicated. This is particularly true in the case of the rainfall-crop yield relationship which is presumably affected by irrigation applications in this area.

Rainfed area : Gedaref - Abu Naama - Kadugli

This elongated area includes centres nearest to the southern boundary of the study area (see Fig. 6.10). Rainfall here is twice as much as that received in the previous area (641 mm p.a.), and it is three times as much as that in the pre-July period (143 mm) with lower evaporation averages throughout the season. Because of these wetter conditions this area came to be famous for growing sorghum which according to its nature, proved to grow successfully in short rainy seasons.

The correlations obtained between rainfall and sorghum yield only became noticeable in August (r = 0.37), followed by July - to - September total (r = 0.35), but none of the rainfall variables in the sample is significant at α = 0.05 (Tables 8.2, 8.9). As can be seen from Table 8.8, the pre-July rainfall showed negative relationships with the yield (r = -0.29), which may be related to water-logging, weeds, and sowing delay. The reason for these low relationships can be related to the fact that rainfall is reliable for the crop growing. Added to that these relationships might have been obscured by other factors (climatic, physical or cultural) as well as the plant adaptability factor.

There were general negative correlations between temperature throughout the growing season and sorghum yield (see Table 8.2). Although temperatures in this region are lower than those in the irrigated area previously described, they showed stronger negative correlations. This seems to be because moisture in the soil, and humidity, are desperately needed in this rainfed area, and temperature is a very important factor in the removal of moisture from the plant and the soil. The highest correlation coefficients are -0.65, -0.63 and -0.53, for September average and minimum and Jult - to - September >35° C temperatures (all significant at α = 0.01). The highest negative correlations in September hint at the bad effect of temperature on the crop as it reaches its highest vegetative stage which coincides

Table 8.2 Correlations between climatic variables and sorghum yield (kg/fd) for Gedaref - Abu Naama - Kadugli area

	Rainfall (mm)	Average temperature (°C)	Temperature >35 °C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humitity (%)	Evaporation (mm)
July	0.04	-0.21	-0.29	-0.33	0.22	0.31	-0.17
August	0.37	-0.41*	-0.35	-0.42*	-0.04	0.57**	-0.41*
September	0.25	-0.63**	-0.48*	-0.65**	-0.40*	0.72**	-0.57**
October	0.04	-0.26	-0.24	-0.13	-0.48*	0.24	-0.38*
November	-	-0.30	-0.17	-0.16	-0.35	-0.17	-0.16
December	-	-0.10	0.12	0.02	-0.16	-0.20	0.05
Year	0.11	-0.26	-	-0.32	-0.12	0.33	-

N = 27

* significant at $\alpha = 0.05$

** significant at $\alpha = 0.01$

with the recession of rainfall. From a study of sorghum in Nigeria, Curtis (1968) reached a similar conclusion, noting the adverse effect of temperature at the time when water in the soil begins to decrease.

There were strong correlations between relative humidity and sorghum yield in September, July - to - September and August with coefficients of 0.72, 0.6 and 0.57 respectively (all significant at $\alpha = 0.01$). Towards the end of the season, November, this relationship became of no significance in this area. Evaporation, as expected, had the opposite effect on sorghum from that of relative humidity. It showed negative correlations especially in September ($r = 0.57$, significant at $\alpha = 0.01$). August and October also showed significant negative correlations with coefficients -0.41, -0.38 respectively (both significant at $\alpha = 0.05$). It is noted that towards the end of the growing season, November, the relationship between evaporation and sorghum yield also ceased to be of any significance.

It can be suggested that the availability of moisture for the use of the crop from the soil or directly from its environment reflected the described patterns of relationships in this study. Rainfall and humidity reflected positive relationships while temperature and evaporation reflected negative ones. This was particularly true during the period prior to maturity. In general, the results obtained from the study of this area matched the sorghum characteristics described in 8.1 which were also shown in the irrigated area. The correlations in this rainfed area were stronger and hence closer to the generalizations made about sorghum.

From this regional study a closer look at the local areas will be taken in the following section. The reason for the consideration of small areas were discussed in sections 7.2.1 and 8.1. Those reasons stressed the differences in climatic, physical and cultural factors between different localities. They suggested the necessity of such local studies.

8.2.2 Local studies

Five centres of sorghum production are used in this study. These are : Kosti, Gedaref, Singa, Abu Naama and Aroma (Fig. 6.10), amongst which sorghum is grown in several different environments. It is totally dependent on rainfall at Singa, Abu Naama and Gedaref, while it is dependent on flood and rain supply at Aroma and on irrigation in Kosti.

Kosti

This area is an irrigated one, yet rainfall is considered as a complementary factor in watering sorghum, as the priority of irrigation in this area is given to other crops, particularly cotton. This area receives a mean annual rainfall of 396 mm. From here and depending on data obtained for 15 years (1960-1974) for which correlation coefficients are shown in Tables 8.3, 8.8 and 8.9, it can be seen that the pre-sowing rain total (June) had a noticeable positive correlation ($r = 0.5$). The August total also had a noticeable positive relationship ($r = 0.49$). The correlation coefficient became significant only in pentad 9 (10-14 August) with a

Table 8.3 Correlations between climatic variables and sorghum yield (kg/fd) for Kosti

	Rainfall (mm)	Average temperature (^{o}C)	Temperature > 35^{o}C (No. days)	Max. temperature (^{o}C)	Min. temperature (^{o}C)	Relative humidity (%)	Evaporation (mm)
July	-0.20	-0.14	0.08	-0.08	-0.23	-0.01	0.09
August	0.49	-0.18	-0.21	-0.20	-0.09	-0.17	-0.22
September	-0.17	-0.06	-0.02	-0.06	-0.02	-0.08	-0.11
October	-0.23	-0.11	0.02	-0.09	-0.10	-0.42	0.19
November	-	0.29	-0.02	0.13	0.40	-0.41	0.32
December	-	-0.02	-0.23	-0.14	0.24	-0.57*	0.71**
Year	0.33	-0.23	-	-0.40	-0.01	-0.01	-0.09

N = 15

* significant at $\alpha = 0.05$

** significant at $\alpha = 0.01$

value of 0.51 (significant at $\alpha = 0.05$). The rest of the rainy months showed negative, though insignificant, correlations with yield. The negative correlations seem partly because of the danger of waterlogging, flooding, weeds and the encouragement of pests and diseases, and partly because the crop in its later stages of growth, as mentioned earlier, prefers drier conditions. This can be looked at in the light of the fact that in these irrigated areas, water supply is almost certain for the plant.

Temperature showed generally weak correlations with sorghum yield except in November where the minimum temperature in particular showed positive correlation ($r = 0.4$). Relative humidity was of no noticeable correlation with yield in the early months of the season, but it tended to have stronger negative values towards the end of the season, reaching -0.57 in December (significant at $\alpha = 0.05$). This and evaporation behaviour with yield confirm the crop's preference for dry conditions at the end of the season. December evaporation had a coefficient of 0.71 (significant at $\alpha = 0.01$) whereas evaporation in earlier stages showed insignificant relationships.

Gedaref

In this rainfed area with a mean annual rainfall of about 579 mm, sorghum is grown as a very important crop for the purpose of supplying other parts of the country. There a data set of 17 cases, and from Tables 8.4 and 8.8, some generalizations about the climate-sorghum relationships can

Table 8.4 Correlations between climatic variables and sorghum yield (kg/fd) for Gedaref

	Rainfall (mm)	Average temperature (°C)	Temperature >35°C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation (mm)
July	0.30	-0.07	0.00	-0.12	0.11	0.25	0.04
August	-0.10	-0.12	-0.03	-0.14	-0.03	0.19	-0.29
September	-0.20	-0.01	-0.17	-0.03	0.06	0.10	-0.23
October	0.65**	-0.15	-0.23	-0.19	-0.37	0.38	-0.19
November	-	-0.42	-0.41	-0.38	-0.40	0.23	-0.05
December	-	0.04	-0.04	-0.02	0.08	0.22	0.14
Year	0.03	-0.09	-	-0.09	-0.07	0.33	-

N = 17

** significant at $\alpha = 0.01$

be made. Considering rainfall it is noted that except in October a weak or zero relationship with sorghum was obtained. A strong positive correlation was shown in October ($r = 0.65$, significant at $\alpha = 0.01$). The reliability of rainfall and the presumed availability of soil moisture early in the season, and the increasing need for water especially for the late-grown sorghum, seems to have affected these relationships. The distribution of rainfall within shorter periods of the month (pentad totals) hinted at differences in the crop reactions through these periods. It can be seen from Table 8.9 that there was a tendency of the crop to prefer rainfall towards the end of July and the correlation coefficient of pentad 6 (26-30 July) reached 0.45. At this time of the season the plant is almost out of the danger of inundation. For pentad 15 (9-13 September) a negative correlation between rainfall and sorghum is shown ($r = -0.45$). This negative association at the flowering period may be related to the suggestion of Balasubramanian (1959), noted by Ali (1974), that heavy rains during flowering may wash the pollen away, or make the stigma less receptive and thus interfere with grain setting.

In relation to the other climatic variables correlations with sorghum yield, negative values with temperature and evaporation, and positive weak correlations with relative humidity were obtained (see Tables 8.4, 8.9). None of the coefficients in this context were significant at $\alpha = 0.05$, but November temperature-yield correlation coefficient was 0.41.

Singa

Sorghum in this area is totally dependent on rainfall, where about 582 mm is annually received. As in many other places, no long, reliable record is available and only 15 years data is considered for correlation study. The failure of rain in a particular year means the failure of the crops but it must not be inferred that direct linear strong correlations are always obtained. The reason for this has been previously discussed (section 8.1).

As can be seen from Tables 8.5 and 8.8, rainfall-sorghum relationships were generally weak. They were only noticeably positive in July ($r = 0.5$) which is just below significant at $\alpha = 0.05$. The pre-July rainfall showed negative correlations ($r = -0.44$) and the monthly rainfall totals of the growing season showed no relationships. It can also be observed from Table 8.9 that noticeable negative correlations occurred between yield and pentad 16 (14-18 September) with a coefficient of -0.42. The suggested reason for negative relationships at the flowering stage was discussed earlier in this section. The reason for the negative association between sorghum yield and the pre-July rainfall, according to Ali's (1974) study at the Sudan Kenana Research Station, may be that high rainfall during this period may cause waterlogging (with a consequent delay in sowing) and may affect germination. Kassam and Andrews (1975) in a study of sorghum in Northern Nigeria found that grain yield decreased with delay in sowing.

Temperature in this area showed the strongest correlations with sorghum yield (see Tables 8.5 and 8.8). Rises

Table 8.5 Correlations between climatic variables and sorghum yield (kg/fd) for Singa

	Rainfall (mm)	Average temperature (°C)	Temperature >35°C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation (mm)
July	0.50	0.03	-0.19	-0.10	0.18	-0.34	-0.10
August	-0.12	-0.40	-0.59*	-0.62*	0.20	0.29	-0.40
September	-0.08	-0.14	-0.20	-0.21	0.47	-0.16	-0.14
October	-0.05	-0.01	0.17	-0.13	0.18	-0.22	-0.05
November	-	0.43	0.25	0.26	0.41	-0.11	-0.26
December	-	0.00	-0.18	-0.09	0.15	-0.34	-0.04
Year	-0.29	0.47	-	0.10	0.50	-0.36	-

N = 15
* significant at $\alpha = 0.05$

in temperature tended to be favourable in the pre-sowing period, especially in June where the minimum and average temperature showed coefficient values of 0.79 and 0.68 respectively (both significant at α = 0.01). A rise in temperature is thought to be harmful in the early and mid growing season. A strong negative correlation between August maximum temperature and sorghum yield is seen (r = -0.62, significant at α = 0.05). Towards the end of the season (November), the temperature-yield relationship, though weak, was positive (r = 0.43). Relative humidity and evaporation displayed generally weak relationships with sorghum yield.

Abu Naama

For the 14 cases obtained for this area, which has a mean annual rainfall of 574 mm and where sorghum is grown as a rainfed crop, correlations are reproduced between the crop yield and the different climatic variables in Tables 8.6, 8.8 and 8.9. Although this area is not far from Singa (see Fig. 6.10), it showed in many instances different results.

August was shown to be the most important month in terms of moisture-sorghum relationships; a relatively high positive correlation was obtained for rainfall (r = 0.55; significant at α = 0.05). Ali (1974) from his six years study of the effect of rainfall on sorghum yield at Kenana Research Station, not far from this study area, found similar results particularly in August. In this particular month he obtained correlations for different rotations with coefficients ranging between 0.34 and 0.64. The remaining months in Ali's study showed similar trends of relationships but the coefficients obtained there were in most cases higher than in Table 8.6. Considering the relationships between pentad rainfall totals and sorghum yield, Table 8.9 showed some pentads with noticeable correlations (positive or negative). The strongest correlation was between pentad 16 (14-18 September) and yield ($r = -0.55$).

Radiation, temperature and evaporation were always negatively correlated with sorghum yield, in this area, while relative humidity was always positively correlated throughout the growing season. Solar radiation acting directly on the plant and indirectly through temperature in this rainfed area tends to help to create dry conditions which might lead to plant dessication. October radiation and relative humidity had correlations with yield of -0.6 and 0.54 respectively (both significant at $\alpha = 0.05$). Although December lies on the edge of the growing season, yet the late grown sorghum might reach that month. However, December minimum temperature and evaporation, when correlated with yield, resulted in strong negative correlations of -0.69 and -0.55 respectively (the first significant at $\alpha = 0.01$ and the second at $\alpha = 0.05$).

Aroma

This area, though having the lowest rainfall (277 mm p.a.), enjoys flood irrigation as it lies in the delta of the seasonal River Gash. Correlations were based on 15 cases data size. From Tables 8.7 and 8.8 it can be seen that positive correlations between the seasons' total rainfall and sorghum yield were obtained. As in the Abu Naama area,

Table 8.6 Correlations between climatic variables and sorghum yield (kg/fd) for Abu Naama

	Rainfall (mm)	Average temperature (°C)	Temperature >35°C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation (mm)	Radiation cal./cm²
July	-0.20	-0.05	-0.19	-0.13	0.06	0.16	-0.20	-0.34
August	0.55*	-0.30	-0.35	-0.36	0.09	0.50	-0.60*	-0.39
September	0.21	-0.13	-0.03	-0.10	-0.05	0.33	-0.34	-0.49
October	-0.11	-0.28	-0.36	-0.24	-0.13	0.54*	-0.26	-0.60*
November	-	-0.08	-0.10	0.10	-0.38	0.03	-0.27	-0.51
December	-	-0.44	-0.32	-0.34	-0.69**	0.27	-0.55*	-0.46
Year	-0.03	-0.24	-	-0.10	-0.31	-0.09	-	-

N = 14
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

Table 8.7 Correlations between climatic variables and sorghum yield (kg/fd) for Aroma

	Rainfall (mm)	Average temperature (°C)	Temperature >35°C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation (mm)
July	0.19	-0.54*	-0.29	-0.44	-0.05	0.42	-0.29
August	0.75**	-0.48	-0.53*	-0.53*	-0.29	0.58*	-0.44
September	0.01	-0.01	0.14	-0.13	-0.12	0.46	-0.08
October	-0.28	0.10	-0.02	0.17	-0.03	0.27	-0.39
November	-	0.11	-0.27	0.16	0.05	0.49	-0.43
December	-	0.05	0.01	0.09	0.00	0.50	-0.25
Year	0.43	-0.09	-	-0.05	-0.16	0.58*	-

N = 15
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

Table 8.8 Correlations between pre-growing and growing period climatic variables and sorghum yield (kg/fd)

Climatic Variables		Wad Medani - Dueim - Kosti	Gedaref - Abu Naama - Kaduglo	Kosti	Gedaref	Singa	Abu Naama	Aroma
Rainfall	June	0.30	-0.26	0.50	-0.24	-0.36	0.03	-0.19
	Pre-July	0.32	-0.29	0.46	-0.23	-0.44	-0.06	-0.28
	Jul. + Aug.	0.31	0.28	0.36	0.14	0.18	0.11	0.64**
	Sept.+ Oct.	0.02	0.21	-0.24	0.07	-0.10	0.16	-0.07
	Jul.to Sept.	0.37	0.35	0.26	0.01	0.09	0.26	0.54*
Average temperature ^{o}C	June	-0.21	0.11	-0.36	0.42	0.68**	0.11	0.04
	Jul.to Sept.	-0.35	-0.46*	-0.16	-0.06	-0.31	-0.10	-0.39
Temperature > $35^{o}C$(No. days)	Jul.to Sept.	-0.36	-0.53**	-0.04	0.11	-0.40	-0.23	-0.06
Max. temperature ^{o}C	April	0.15	0.07	-0.31	0.08	0.23	0.02	-0.23
	May	0.22	0.05	0.11	0.07	0.24	0.43	0.36
		-0.23	-0.02	-0.44	0.38	0.48	0.32	-0.02
Min. temperature C	April	-0.20	-0.06	-0.41	0.03	0.31	-0.22	-0.42
	May	-0.10	0.08	0.09	-0.19	0.47	0.01	-0.63*
	June	-0.20	0.31	-0.19	0.43	0.79**	0.40	0.09
Relative humidity %	May	0.05	-0.21	0.00	0.19	-0.19	-0.18	-0.28
	June	0.08	-0.09	0.25	-0.12	-0.36	-0.24	0.37
	Jul.to Sept.	0.33	0.60**	0.03	0.24	-0.12	0.36	0.57*
No.of cases		26	27	15	17	15	14	15

* significant at $\alpha = 0.05$

** significant at $\alpha = 0.01$

August was the most important month in terms of rainfall-sorghum relationships. A strong correlation coefficient of 0.75 between August rainfall and yield was obtained. Table 8.9 shows an even stronger relationship (r = 0.89) for pentad 11 (20-24 August). The following pentad (11) also showed a significant correlation (r = 0.55, significant at α = 0.05). Relative humidity behaved in a like manner to rainfall. It showed a general positive correlation especially for August and the annual average with coefficients of 0.58 each (significant at α = 0.05). Temperature relationships with yield were only significant in May and early in the growing season. May minimum, July average and August maximum temperatures showed negative correlations with coefficients of -0.63, -0.54 and -0.53 respectively (all significant at α = 0.05). Although evaporation had negative relationships with yield throughout the growing season, it failed to reach significance at α = 0.05. The highest correlation coefficient was shown in August (r = 0.44).

As a summary to the correlations it can be said that rainfall had positive correlations with yields early in the season, and neutral or negative ones towards the end of the season. Strong relationships between rainfall in August at Aroma, Abu Naama and Kosti matched those statements in section 8.1, remembering that August is the period just preceding flowering and in that particular month considerable amounts of water are added to the soil moisture total. Singa showed this relationship in July, a month earlier in the growing season. Gedaref is the only area showing a strong correlation at a later period : October. Other reasons, of

Table 8.9 Correlations between pentad rainfall (mm) and sorghum yield (kg/fd)(1)

Pentad No.	Pentad Calendar	Wad Medani-Dueim-Kosti	Gedaref - Abu Naama - Kadugli	Kosti	Gedaref	Singa	Abu Naama	Aroma
1	1-5 July	-0.07	-0.30	-0.34	-0.13	-0.03	0.00	-0.22
2	6-10	0.01	0.17	-0.04	0.25	0.25	0.06	-0.21
3	11-15	0.14	0.14	-0.07	0.12	0.32	0.06	0.22
4	16-20	0.21	0.07	0.19	-0.16	0.20	-0.05	-0.18
5	21-25	0.07	0.13	0.08	0.25	0.11	0.08	-0.20
6	26-30	0.32	0.07	0.07	0.45	0.17	0.01	0.38
7	31 Jul-4 Aug.	0.05	-0.02	0.37	-0.29	-0.08	0.29	0.26
8	5-9	0.27	0.17	0.41	0.10	-0.14	0.09	0.17
9	10-14	0.28	0.13	0.51*	0.19	0.16	-0.17	0.01
10	15-19	-0.01	0.07	0.22	0.22	-0.08	-0.30	-0.02
11	20-24	0.01	0.14	-0.04	0.14	-0.12	0.21	0.89**
12	25-29	-0.20	0.25	-0.21	-0.14	0.30	0.52	0.55*
13	30 Aug-3 Sep.	0.36	0.09	0.44	0.22	0.13	-0.15	0.04
14	4-8	-0.28	0.06	-0.41	-0.15	0.04	-0.04	-0.18
15	9-13	0.05	0.24	-0.41	-0.45	-0.08	0.44	-0.02
16	14-18	-0.04	0.17	-0.10	0.11	-0.42	-0.55*	0.05
17	19-23	0.15	0.00	0.27	-0.24	-0.37	-0.32	-0.26
18	24-28	0.26	0.33	0.22	0.08	0.36	0.32	0.22
19	29 Sept-3 Oct.	-0.12	0.01	-0.19	0.19	0.08	0.21	-0.04
No. of cases		26	27	15	17	15	14	15

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

(1) The numbering of pentads here is different from the conventional system.

which probably the different starting dates of the growing season or the different characteristics of varieties, such as earliness of heading in relation to rainfall recession, might have their effect.

It is noted that evaporation generally had a negative correlation with crop yields, except in Kosti (irrigated) toward the end of the season. Relative humidity had negative correlations with sorghum yields in Kosti and Singa, and positive in the rest of the centres.

Temperature also showed some general trends in relation to yield. Average and maximum temperatures showed general negative correlations except in November while minimum temperature showed weak or no relations throughout the season. This contradicted what was maintained by William et al. (1977), from the study in Kimberley of Australia that minimum temperature is important in the later part of the crop development. Towards the end of the season (i.e. maturity stage), the adverse effect of temperature is reduced and even a general positive correlation of November maximum temperature with sorghum yield was obtained.

This correlation study is followed by a study of the effect of rainfall on sorghum yield in shorter periods of the growing season, using the Fisher method.

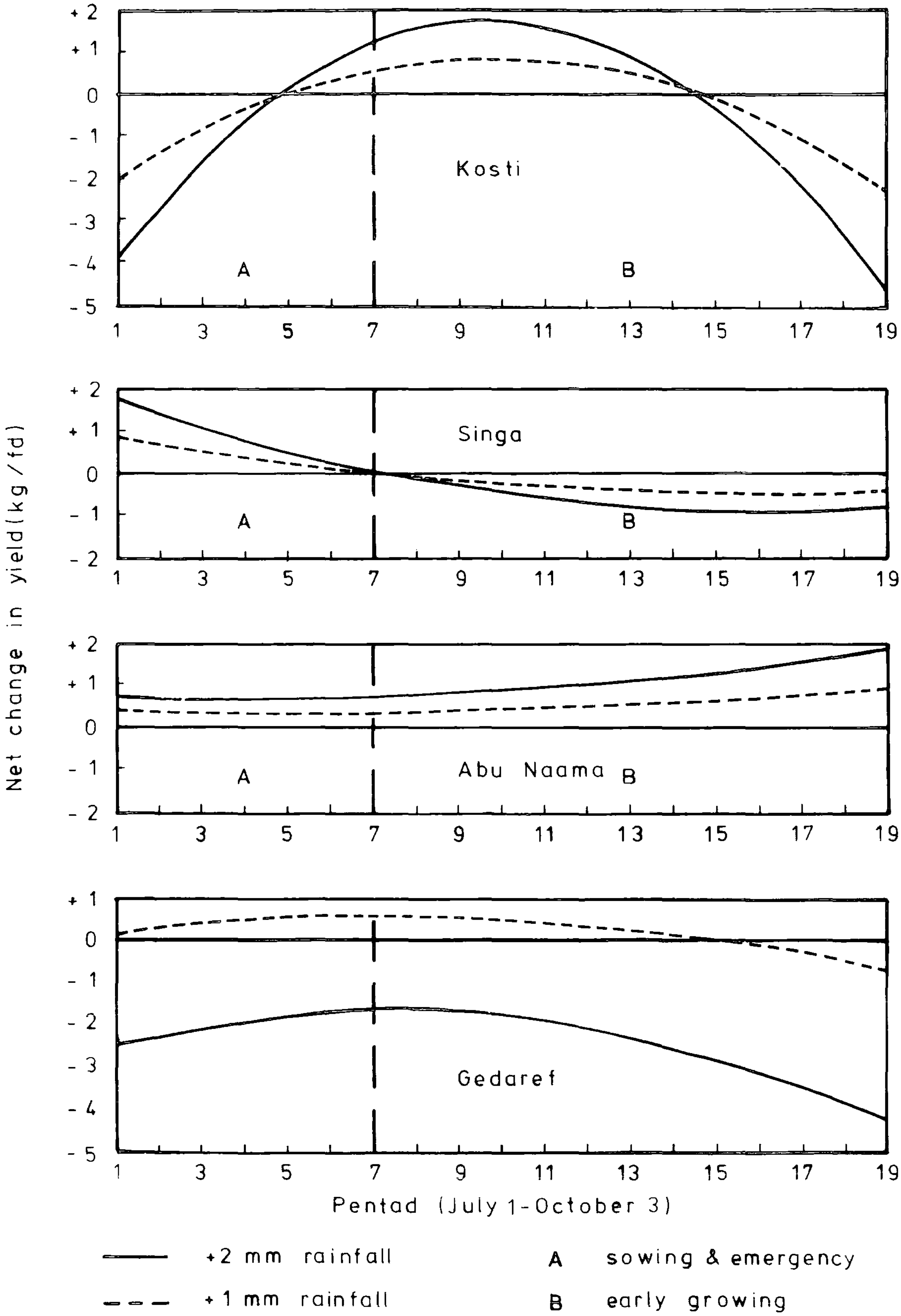
8.3 Effect of pentad rainfall changes on sorghum yield

The Fisher's (1924) model which was described in section 6.3.3 and applied to cotton in section 7.3 is also used here. The effects of increases in rainfall (1 or 2 mm) above the average pentad rainfall were tested at 4 stations : Kosti, Gedaref, Singa and Abu Naama.

In the Kosti area, as can be seen from Figure 8.1, the increase of rainfall by 1 or 2 mm above the pentad average tends to behave in such a way that the effect of a 2 mm increase is an exaggeration of the effect of a 1 mm increase. The increase of rainfall is harmful at the beginning of the growing season resulting in a decrease of about 4 kg/fd if the rainfall is increased by 2 mm. This bad influence is reduced with the progress of the season and the increase of yield occurs from the fifth pentad (late July) reaching a value of +1.7 kg/fd and then declines till it again has a negative effect after pentad 14 (early September). The bad influence is deepened towards the end of the study period and pentad 19 (end of September) showed that a decrease of 4.5 kg/fd is likely to happen with the increase of 2 mm rainfall above the average. The results shown here shows some agreement with the trends of correlations of rainfall with yield and with the assumptions provided there, in relation to the crop development.

In the Gedaref area (Fig. 8.1) the increase of 2 mm above the average pentad rainfall is always harmful and it suggests a decrease in sorghum yield by 4.2 kg/fd at the end of September. A slight increase of rainfall (i.e. 1 mm)

Fig. 8.1 EFFECT OF 1 AND 2MM ABOVE AVERAGE PENTAD RAINFALL ON SORGHUM YIELDS IN 4 AREAS



Pentad calendar is shown in Table 8.9

is slightly useful for the crop in July and August and slightly harmful in September resulting in -0.6 kg/fd by the end of the period.

From Figure 8.1, it can be observed that at Singa the rise of rainfall over the average is shown to be preferable at the start of the period (early July) and harmful towards the end of the period, and the change is relatively larger at the beginning. The increase of 2 mm above the average pentad rainfall is observed to result in an increase of yield by 1.8 kg/fd. This increase diminishes with the progress of the season and at pentad 8 (early August) it tends to have a harmful influence which reaches about -0.8 kg/fd in pentad 19 (end of September).

At Abu Naama (Fig. 8.1) the pattern of change is rather simple. The increase of pentad rainfall is always preferable. It is noted that the scale of change was rather small, especially at the beginning of the period where an increase of 2 mm implies an increase of yield of only 0.7 kg/fd. Towards the end of the period this increase suggests a 1.9 kg/fd increase in sorghum yield.

The value of Fisher's model is that it shows the gradual net effect of rainfall through short periods. This gradual change is assumed to be more likely to happen than abrupt erratic change, especially when considering the crop-weather interaction. Using the curves provided for each area the planner of agriculture can judge the effect of rainfall at any stage of the crop development and can adjust his plans of management accordingly.

After this step of weather-sorghum yield evaluation, a step further is taken in the following section to deal with the multiple correlations and multiple regression analysis.

8.4 Regression analysis and sorghum yield estimation

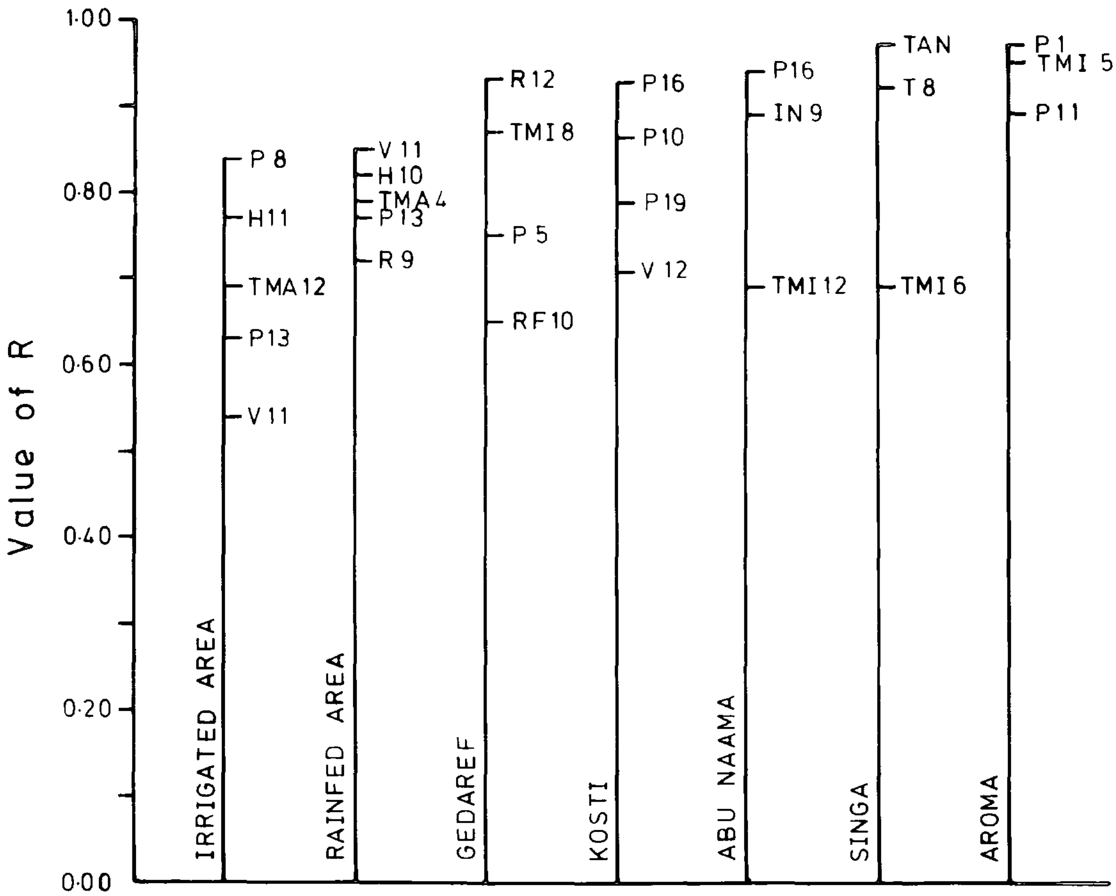
8.4.1 Regression analysis

The discussion provided in this section concentrates on the results of the stepwise regression made for sorghum yield. The same regions and localities, for the same period (1960-1978) studied in sections 8.2.1 and 8.2.2, are studied here. The coefficients of multiple correlation are discussed showing the total value contributed by variables at each step, considering between 3 and 5 variables in the different areas. The advantages and the shortcomings of the regression method are discussed in sections 5.2.3 and 6.3.3. This study will be followed by a discussion of the results of sorghum yield estimations obtained by applying the multiple regression formulae.

Irrigated area : Wad Medani - Dueim - Kosti

In the data sample studied in this area, the most important variable in the multiple regression (Fig.8.2) is November evaporation ($r = 0.55$), which was taken as the first contributor to the coefficient of multiple correlation. The second step identified pentad 13 total rainfall as the second most influential variable affecting sorghum yield. At this step the coefficient is raised to 0.63. The third variable identified was December maximum temperature which was still unable to cause the coefficient of the multiple

Fig. 8.2 COEFFICIENTS OF MULTIPLE CORRELATIONS FOR SORGHUM CROP IN DIFFERENT AREAS



For the interpretation of symbols see Table 8.10

correlation to reach 0.7 steps 4 and 5, which included October number of days with temperature >35°C, and pentad 5 total rainfall, raised the coefficient to 0.77, then to 0.84. November evaporation and December maximum temperature showed a negative influence on sorghum yield and the remaining variables showed a positive influence (Table 8.11). As mentioned in section 6.3.3 the stepwise regression identifies the controlling variables on the bases of partial correlations and after the first step the variables are not necessarily ordered according to the value of coefficients they obtain in bivariate correlations.

The low coefficient ($R = 0.84$, $R^2 = 0.71$) resulting from the five variables included in the regression process suggests a low efficiency of the model applied to this region in estimating sorghum yield. This can be seen from Table 8.10, where the standard error obtained was 212, which is equivalent to 40% of the average yield (530 kg/fd). This result, as will be seen later, is the worst amongst those obtained in the areas studied here.

Rainfed area : Gedaref - Abu Naama - Kadugli

In this area, as can be seen from Figure 8.2, the most important climatic variable in the multiple regression of sorghum yield was September relative humidity ($r = 0.72$). The remaining 4 variables together could only raise the coefficient of the multiple correlation to a value of 0.86 ($R^2 = 0.74$). Those variables, as they come in order of importance, were pentad 13, April maximum temperature, October number of days with temperature >35°C, and November

Table 8.10 Regression analysis of sorghum yield

Area	No.of Cases	Average yield kg/fd	R	R^2	S.E.
Wad Medani-Dueim-Kosti	26	530	0.84	0.71	212
Gedaref-Abu Naama-Kadugli	27	353	0.86	0.74	52
Kosti	15	598	0.93	0.86	147
Gedaref	17	292	0.93	0.86	47
Singa	15	338	0.97	0.94	31
Abu Naama	14	351	0.94	0.88	45
Aroma	15	503	0.97	0.94	70

Table 8.11 Regression formulae for estimation of sorghum yield (kg/fd)

1. Wad Medani - Dueim - Kosti

$$y = 5133.762-99.40792V11+4.60259P13-132TMA12 +27.06129H10+5.55696P8$$

2. Gedaref - Abu Naama - Kadugli

$$y = 313.6321+20.83902R0-1.542529P13-13.32427TMA4 +7.00922H10-15.23573V11$$

3. Kosti

$$y = -4186.46+535.2368V12-142.3197P19+4.83972P10-7.00321P16$$

4. Gedaref

$$y = -3211.726+4.3293RF10+1.80596P5+145.8487TMI8+9.04559R12$$

5. Singa

$$y = -1490.014+39.16379TMI6-124.7454T8+149.6718TAn$$

6. Abu Naama

$$y = 2405.461-62.91277TMI12-1.937868IN9-2.2373P16$$

7. Aroma

$$y = 2973.372+11.32417P11-103.2552TMI5-10.21856P1$$

Symbols

RF10 = Oct.total rainfall (mm)
T8 = Av.Aug.temperature (^{o}C)
TMA4 = April Max.temp. (^{o}C)
TMA12= Dec. Max. temp. (^{o}C)
TMI5 = May min. temp. (^{o}C)
TMI6 = June "
TMI8 = August "
TMI12= December "
H10 = Oct.No. days with > 35 ^{o}C
TAn = Av.ann. temp. (^{o}C)
R9 = Sept.rel.humidity (%)
R12 = Dec. "
IN9 = Av.Sept.radiation cal/cm^2
P1 - Pentad 1 tot.rainfall(mm)

P5 = Pentad 5 tot.rainfall (mm)
P8 = Pentad 8 "
P10 = Pentad 10 "
P11 = Pentad 11 "
P13 = Pentad 13 "
P16 = Pentad 16 "
P19 = Pentad 19 "

V11 = Nov.Evaporation (mm)
V12 = Dec. "

* Pentad Calendar is shown in Table 8.9.

Table 8.12 Correlations between observed and estimated sorghum yields (kg/fd)

Area	Period			
	N	original	N	extended
Kosti	15	0.93	17	0.92
Gedaref	17	0.90	19	0.82
Singa	15	0.97	17	0.80
Abu Naama	14	0.93	-	-
Aroma	15	0.95	17	0.81

All significant at $\alpha = 0.01$

evaporation. The contributions of these variables were almost equal to each other. Table 8.10 shows that the September relative humidity and October temperature variables showed a positive correlation while the remaining 3 variables showed negative correlation.

Table 8.10 shows that the standard error obtained from the regression, 52, is only 15% of the average yield of sorghum (353 kg/fd). This result is far better than that obtained in the study of the irrigated area. However, this result is still not expected to give the best estimations of the sorghum yield in the area because the value of R^2 (0.74) is not very high.

Local areas

The results obtained at the local level were better than the results from the larger regions. None of the 5 localities obtained a coefficient of multiple correlation lower than 0.9. The number of climatic variables considered in each area study is 4 at most (see Fig.8.2 and Table 8.11).

At Kosti, in the first 4 variables idenfied by the multiple regression procedure, December evaporation was the most contributive one to the coefficient of multiple regression (r = 0.71). The remaining 3 variables were all of the pentad rainfall totals. Those, in the regression order, are of pentad 19, 10 and 16. Here, pentads 19 and 16 reflected a negative correlation and pentad 10 reflected a positive one (see Table 8.11). The inclusion of the pentad 19 rainfall variable raised the coefficient to 0.79, that of pentad 10 to 0.87 and that of pentad 16 to 0.93 (R^2 = 0.86).

It can be observed from Table 8.10 that the standard error, 147, is about 25% of the average yield (598 kg/fd). Although this value of the standard error is big if compared with those of the other localities, it is far better than that of the larger irrigated region (40%) that included Kosti.

Regressing sorghum yield on climatic variables at Gedaref showed October rainfall as the most important, out of 4 variables, to the coefficient of multiple correlation ($r = 0.65$). In the next step the total rainfall of pentad 5 was entered raising the coefficient to 0.75, followed by August minimum temperature raising it to 0.87. The final step (4), which included December relative humidity, shows a value of $R = 0.93$ ($R^2 = 0.86$). It can be observed from Figure 8.2 that although this locality showed the lowest coefficients of the different steps, compared with the other localities, it finished with a high coefficient ($R = 0.93$). From Table 8.10 it can be observed that good results were reflected in the low standard error, 47, which is only 16% of the average sorghum yield (292 kg/fd).

At Singa only 3 variables could result in R value of 0.97 ($R^2 = 0.88$). Those, as ordered in the stepwise regression, were June minimum temperature, August average temperature and mean annual temperature. The June minimum temperature contributed 0.79 to the coefficient of the multiple correlation, and the August average temperature raised it to 0.92. The result obtained was the highest amongst the areas studied here. It is noted that the 3 influential variables included concerned temperature. June and annual temperatures showed positive influences on sorghum while August temperature showed a negative one. The good result shown in this area (Table 8.10) was also reflected by the lowest standard error (31) amongst the areas studied, presented as only 9% of the average sorghum yield (338 kg/fd).

The regression of sorghum yield on climatic variables at Abu Naama showed December minimum temperature as the most important variable in the coefficient of multiple correlation ($r = 0.69$), followed by September average radiation. At this stage the value of R reached 0.89 (see Fig. 8.2). The third important variable was pentad 16 rainfall by which the R value of 0.94 ($R^2 = 0.88$) was reached. All the included variables at this stage had negative influence on sorghum yield in this area. The standard error, 45, is only 13% of the average yield (351 kg/fd).

The Aroma (flood irrigated) sorghum yield reflected remarkably strong positive relationship with August rainfall, particularly pentad 11 ($r = 0.89$). The stepwise regression, considering this in the first step, showed the May minimum temperature as the second most important variable in the second step. The value of R at this stage reached 0.94. At the third step pentad 1 was identified, to raise the value of R to 0.97 ($R^2 = 0.94$). This area showed a standard error value of 70 (Table 8.10), which is 14% of the average sorghum yield (503 kg/fd).

From the previous discussion it can be observed that each area in this study had its own set of significant variables. However, the generalization that can be made here is the temperature variables were commonly significant in all the rainfed area. At Kosti (irrigated) the effect of the temperature factor may be observed through the importance of evaporation. The strengths and the orders in the regression hierarchy varied between the areas (see Fig. 8.2). Rainfall was the main factor at Aroma and Gedaref and to a lesser extent at Kosti. At Singa and Abu Naama the regression hierarchy showed no rainfall variable. It must not be thought that rainfall is not important in those areas. As mentioned in section 6.3.3, the way in which the stepwise regression identifies the variables and the problem of collinearity may cause an important variable to be redundant.

Abu Naama showed radiation variables to be important, but since there are no radiation data for the other areas in the study, it cannot be said whether radiation variables would occupy important places in the coefficients of multiple correlation. It can generally be assumed from the temperature results (where radiation has a strong relationship) that radiation could possibly have had a noticeable relationship with yield, and it might have appeared within the steps of regressions considered in this study.

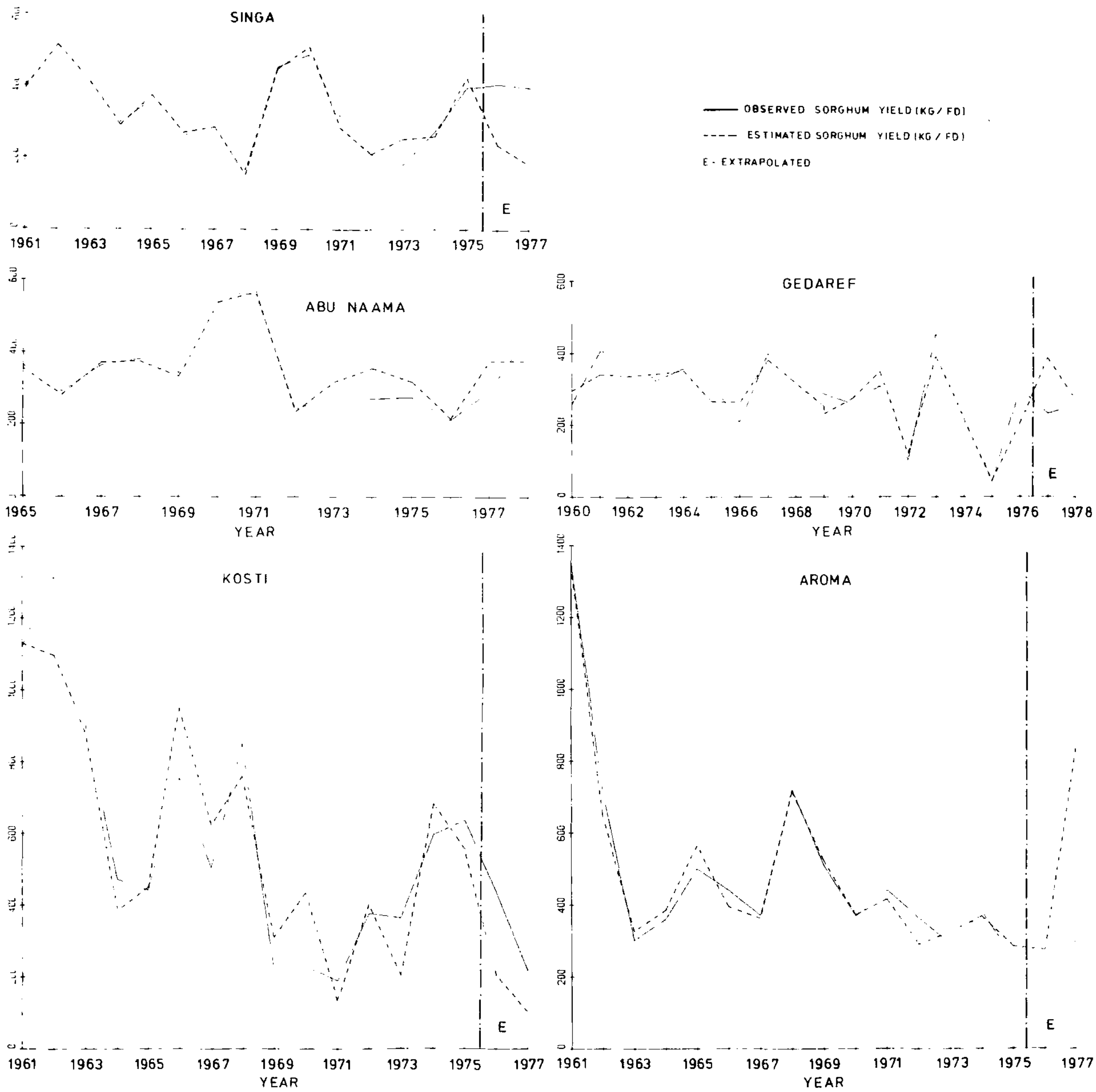
The stepwise regression procedure produces coefficients of regression formula at each step that can be used for estimations and predictions of the crop yields. Sorghum was treated in the same way as the cotton crop in section 7.4.2, and the discussion of the results is given in the following section.

8.4.2 Sorghum yield estimation

Table 8.11 shows the formulae derived from the regression procedure at the steps specified in section 8.4.1 to estimate sorghum yield from climatic variables in different areas. The estimations were made for the local study areas as they provided higher multiple correlation coefficients with stronger R^2 values. They were made for the same period as the original calculations or regressions and correlations. An extended period of two years in each area was used for prediction. Abu Naama was the only area where this extended period was not available because of the small size of its data set. Correlations between the observed and the estimated or predicted sorghum yields were made.

Considering the original period of the regression formulae (Table 8.12), close correlations between observed and estimated sorghum yields were obtained when the coefficient was never less than 0.9 at any time. At Kosti, the largest discrepancies between the observed and the estimated sorghum yield occurred in 1962 and 1970 with an underestimation of about 215 kg/fd and an overestimation of about 210 kg/fd for these years respectively. Compared with the other areas in the study Kosti showed the largest discrepancies throughout the original study period (see Fig. 8.3). Gedaref showed less discrepancy, with the largest as an underestimation of 65 kg/fd in 1960, followed by an overestimation of 55 kg/fd in 1968. The discrepancies at Singa were very small and it became considerable only in 1973 where an overestimation of 70 kg/fd occurred. At Abu Naama very good estimations were noticed in the first part of the

Fig. 8.3 OBSERVED AND ESTIMATED SORGHUM YIELDS FOR 5 AREAS



study period up to 1972, then the gap between the observed and the estimated figures became considerable. The largest difference was 85 kg/fd which occurred in 1974. Aroma showed the largest gap between the observed and predicted yield during the original period in 1972 with a value of 70 kg/fd.

In relation to the extended period, the best results were shown at Kosti where the observed and the estimated yields were close together, followed the same trend and the correlation coefficient obtained for the whole period dropped very slightly (r = 0.92). The rest of the stations when two years were added to the original period showed weaker correlations between observed and estimated sorghum yield with coefficients around 0.81 (see Table 8.12). It can be seen from Figure 8.3 that in the Gezira, and the Blue Nile Provinces, Kosti and Singa, there was an underestimation of the predicted yield. In Kassala province, Gedaref and Aroma, there was an overestimation. At Kosti, recession of yield was predicted which was found to be true for the observed yield. There is however, an exaggeration in the prediction especially in 1976 where about 230 kg/fd was suggested. Aroma also suggested an agreement in the trend of yield between observed and predicted figures. While the first year's (1976) predicted yield in Aroma was close to the observed one,the following year's prediction suggested a sharp rise of 560 kg/fd which was not fulfilled. The rise was only 60 kg/fd. Singa results showed the opposite trends of observed and predicted yield in the first year of the extended period and compatible trends in the second year.

The discrepancies in Singa were considerable but they were less than those of Kosti. Gedaref showed opposing trends in both of the years, but the discrepancy between the observed and the predicted yields became smaller (20 kg/fd).

In conclusion to this chapter it can be said that general positive correlations of sorghum yield with rainfall and relative humidity and negative ones with temperature and evaporation for the period before ripening were shown. It was noted that even in the rainfed areas, rainfall relationships with sorghum yield were not always clear, because of the complexity of the climate-crop relationship. However, the lack of moisture was particularly harmful to sorghum at the flowering stage. In the ripening period temperature correlation became weaker or became positive. The effect of temperature on sorghum can also be suggested through the negative correlations the crop obtains with evaporation. The results obtained for sorghum in this chapter in many cases matched those reached for cotton in the previous chapter.

The correlation/regression methods are useful in this study as they provide an idea about the relationships between climate and sorghum yield and the nature of that relationship. Estimations through the regression method are believed to be of use in filling the gap encountered in the sorghum yield records at the different production centres. They can also be used for extrapolation for periods before and after the study period. This can be particularly useful if more data is needed for special purposes such as agricultural survey and planning, where the estimation methods have the advantage over the total dependence on the average yields. Another advantage of these correlation and regression methods is that they help to direct the attention of experimental work to inspect any cause-and-effect of particular climatic elements.

This study provides a comprehensive view of climate-sorghum yield relationships and is not restricted to one element of the climate. Perhaps one of the values of the study is that it gives an example of how far use can be made of the readily available climatic data in the assessment of sorghum yield. The study also gave an opportunity to compare the climate-sorghum yield relationships of different areas in the country.

However, the results obtained in this chapter need further testing when more climatic and crop yield data become available. Modification may need to be made after that testing, and more variables other than the climatic ones might be included if sufficient satisfactory data became available.

The study of the relationships of climate with sorghum yield, presented in this chapter, is followed by a similar study of these relationships with sesame and groundnuts (oil seeds) in chapter 9. The results obtained there will be compared with those of climate-cotton/sorghum yield results for the purpose of generalization.

CHAPTER NINE

THE RELATIONSHIP BETWEEN CLIMATE, AND SESAME AND GROUNDNUT YIELDS IN THE SUDAN

9.1 General

The study in this chapter is allocated to the relationship between climatic variables and the yields of sesame and groundnuts within the area specified in section 6.3.1. The statistical methods (correlation and regression) described in sections 5.2.2, 5.2.3 and 6.3.3 and applied in Chapters 7 and 8 are also adopted here. The crop yield data used in this study is shown in Table A.13.

It has been mentioned in Chapter 7 that no strong relationships are expected from climatic variables with crop yields for an extensive area such as the Sudan. This would also be true for large areas within such a country. As will be seen later in more detail, this conclusion proved to be applicable in this chapter where the relationship of climatic variables with sesame and groundnut yields are dealt with. Again a local base is suggested to be the best for such a study. Due to the fact that both the crops have few data sets of even poorer quality compared with cotton and sorghum, the study is restricted to a few centres. It is also noted that the literature about these two crops is not as rich as that of cotton and sorghum. Most of the literature consulted refers only to the general conditions and environment of the crop growing rather than to specific geographical work which applies the statistical methods adopted in this study.

The study of climate-sesame yield relationships was made for three areas : Dueim, Gedaref and Abu Naama (see Fig. 6.10). These are first grouped together to examine the relationships with a whole region, and then each locality is taken alone for the statistical analysis of that relationship. For groundnuts only two areas, Wad Medani and Kosti, are considered. They are treated in the same way as the sesame areas i.e. first grouped and then separately studied.

The procedure followed in this study is first, the study of bivariate correlations, followed by the study of the effect of rainfall change on the crop yield, and finally regression analyses and crop yield estimations.

9.2 Correlation between climate and sesame yield

Sesame is a summer crop grown in subtropical or tropical lowlands under semi-arid conditions. It thrives in fertile soils with moderate amounts of rainfall (Macmillan, 1956; Ochse et al., 1961; Irvine, 1969). It is noted that well drained and soil that is not water-logged is best, and heavy rains or high humidities, especially after sowing, may seriously affect the crop (Ochse et al., 1961, Kumar, 1963).

The Central Rainlands of the Sudan were the best areas for sesame cultivation. In those areas the crop ranks as the second most important, after sorghum. It has long been grown by traditional peasant methods on small patches of land of a few acres (Tahir, 1964).

The three centres of sesame production studied, Dueim, Gedaref and Abu Naama, have data sets of 13, 16 and 15 cases respectively. These areas are entered for correlation study in the following section.

9.2.2 Correlation coefficients

Whole area : Dueim - Gedaref - Abu Naama

The area considered here is a large triangle including different climatic conditions. It can be seen from Tables 9.1, 9.5 and 9.6 that no significant relationships were obtained from correlating monthly or pentad rainfall with sesame yield. However, negative correlations were frequent throughout the period. This relationship, though weak, can be understood in the context of the undesirable increase in rainfall, as previously mentioned. The highest correlations were with September rainfall ($r = -0.26$) and pentad 6 (31 July - 4 August) rainfall ($r = 0.28$).

The temperature variables showed significant relationships only in September and December. In September positive correlations were obtained for the maximum temperature, the number of days with >35°C and the average temperature, with coefficients 0.43, 0.38 and 0.31 respectively, all significant at $\alpha = 0.05$ and the first two at $\alpha = 0.01$. In December, on the other hand, negative correlations with sesame yield were obtained for maximum temperature ($r = 0.33$) and number of days with temperatures >35°C ($r = -0.31$) and both are significant at $\alpha = 0.05$. It can be observed that throughout the growing season, minimum temperature showed weak or no relationships with sesame yield. Temperatures in the pre growing period showed relatively strong relationships : the minimum temperature of April and May had coefficient values of -0.37 and -0.4 respectively. May maximum temperature showed a positive correlation with

Table 9.1 Correlations between sesame yields and climatic variables for Dueim - Gedaref - Abu Naama

	Rainfall (mm)	Temperature (^{o}C)	Temperature >35^{o}C No.days	Max. temperature (^{o}C)	Min. temperature (^{o}C)	Relative humidity (%)
July	-0.01	0.04	0.12	0.14	-0.13	-0.30
August	-0.12	0.09	0.08	0.10	0.04	-0.19
September	-0.26	0.31*	0.38**	0.43**	0.06	-0.40**
October	-0.14	0.09	0.15	0.21	-0.02	-0.01
November	-	-0.07	-0.13	-0.12	0.03	-0.27
December	-	-0.19	-0.31*	-0.33*	0.10	0.16
Year	-0.20	-0.10	-	-0.16	-0.05	-0.14

N = 44

* significant at α = 0.05

** significant at α = 0.01

sesame yield (r = 0.34, significant at α = 0.05). From these results it can be suggested that in the early, pregrowing period a relatively wide range of temperature can be tolerated. In the vegetative phase large rise in temperatures can be tolerated and in the harves time lower temperatures are preferred. Relative humidity showed negative relationships throughout the pre growing and the growing season; highest in September (r = -0.4, significant at α = 0.01), followed by May and June, with r = -0.35 and -0.32 respectively.

The assumption made in section 9.1, that it is unlikely that strong relationships between climatic variables and crop yield for an extensive area would be found, is borne out. This will be further shown from the study of the multiple correlation and regression analysis and by comparison with the following study of local areas.

Dueim

In this area, where the mean annual rainfall is 270 mm, an amount less than half those of the other two areas and of greater variability, rainfall is crucial for agriculture. It is particularly important during the beginning of the growing season (July). Before this period i.e. in June, rainfall showed no relationship with sesame yield. From Tables 9.2, 9.5 and 9.6, the importance to the sesame crop of total July rainfall and frequency of July pentads rainfall, can be seen. The correlation between total rainfall and the crop yield was 0.72. Correlations were 0.71, 0.8 and 0.67 during pentads 2, 3 and 6 respectively (significant at α = 0.05). The reason for the general

Table 9.2 Correlations between sesame yields and climatic variables for Dueim

	Rainfall (mm)	Temperature (°C)	Temperature >35°C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)
July	0.72**	-0.72**	-0.64*	-0.53	-0.77**	0.03
August	0.33	-0.57*	-0.34	-0.52	-0.57*	0.31
September	-0.38	-0.07	0.42	-0.48	-0.54	-0.58*
October	-0.24	-0.51	0.03	0.19	-0.73**	0.42
November	-	-0.12	0.28	0.40	-0.46	0.33
December	-	-0.46	-0.23	-0.34	-0.32	-0.23
Year	0.58	-0.49	-	-0.21	-0.63*	-0.25

N = 13
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

pattern of alternating strong-weak relationships within July (see Table 9.6) might be due to the need for well distributed amounts of rainfall for the plant's best use. The relationships of the total rainfall of both July and August with sesame yield resulted in a coefficient value of 0.67. Later in the season (September and October) rainfall ceased to be of importance in terms of correlations. These results match the suggestion of Irvine (1969), that the crop needs good rainfall during the first two months of the growing season.

As mentioned earlier in this chapter, temperature tended to have a noticeable effect on the sesame crop (represented by its yield) at Dueim. A rise in temperature seems to decrease rainfall effectiveness especially at the peak of water need. Strong negative correlations were obtained with July average temperature ($r = -0.72$) and July minimum temperature ($r = -0.77$). It seems that there is a tendency for crop sensitivity towards any rise of the minimum temperatures in this area; this effect is strongest in the pre-sowing (June), early growing (July) and towards the end of the growing season (October) where correlations obtained were -0.73, -0.77 and -0.73 respectively.

Relative humidity showed weaker relationships with sesame yield than rainfall and temperature. The relationship in many cases was positive. It became significantly negative only in September where it showed a coefficient value of -0.58 (significant at $\alpha = 0.05$).

Gedaref

Gedaref receives an annual rainfall more than twice that of Dueim (i.e. 579 mm). This suggests weaker correlations between rainfall and crop yield than those obtained at Dueim (Tables 9.2, 9.3 and 9.6). Rainfall here is more reliable and the crop water requirement is almost satisfied.

The pre-season (June) rainfall showed no significant relationships with the crop yield (r = -0.23). The early growing seasons months rainfall, July and August, opposed each other in their relations with sesame yield. Thus while total July and July pentad rainfall always displayed positive correlations with crop yield, the correlation figures for August always showed negative values. The largest correlations with yield were total July and pentad 12 rainfall with a coefficient value of -0.49 each (significant at α = 0.05). It can be suggested here that as more water is needed at the pre-sowing and sowing period (July) heavy rainfall becomes harmful to the plant at its early growing stage. This agrees with what was maintained by Ochse et al. (1961) that heavy rainfall is detrimental to sesame. The following two rainy months, September and October, have no significant correlations with sesame yield.

Temperature, relative humidity and evaporation (except December evaporation) variables showed weak or no relationships with sesame yield and this phenomenon was observed both in the pre-sowing and throughout the growing season. The correlation coefficients rose to just above 0.4 for the annual temperature variables. It is noted that many tropical crops need a drier period to ripen (Nieuwolt, 1977) and this is fulfilled by the recession of rainfall preceding

Table 9.3 Correlations between sesame yields and climatic variables for Gedaref

	Rainfall (mm)	Temperature (°C)	Temperature >35°C (No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation mm.
July	0.49*	0.36	0.18	0.38	0.26	-0.39	0.21
August	-0.43	0.10	0.03	0.08	0.12	-0.03	-0.12
September	0.03	0.17	0.00	0.13	0.24	-0.10	-0.05
October	0.21	0.00	0.14	0.05	0.01	0.21	0.35
November	-	0.15	0.18	0.17	0.13	0.15	-0.01
December	-	0.19	0.01	0.10	0.28	0.28	0.66**
Year	-0.01	0.44	-	0.40	0.43	0.03	-

N = 16

* significant at $\alpha = 0.05$

** significant at $\alpha = 0.01$

this stage and by a strong positive correlation between December evaporation and sesame yield ($r = 0.66$, significant at $\alpha = 0.01$).

Abu Naama

This area receives an annual rainfall of 574 mm which is similar to that of Gedaref and more than twice as much as that of Dueim. From Tables 9.4, 9.5 and 9.6 it can be seen that the distribution of rainfall during shorter periods (pentads) was more important than the monthly totals. Total June (pre-sowing) and total July (sowing) rainfall showed relatively stronger correlation than the rest of the season, with $r = 0.39$ and -0.34 respectively. These relationships, though weak, hint at the general requirement of the crop for water in the soil in the pre-sowing period followed by a period without heavy rainfall which might cause water-logging. In this area in particular it is noted by Lebon (1965) that drainage is imperfect and water lingers for a longer time when compared with Gedaref, where the area has a better drainage system. Most of the July and August pentad rainfall showed negative correlations with sesame yields, and except for pentad 10 ($r = -0.59$), none is found to be significant at $\alpha = 0.05$. By the end of August and the beginning of September (pentad 13) a very strong positive correlation between rainfall and the crop yield was obtained ($r = 0.77$). A relatively strong negative correlation was shown also towards the end of September (pentad 17) where the correlation coefficient had a value of -0.5. The negative relationships of sesame yields with many of the pentad rainfall totals may be related to drainage

Table 9.4 Correlations between sesame yields and climatic variables for Abu Naama

	Rainfall (mm)	Temperature (°C)	Temperature > 35°C (No.of days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation mm.
July	-0.34	0.09	0.14	0.14	-0.04	-0.15	0.04
August	-0.05	0.24	-0.05	0.36	-0.21	0.04	0.14
September	0.05	-0.09	0.00	-0.01	-0.37	0.07	-0.05
October	0.01	0.12	0.20	0.15	0.00	0.08	0.13
November	-	0.00	-0.21	-0.04	0.11	0.18	-0.10
December	-	0.27	0.33	0.33	0.19	0.07	0.08
Year	-0.02	-0.22	-	-0.10	-0.29	-0.06	-

N = 15

Table 9.5 Correlations between climate variables of the pre-sowing and early growing season and sesame yield (kg/fd)

Climatic element	Calendar	Region			
		Dueim	Gedaref	Abu Naama	All
Rainfall	June	0.06	-0.23	0.39	-
	Jul.+ Aug.	0.67*	0.11	-0.32	-0.08
	Sept.+ Oct.	-0.39	0.03	-0.05	-0.28
Average temperature (°C)	Jul.+ Sept.	-0.67*	0.28	0.10	0.14
Max.temp. (°C)	April	0.02	0.22	-0.49	-0.23
	May	0.64*	-0.02	-0.20	0.34*
	June	-0.07	0.39	-0.32	0.24
Min.temp. (°C)	April	-0.50	0.21	-0.69**	-0.37*
	May	-0.48	0.12	-0.36	-0.40**
	June	-0.73**	0.19	-0.29	0.18
Relative humidity	May	-0.45	-0.04	-0.26	-0.35*
	June	-0.21	-0.13	-0.14	-0.32*
No. of cases		13	16	15	44

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

Table 9.6 Correlations between sesame yields and pentad rainfall for 3 stations(1)

Pentad	Calendar	Dueim	Gedaref	Abu Naama	All
1	1 - 5 July	0.71**	0.35	-0.30	-0.04
2	6 - 10	-0.08	0.28	0.07	-0.05
3	11 - 15	0.80**	0.11	-0.32	0.18
4	16 - 20	0.51	0.37	0.00	0.10
5	21 - 25	0.00	-0.05	-0.43	-0.13
6	26 - 30	0.67*	0.17	0.02	0.28
7	31 July.- 4 Aug.	0.01	-0.02	-0.34	-0.17
8	5 - 9	-0.09	-0.04	-0.13	-0.15
9	10 - 14	0.12	-0.37	0.50	0.02
10	15 - 19	0.24	-0.01	-0.59*	-0.10
11	20 - 24	0.33	-0.11	-0.34	-0.01
12	25 - 29	0.52	-0.49*	-0.14	-0.09
13	30 Aug.- 3 Sept.	-0.09	0.26	0.77**	0.06
14	4 - 8	-0.18	0.14	-0.07	-0.10
15	9 - 13	-0.25	-0.28	-0.05	-0.23
16	14 - 18	-0.12	-0.10	0.33	-0.12
17	19 - 23	-0.19	0.11	-0.50	-0.22
18	24 - 28	-0.09	0.29	-0.20	-0.15
19	29 Sept.- 3 Oct.	-0.07	-0.41	-0.23	-0.24
No. of Cases		13	16	15	44

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

(1) The numbering of pentads here is different from the conventional system.

characteristics of the area previously mentioned and to what was maintained by Ochse et al. (1961) and Kumar (1963) that heavy rains or high humidities may seriously affect the crop. Added to this is the possibility that heavy rain storms may cause mechanical damage to this delicate crop (Bacon, 1948). If the significant correlations only are considered (Table 9.6) alternating periods of dry and wet conditions seem to be preferable for sesame cropping. In addition to the reasons above this permits agricultural processes, such as weeding, to be executed.

In the pre-growing period (April, May and June) both maximum and minimum temperatures showed negative relationships; highest was April minimum temperature ($r = -0.69$, significant at $\alpha = 0.01$). During the growing season temperature showed no significant correlations with sesame yield. This situation is similar to that of Gedaref and opposite to that of Dueim. It can be suggested here that in this area as in Gedaref rainfall is almost adequate so the effect of temperature is less significant than in a drier area such as Dueim, where temperature may be harmful by encouraging drier conditions. Evaporation and relative humidity in this area also showed weak or no correlations with sesame yield.

This discussion of correlation is followed by a detailed study of the effect of the change of rainfall through the growing season on sesame yield.

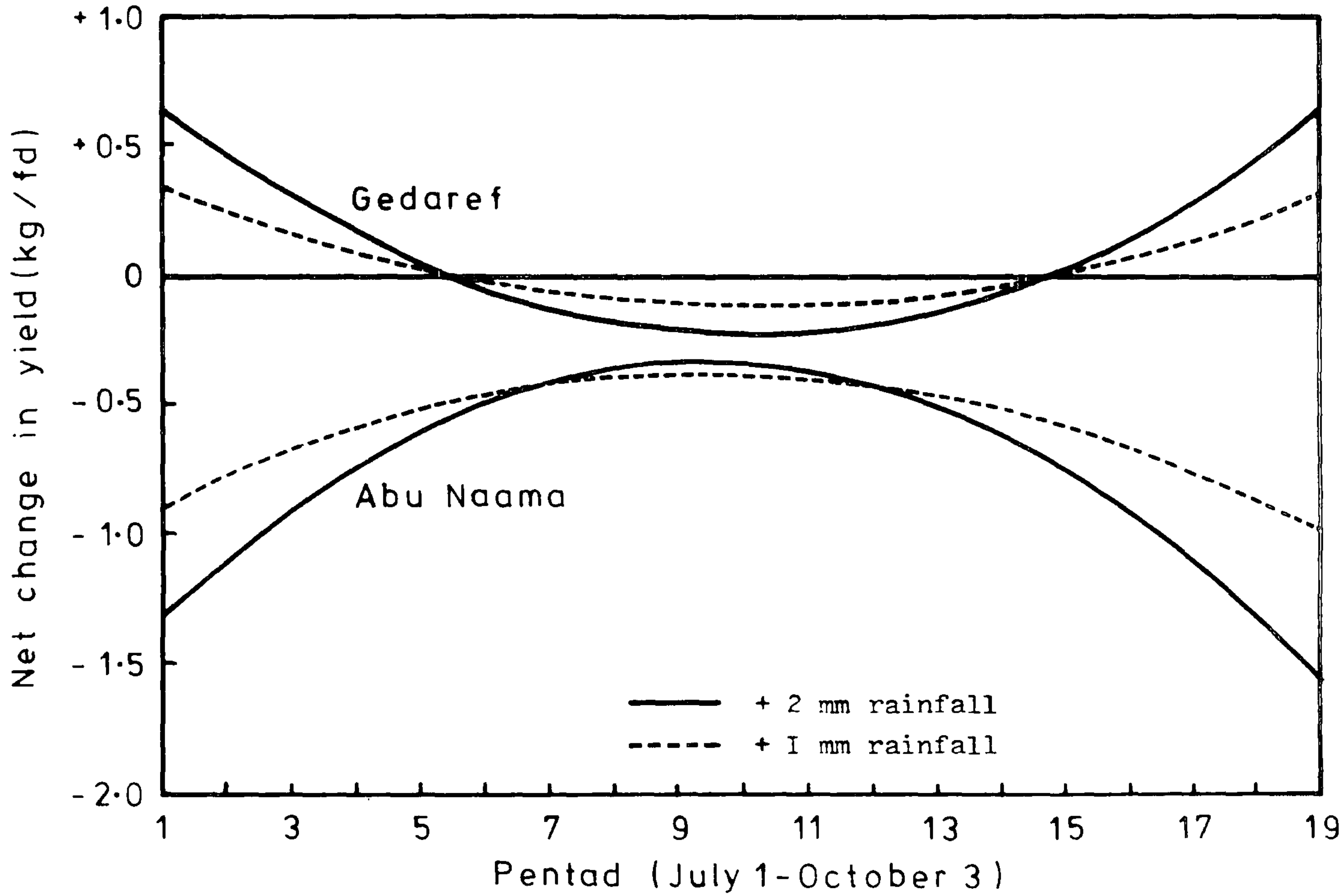
9.2.3 Effect of pentad rainfall change on sesame yield

The Fisher model described in section 6.3.3 and applied in chapters 7 and 8 is also applied here. The effect of an increase in rainfall of 1 or 2 mm above the average pentad rainfall on sesame yield has been tested at Gedaref and Abu Naama using data for pentads from the beginning of July to the third of October. In this statistical model, a decrease of 1 or 2 mm below the average rainfall is a mirror image of the equivalent increases. It can be observed from Figure 9.1 that in this method the curves produced by an increase of rainfall by either 1 or 2 mm were similar to each other, the 2 mm curve being an exaggeration of the 1 mm curve. Therefore, in this discussion the 2 mm rainfall increase only will be elaborated.

In the two areas studied opposite behaviours in the net change in the sesame yield can be seen. At Gedaref it is noted that both early in July and late in September the increase of pentad rainfall above the average was reflected in a positive change in sesame yield. Between these periods, negative change was observed. In pentad 1 an increase of 2 mm rainfal reflected an increase in sesame yield by 0.8 kg/fd. This increase in yield diminished with the advance of the season until in pentad 6 it became a decrease. In pentad 10 the increase of rainfall corresponded with a slight decrease in sesame yield (-0.25 kg/fd). Towards the end of September the curve of yield change shifts to the positive side, i.e. an increase of rainfall was likely to result in an increase of sesame yield. In pentad 19 an increase of sesame yield by 1.4 kg/fd corresponded with the increase of rainfall.

At Abu Naama the increase of 2 mm above the average pentad rainfall was always reflected in a decrease in sesame yield. This effect was greater towards the beginning and

Fig. 9.1 EFFECT OF 1 AND 2MM ABOVE AVERAGE PENTAD RAINFALL ON SESAME YIELDS IN 2 AREAS



Pentad calendar is shown in Table 9·6

the end of the rainy period (pentads 1 and 19) with -1.3 and -1.6 kg/fd respectively. These negative effects reduce to -0.4 kg/fd in the middle of the period (pentad 9). In the period between pentads 6 and 16 (26 July - 18 September) crop yield in both Gedaref and Abu Naama react similarly by decreasing in response to an increase in rainfall.

These results generally supported the correlation results between the rainfall, principally pentad rainfall, and sesame yields. From Table 9.6 August pentads in both areas were observed to have general negative correlations. This situation was also observed at Abu Naama for July and September, whereas at Gedaref the pentad rainfall of these months in most cases showed positive relationships.

From this discussion it seems that the increase of rainfall above the average is generally detrimental to sesame growing. Figures from Abu Naama suggest a harmful effect throughout the growing season, while those from Gedaref suggest the main damage at the vegetative period of the crop. A comparison between the drainage systems of these areas might show a relationship with these results (section 9.2.2). The sesame at Abu Naama suffered from the danger of water-logging early in the season and the lingering of water on the soil for long periods; at Gedaref this danger was absent.

This particular examination of the effect of rainfall change on sesame yield change is now followed by a discussion of multiple correlation and the stepwise multiple regression procedure used to assess the sesame yield. At the final stage of the regression analysis, a study of sesame yield estimation resulting from the regression formulae will be made.

9.2.4 Regression analysis and sesame yield estimation

Regression analysis

The stepwise regression procedure chosen here has been described in sections 5.2.3 and 6.3.3 and applied for crop yields assessment in Chapters 7 and 8. The study made here covers the same areas used in the correlation section (9.2.2). Several regression steps are considered according to the different areas and data sets. There are 5 steps for the whole area, 4 for Gedaref and Abu Naama and only 3 for Dueim.

The total area, which included the three areas of sesame production, as can be seen from Table 9.7, showed poor results in the multiple correlation and regression analysis. At the first step, September minimum temperature was entered as the most important variable (r = 0.43). Entering October minimum temperature, pentad 19 rainfall, July - September relative humidity and pentad 4 rainfall only resulted in R = 0.76 (R^2 = 0.58). This poor result was also confirmed by the small contribution to the value of R when 10 variables in aggregate were included (R = 0.86). The value of R reached 0.9 after including 13 variables. The most contributive variables here were generally the minimum temperatures of the late growing season. The standard error after entering 5 variables in the regression procedure was 59.3 kg/fd, 38% of the average yield (see Table 9.7). This result was the worst amongst the areas of the study and in fact it discouraged further computations of sesame crop.

In the Dueim area (Tables 9.7 and 9.8), it can be seen that within the three regression steps considered in this area, pentad 3 rainfall was the most important variable ($r = 0.8$) followed by pentad 11 rainfall and July relative humidity, raising R to a value of 0.95 ($R^2 = 0.9$). In this area the moistness of July had particular importance. The standard error, 46.5 kg/fd, which represented 22% of the average sesame yield in this area is considered comparatively high but it was better than when the area was considered as a whole.

In the Gedaref area, as shown from Tables 9.7 and 9.8, the most important variable entered in the regression procedure was December evaporation ($r = 0.67$) followed by pentad 12 rainfall resulting in an R value of 0.82. The third step identified September evaporation ($R = 0.9$) and the final step identified September average temperature ($R = 0.95$; $R^2 = 0.9$). The standard error here, 18.4, was only 12% of the average sesame yield, and it was the lowest amongst the areas studied.

In the Abu Naama area pentad 13 rainfall was the first variable in the regression hierarchy ($r = 0.77$). This variable was followed by April maximum temperature which resulted in $R = 0.89$. The third and fourth steps identified November average temperature and pentad 11 rainfall by which the value of R was raised to 0.96 ($R^2 = 0.92$). The result obtained in this area was the second result from the best areas in the study. The standard error here was only 18.2 which was only 15% of sesame yield (see Table 9.7).

Sesame yield estimation

The formulae derived from the stepwise regression described earlier were used to estimate sesame yields for the three centres of production selected for this study (see Table 9.8). It is noted that since the size of the data sets in the study area were small, no extrapolation was calculated for sesame yield beyond the years originally used to formulate the regression equation. It is also noted that the poor result obtained from grouping all the sesame production centres into one unit discouraged the further computation of sesame yield.

In the three areas studied the correlations between the observed and estimated sesame yields were about 0.95. It can be observed from Figure 9.2 that in the Gedaref and Abu Naama areas the discrepancy, although clearly observed in two years within the study period, was never more than 35 kg/fd. In the Dueim area, although a similarity was noted between the observed and the estimated yields, larger discrepancies occurred. These reached 80 kg/fd at their greatest. In this area also, an overestimation can be observed for most of the second half of the period of the study.

This discussion is followed by a study of groundnuts, also an oil seed crop, following the same procedures and the same statistical methods. The importance of sesame and groundnuts in the Sudan economy was shown in Chapter 6.

Table 9.7 Regression analysis of sesame yield for different areas in the Sudan

	Dueim	Gedaref	Abu Naama	All
No. of cases	13	16	15	44
Average yield (kg/fd)	203.2	147.7	122.1	155.4
R	0.95	0.95	0.96	0.76
R^2	0.90	0.90	0.92	0.58
S.E. (kg/fd)	46.5	18.4	18.2	59.3
R at step 1	0.80	0.67	0.77	0.43
2	0.88	0.82	0.89	0.59
3	0.95	0.90	0.94	0.67
4		0.95	0.96	0.72
5				0.76

Table 9.8 Regression formulae for sesame yield estimations (kg/fd)

1. Dueim

$$y = 424.3024 + 5.698742\ P3 + 2.626\ P11 - 8.9313\ R7$$

2. Gedaref

$$y = -\ 1149.183 + 46.82841\ V12 - 1.115643\ P12 - 48.92376\ V9 + 37.66946\ T9$$

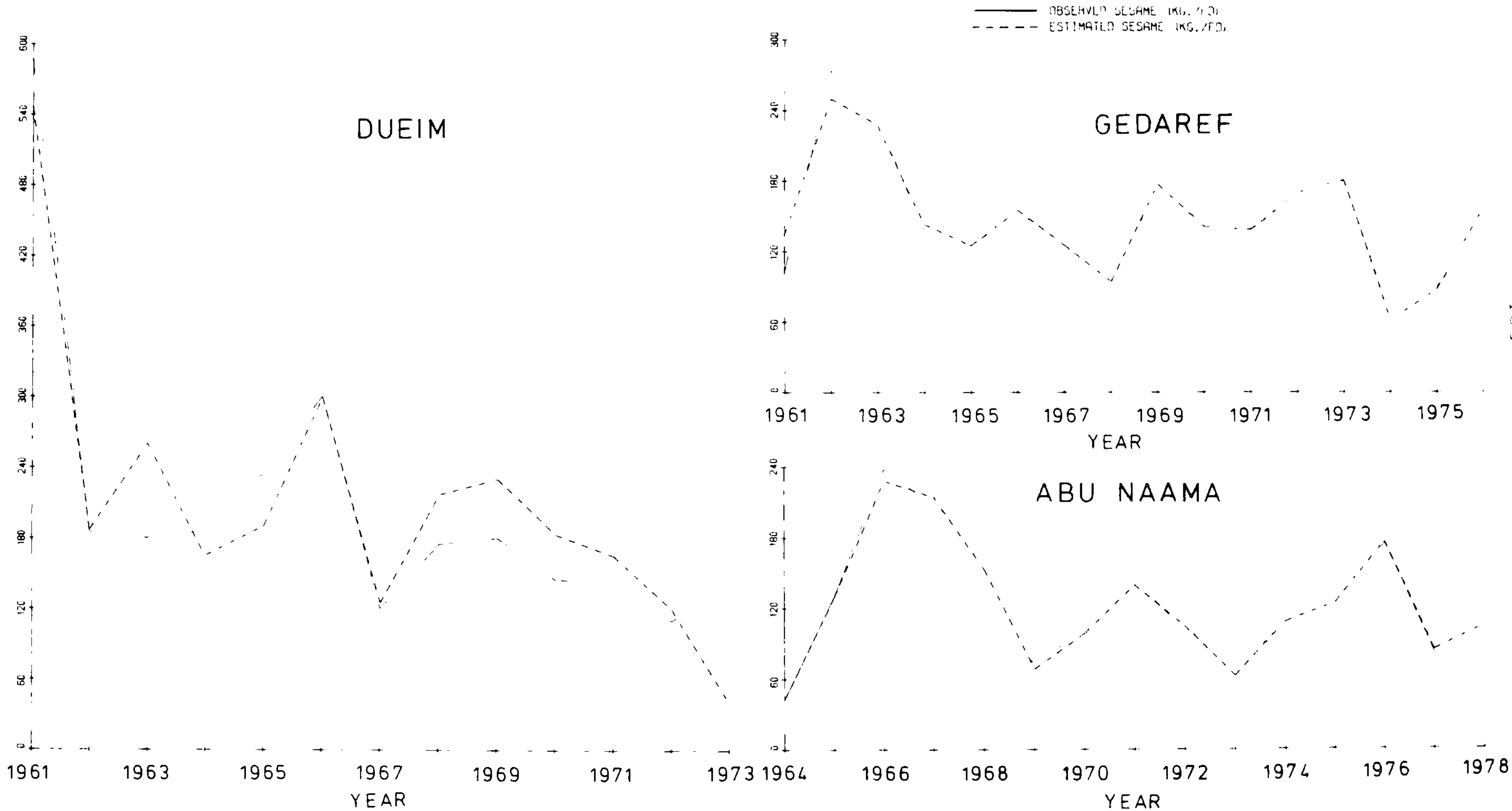
3. Abu Naama

$$y = 867.6499 + 1.519192\ P13 - 31.15844\ TMA4 + 18.73054\ T11 - 1.10846\ P11$$

Symbols:

T9	=	September temperature (°C)
T11	=	November temperature (°C)
TMA4	=	April maximum temperature (°C)
R7	=	July relative humidity (%)
P3	=	Pentad 3 (Table 9.6) rainfall (mm)
P11	=	" 11 ditto
P12	=	" 12 ditto
P13	=	" 13 ditto
V9	=	September evaporation (mm)
V12	=	December evaporation (mm)

Fig. 9.2 OBSERVED AND ESTIMATED SESAME YIELDS FOR 3 AREAS



9.3 Correlation between climate and groundnut yield

The groundnut is a warm-season crop and it is found in tropical or subtropical climates (Klages, 1961; Thorne, 1979). The crop demands moderate rainfall during the growing season (Wolfe and Kipps, 1959; Klages, 1961; Ochse et al. 1961; Irvine, 1969), so its growth and yield are very sensitive to moisture stress (Goldberg et al., 1967; Holford, 1971; Kassam et al., 1975; Thorne, 1979) during any stage of growth (Billaz and Ochs , 1961). Because of this characteristic the crop thrives better in the irrigated than in the rainfed areas of the Sudan. The groundnut yield is 807 kg/fd in the irrigated and only 266 kg/fd in the rainfed areas (see Table 6.2). Wad Medani and Kosti (south west Gezira scheme) are the only two areas of groundnut production that have been chosen for this study. They are the only areas with relatively reasonable sizes of reliable data. Both areas in the Gezira, where irrigation is available and rainfall is a complementary factor in watering the crop. These two producing centres were first treated as one unit and then studied as separate areas.

9.3.1 Correlation coefficients

A look at the relationship in the whole area suggested the familiar conclusion : that it is unlikely that good results will be obtained when compared with local studies. However, this overview gives a chance to examine the significant relationships in the unified areas. In relation to rainfall it can be observed from Tables 9.9, 9.12 and 9.13 that negative relationships in the pre-sowing (June) and

Table 9.9 Correlations between groundnut yields and climatic variables for Wad Medani - Kosti

	Rainfall (mm)	Temperature (^{o}C)	Temperature >35^{o}C (No.days)	Max. temperature (^{o}C)	Min. temperature (^{o}C)	Relative humidity (%)	Evaporation (mm)
July	0.12	-0.44*	-0.50**	-0.36*	-0.04	0.57**	-0.55**
August	0.02	0.03	0.03	-0.04	0.50**	0.22	-0.19
September	0.32	-0.33	-0.41*	-0.38*	0.15	0.51**	-0.36*
October	-0.45*	0.21	-0.21	0.10	0.30	0.24	-0.27
November	-	0.29	0.11	0.02	0.36*	0.35	-0.28
December	-	0.04	-0.12	-0.28	0.24	0.47**	-0.30
Year	0.44*	-0.04	-	-0.38*	0.22	0.51**	-

N = 31
* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

the late growing period (October) were obtained with coefficient values of -0.5 and -0.45 respectively. The pentad rainfall showed no significant relationships. Maximum temperature was negatively related to groundnuts in the pre-sowing and sowing period (June and July) and in the vegative period (September), highest in June ($r = -0.51$; significant at $\alpha = 0.01$). Minimum temperature on the other hand showed positive relationships in most months of the growing period, but it was only relatively strong in August ($r = 0.5$). Relative humidity was the most important variable in the relationships with groundnut yield as the several months of the growing season showed the highest correlations. Positive correlations were encountered throughout the months of the growing season. The highest correlation was in July ($r = 0.57$). The evaporation relationships with groundnut yield opposed those of the relative humidity. Evaporation variables generally showed negative correlation. Here it was also in July where the correlation coefficient was the highest ($r = -0.55$). These results match the suggested sensitivity of the crop to water stress which might be caused by inefficient irrigation, increased evaporation or a drop in relative humidity.

At the local level, in both the Wad Medani and the Kosti areas, as can be seen from Tables 9.10, 9.11 and 9.12, rainfall was almost always positively correlated with groundnut yield throughout the pre-sowing and the early growing season (June - September, inclusive). One exception to that is seen in the negative correlation with August rainfall at Wad Medani. It seems that the difficulties of

Table 9.10 Correlations between groundnut yields and climatic variables for Wad Medani

	Rainfall (mm)	Temperature (°C)	Temperature > 35°C No. days)	Max. temperature (°C)	Min. temperature (°C)	Relative humidity (%)	Evaporation mm.
July	0.25	-0.52*	-0.51	-0.54*	-0.41	0.65**	-0.60*
August	-0.57*	0.41	0.40	0.32	0.57*	-0.32	0.34
September	0.51	-0.08	-0.11	-0.06	-0.12	0.06	0.15
October	-0.42	0.28	0.13	0.40	0.15	-0.19	0.11
November	-	0.38	0.43	0.36	0.34	0.05	0.11
December	-	0.16	-0.02	-0.05	0.13	0.69**	0.07
Year	-0.12	-0.12	-	-0.16	-0.07	0.37	-

N = 15
* significant at α = 0.05
** significant at α = 0.01

Table 9.11 Correlations between groundnut yields and climatic variables for Kosti

	Rainfall (mm)	Temperature (^{o}C)	Temperature > $35^{o}C$ (No. days)	Max. temperature (^{o}C)	Min. temperature (^{o}C)	Relative humidity (%)	Evaporation (mm)
July	0.00	-0.33	-0.33	-0.11	-0.07	0.36	-0.33
August	0.45	-0.18	-0.21	-0.11	0.27	0.31	-0.27
September	0.11	-0.55*	-0.53*	-0.53*	-0.10	0.65**	-0.58*
October	-0.50*	-0.11	-0.20	0.02	0.01	0.06	-0.08
November	-	0.03	0.15	-0.01	0.12	0.28	-0.02
December	-	-0.35	-0.20	-0.42	-0.04	0.23	0.07
Year	0.69**	-0.29	-	-0.40	-0.15	0.55*	-

N = 16

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

Table 9.12 Correlations between climatic variables of the pre-sowing and early growing season and groundnut yields (kg/fd)

Climatic element	Calendar	Area		
		Wad Medani	Kosti	All
Rainfall	June	0.41	0.48	-0.50**
	Jul.+ Aug.	-0.40	0.43	0.10
	Sept.+ Oct.	0.15	-0.05	0.08
	Jul.to Sept.	-0.21	0.50*	0.28
Average temperature (°C)	Jul.to Sept.	-0.05	-0.37	-0.28
Max.temp. (°C)	April	0.13	0.22	0.24
	May	-0.32	0.14	-0.12
	June	-0.40	-0.40	-0.51**
Min.temp. (°C)	April	-0.10	-0.16	0.06
	May	-0.19	0.29	0.24
	June	-0.35	-0.15	-0.21
Relative Humidity	May	0.22	-0.25	0.17
	June	0.21	0.06	0.28
	Jul.to Sept.	0.16	0.55*	0.50**
No. of cases		15	16	31

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

Table 9.13 Correlations between groundnut yields (kg/fd) and pentad rainfall for 3 regions (1)

Pentad	Calendar	Wad Medani	Kosti	Wad Medani - Kosti
1	1 - 5 July	0.09	0.02	0.11
2	6 - 10	0.40	-0.14	0.08
3	11 - 15	0.27	0.11	0.17
4	16 - 20	0.18	0.12	0.14
5	21 - 25	0.10	0.14	0.13
6	26 - 30	-0.13	-0.18	-0.15
7	31 July - 4 Aug.	-0.27	0.45	-0.09
8	5 - 9	-0.53*	0.26	0.01
9	10 - 14	0.13	0.33	0.31
10	15 - 19	-0.50	0.13	-0.08
11	20 - 24	-0.28	0.20	0.08
12	25 - 29	-0.34	-0.06	-0.22
13	30 Aug. - 3 Sept.	0.29	0.43	0.37
14	4 - 8	0.01	0.23	0.20
15	9 - 13	0.19	0.29	0.17
16	14 - 18	-0.30	-0.08	-0.02
17	19 - 23	0.64**	-0.03	0.26
18	24 - 28	0.21	-0.34	-0.13
19	29 Sept.- 30 Oct.	-0.13	-0.05	-0.16
No. of cases		15	16	31

* significant at $\alpha = 0.05$
** significant at $\alpha = 0.01$

(1) The numbering of pentads here is different from the conventional system.

drainage during that particular period of the season in that area might contribute to this relationship, unlike the Kosti area, where drainage is better because of the steeper gradient. The need for good drainage is one of the requirements for a good groundnut yield (Wolfe, and Kipps, 1959; Thorne, 1979) especially in heavy soils (Bacon, 1948). As mentioned by Ochse et al. (1961), the danger of bacterial wilt attack increases if the soil is too wet. In addition to the danger of water-logging, heavy rainfall in August might cause a delay in sowing, a situation which might result in declining yield. At the Katherine Research station in Australia, Stern (1968) found an agreement between a delay in sowing and a drop in groundnut yield. Irrigation amounts and timing in relation to rainfall (statistic unavailable) are mentioned by Matlock et al (1961) to be important in affecting the crop yields, and may throw some light on this problem. However August in the Wad Medani area is known to be the wettest month. It is the month of the highest rainfall and relative humidity, and the lowest evaporation as was noted from the climatic normals (1941-1970) of the Sudan Meteorological Department.

Relationships between rainfall and groundnut yield in October (late growing season) showed negative correlation coefficients both at Kosti (-0.5; significant at $\alpha = 0.05$) and Wad Medani ($r = -0.42$). This result generally matched that of Holford (1971) in Fiji. The interpretation of such a result, which seemed contradictory to the general nature of the crop's need for water, was that the harmful tendency of excessive rainfall to the crop "could be due to the promotion of extra vegetative growth during the normal period of pod development and consequent delay in maturity of the pod" (Holford, 1971). Ochse et al. (1961) recognized the harmful nature of rainfall increase in the period of pod development and ripening. However the strongest correlations between rainfall and crop yield were with the annual (r = 0.69) and October (r = -0.5) rainfalls at Kosti, and with the August (r = -0.57) and September (r = 0.51) rainfalls at Wad Medani, which are all significant at $\alpha = 0.05$.

Relative humidity reflected relationships as consistent with groundnut yield as those of rainfall... The strongest correlations were those of July (r = 0.65) and December (r = 0.69) at Wad Medani, and those of September (r = 0.65) and the annual average (r = 0.55) at Kosti. Temperature and evaporation relationships with groundnut yield were, as expected, in agreement with each other, and they opposed the relationships of rainfall and relative humidity with crop yield. The strongest correlations with crop yield were of July maximum temperature (r = -0.54) and July evaporation (r = -0.65) in the Wad Medani area, and September average temperature (r = -0.55) and September evaporation (r = -0.58) at Kosti.

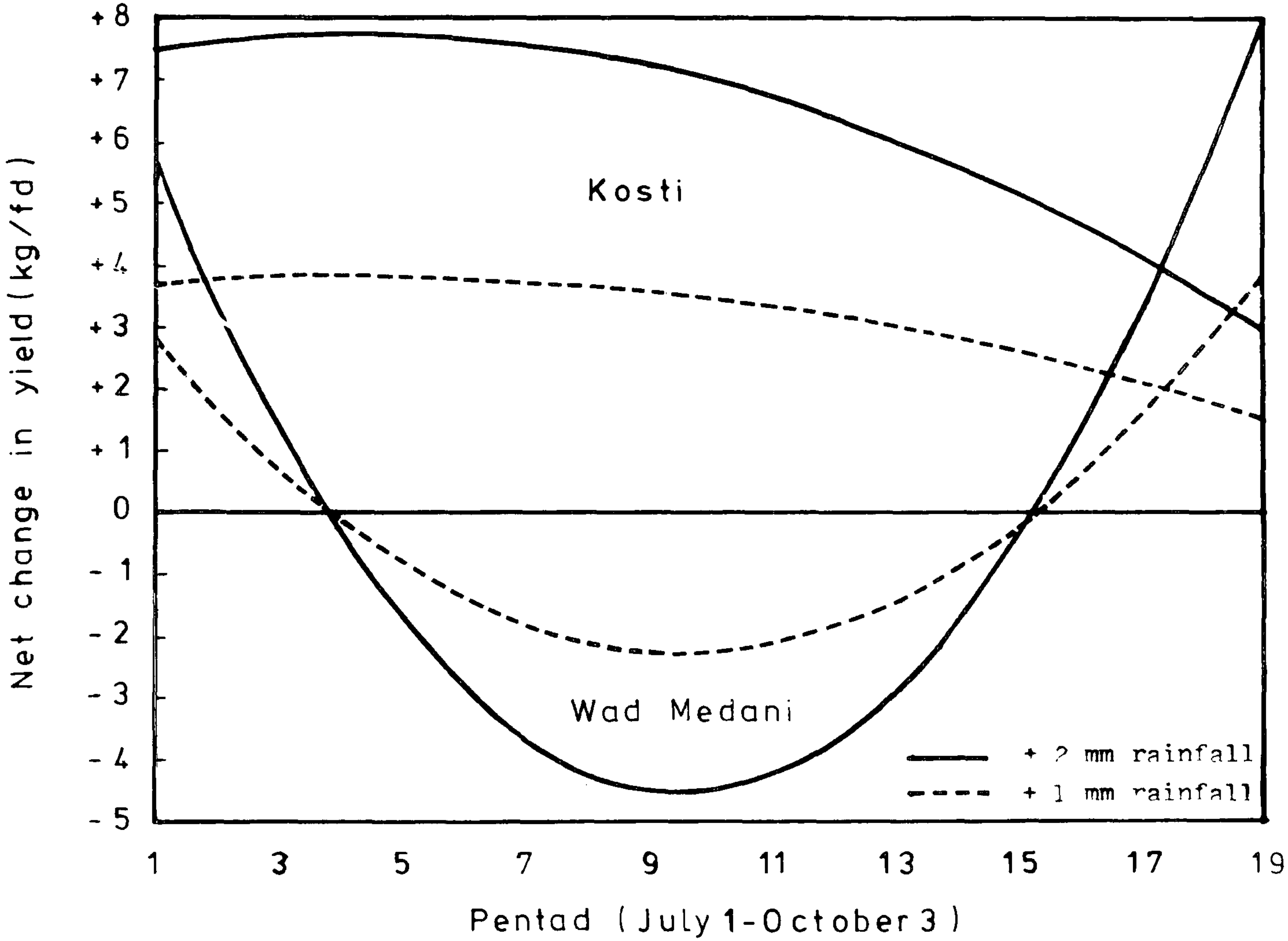
It can generally be observed that the strongest relationships between climatic variables and groundnut yield were obtained in July at Wad Medani and in September at Kosti. These showed quite similar patterns and almost the same values of correlation coefficients. In both centres moisture and humidity factors generally had the strongest relationships with the crop yield.

9.3.3 Effect of pentad rainfall changes on groundnut yield

The Fisher model is used here also to show the effect of the increase of 1 or 2 mm above the average pentad rainfall. From Figure 9.3 conjunction with Tables 9.10 and 9.11, it can be seen that although the Fisher model shows the trends in smooth curves, it generally matches the correlations between monthly rainfall and groundnut yield. To illustrate figures from Wad Medani showed a positive correlation in June, decreasing in July, negative in August and positive again in September, and the same pattern emerged from the Fisher model. Again in the Kosti area where positive correlations were decreasing from June towards the beginning of October, the model also showed this general trend.

In both areas the very early and late pentad periods showed an increase in groundnut yield in response to rainfall increase. For the middle part of the period, as mentioned earlier, the behaviours were different. The increase of 2 mm above the average rainfall for pentads 1, 9 and 19 showed the following changes : +5.6, 4.5 and +8.0 kg/fd at Wad Medani, and +7.5, +7.3 and 2.8 kg/fd at Kosti. The previously mentioned fact that the Kosti area is better drained than the Wad Medani area suggested positive relations with rainfall throughout the period considered here.

Fig.9.3 EFFECT OF 1 AND 2MM ABOVE AVERAGE PENTAD RAINFALL ON GROUNDNUT YIELDS IN 2 AREAS



Pentad calendar is shown in Table 9.13

9.3.4 Regression analysis and groundnut yield estimation

Regression analysis

From Table 9.14 it can be seen that results for the whole area were poor. Five variables could raise R to a value of 0.86 (R^2 = 0.74), out of which the July relative humidity was the most important (r = 0.57). The second variable, October rainfall, made a considerable contribution to the multiple correlation coefficient resulting in a value of 0.74, after which the contributions were slight. The standard error was 24% of the average yield.

In Wad Medani area the most important variable identified by the stepwise regression was December relative humidity (r = 0.69) followed by July evaporation resulting in an R value of 0.84. August and September minimum temperatures were identified at the third and the fourth steps, to result in R = 0.95 (R^2 = 0.9).

In the Kosti area, in the first step of the regression procedure, the total annual rainfall was identified as the most important climatic variable in the assessment of the groundnut yield with r = 0.69. The second variable, November number of days with temperatures >35 ^{o}C, raised the R value to 0.79. These are followed by pentads 12 and 2 rainfall to result in a final value of R as 0.95 (see Table 9.15).

These results suggest that at Wad Medani a wet period period at the sowing time followed by a dry period at the germination, emergence and early growth of the plant might be preferable. In Kosti it might be suggested that abundant

Table 9.14 Regression analysis of groundnut yields

	Wad Medani	Kosti	All
No. of cases	15	16	31
Average yield (kg/fd)	714.3	971.9	847.3
R	0.95	0.95	0.86
R^2	0.90	0.90	0.74
S.E. (kg/fd)	112.7	143.4	202.8
R at step 1	0.69	0.69	0.57
2	0.84	0.79	0.74
3	0.92	0.91	0.78
4	0.95	0.95	0.84
5			0.86

Table 9.15 Regression formulae for groundnut yield estimations (kg/fd)

1. Wad Medani

$$y = -3484.435 + 122.1336\,R12 - 25.28314V7 + 330.7947TMI8 - 421.7365TMI\,9$$

2. Kosti

$$y = -2222.922 + 6.055973RFA + 52.39546H11 - 15.54527P12 + 6.177907\,P2.$$

3. All (Wad Medani - Kosti)

$$y = -1888.31 + 25.93323R7 - 11.77368RF10 + 32.1183\,R9 + 63.2354V8 - 6.143477\,P16$$

Symbols:

RFA	=	Annual rainfall (mm)
RF10	=	October rainfall (mm)
P2	=	Pentad 2 (Table 9) rainfall (mm)
P12	=	Pentad 12 ditto
P16	=	Pentad 16 ditto
H11	=	November relative humidity (%)
TMI8	=	August minimum temperature (°C)
TMI9	=	September minimum temperature (°C)
R7	=	July relative humidity (%)
R9	=	September ditto
R12	=	December ditto
V7	=	July evaporation (mm)
V8	=	August evaporation (mm)

annual rainfall and warm conditions towards the harvest period are beneficial to the crop. The standard error in both areas was small (16%) and the results obtained here generally hint at good groundnut yield estimations.

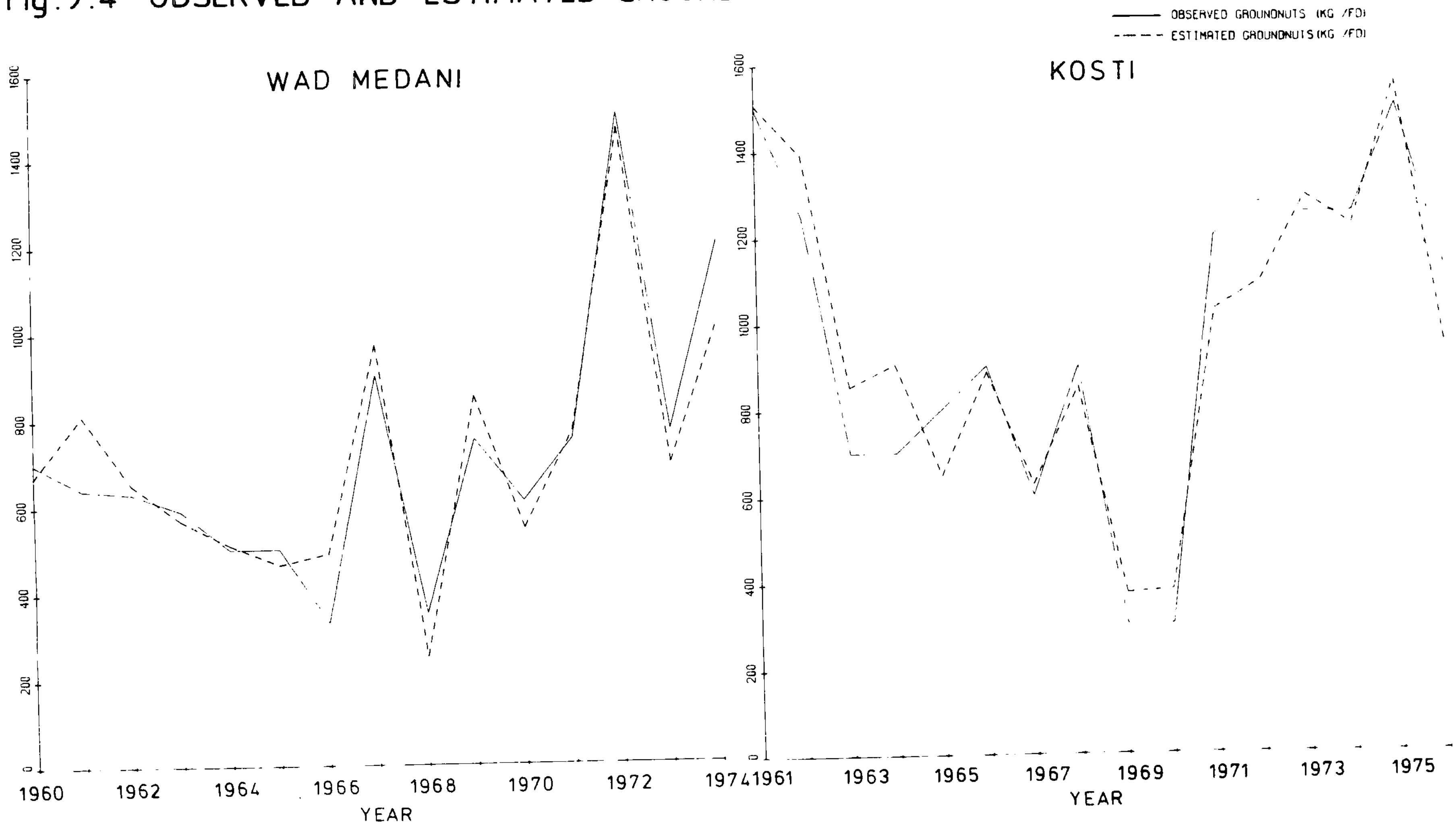
Groundnut yield estimation

From the regression formulae shown in Table 9.15 estimations for groundnut yield for Wad Medani and Kosti were calculated. The estimated yields were compared with the observed ones and the result is shown in Figure 9.4. It is noted that the greatest discrepancy between observed and estimated yields was 170 kg/fd in the Wad Medani area and 200 kg/fd in the Kosti area. Figure 9.4 shows that the correlation between observed and estimated groundnut yields was very high in both areas (r = 0.95). It is noted that because of the small data sets, no extended periods were considered for the purposes of prediction in this study.

One of the main conclusions reached in this chapter, as in Chapter 7 and 8, is that the climatic variables considered in this study for assessing the climatic relationship with the crop yield should not be taken as a total replacement of all other variables. The inclusion of cultural and physical weightings in the application of statistical models produced would be beneficial to a better assessment of crops. The reason for the concentration on climatic variables in this assessment were mentioned in chapter 1.

The small data set used and the few centres considered in this study mean that the results are a general elucidation of the nature of climate-crop relationships at those localities.

Fig.9.4 OBSERVED AND ESTIMATED GROUNDNUT YIELDS FOR 2 AREAS



More accurate and sizeable data will surely improve these generalizations. The expansion of agrometeorological stations will certainly help to introduce better quality data which in itself will give a better chance of improving the results from the model used.

The results shown in this chapter agree with the general conditions needed by sesame and groundnuts in other parts of the world and described at the start of each section. The Fisher model is seen to support trends shown by correlations for both the crops, although differences are seen as the former represents a smoother change in the crop yield.

It is clear from the discussion in this chapter, especially of sesame yield, that rainfall relationships with crop yield are affected by the rainfall amount at the locality, i.e. when rainfall is small, positive correlations are expected, and vice versa. It is also observed, in this context, that the distribution of rainfall within shorter periods, i.e. pentads, allows for a better viewing of the correlations with crop yield.

CHAPTER TEN

CONCLUSIONS

10.1 Climatic study

In this study it has been shown that the tropicality, the continentality and the absence of high and extensive mountain ranges, the alternating seasonal prevalence of the south westernly and the north easterly winds, and the I.T.C.Z. marking air mass convergence all greatly affect the climate of the vast country of the Sudan. The short rainy season and the long dry season affect many aspects of life in the Sudan and make the availability of water for many activities exceptionally important.

The climatic regionalizations of the Sudan made by different methods aiming for generalization and simplification can provide a basis for comparative studies of types of land use, and the tropic-to-equator climatic regionalization of the Sudan identified by the conventional Köppen and Thornthwaite methods were generally considered along with a factor analysis classification applied for the first time to the Sudan. The Köppen and Thornthwaite methods describe most of the Sudan as dry, with the characteristic of the latter being of greater discrimination in regional delimitation, something which is particularly relevant and valuable in southern Sudan. The factor/cluster method has the advantage over both earlier methods in that it provides more power of regional discrimination for the whole country. The climatic regions proposed by factor and cluster analysis procedures are particularly useful for agricultural planning since the potential characteristics of each region are distinguished more meaningfully for factor and cluster analysis than by other methods.

These climatic regions are also useful for other purposes such as hydrological studies, regional development planning and multipurpose surveys. They provide references for rapid extraction of information as well as for comparisons, and provide options for those who aim for geographical applications of general economic projects.

The realization of the drawbacks of each of the climatic classification methods studied suggests that the best course is to utilize each and every method rather than to rely wholly on one. In the factor analysis of the climate of the Sudan in this thesis it was necessary to restrict analysis to data for the annual period, for January and for July. It is appreciated that any expanded work on this topic would require the examination of climatic variables for other months, such as April and October, since these would enhance the climatic view over different seasons of the year. The inclusion of so many climatic variables in the factor analysis needs to be based on a large number of climatic stations to keep the balance between the number of cases and the number of variables used.

The results provided by calculating Penman's evaporation (Eo) in Chapter 3 from the monthly averaged data are found to be useful as they are comparable with the Eo computed from the daily data and then averaged. The curves obtained for both these two treatments were almost parallel. Computation for more stations on this basis helps to give a clearer view. Curves obtained for different areas can be produced and monthly averaged discrepancy between monthly and daily computed Eo can be computed from those curves. For climatic purposes and studies that need quick approximations with minimal computation, these discrepancy values may be suitable references.

The daily rainfall estimation from satellite imagery showed some usefulness. The results obtained showed the generally expected trends. They reflected positive relationships between daily rainfall with cloud amounts and cloud types. Negative relationships between rainfall at a station with the distance of cloud from the station are also reflected. However it was not possible to build up good, reliable models for rainfall estimation from the multiple regression procedure. The reasons cited in Chapter 5 suggest ways of improving the modelling procedure :

1. The use of better quality, higher resolution satellite imagery than that of the ESSA 3 and 5 satellites used in the present study.

2. The use of shorter interval satellite imagery than the once-daily images used here. This will result in closer views of the daily weather change. The geostationary satellites (e.g. Meteosat) which provide an image each 30 minutes throughout the day and might well be useful in this context.

3. The use of as many raingauge stations as possible would give better evaluation, and allow modification or replacement of the model.

4. The inclusion, in the model, of some ground-based variables such as wind speed and wind direction.

5. There is a need to obtain more accurate measurements from many raingauges within each gacell, and at shorter intervals than the 24 hrs. to investigate the suggested relationships.

It should be noted here that the idea behind applying such a remote sensing technique is to contribute to a better understanding of weather. These techniques must not be looked on as replacements of, but as complementary to, the conventional methods. It is also noted that if successful methods of rainfall estimation from satellite imagery, can be found, then they will be useful in contributing to a better understanding of climate-crop relationships by providing detailed data for data-sparse regions. The weather satellites provided huge amounts of data for weather analysis, particularly on cloud type , cloud amount and weather systems covering the whole country, as well as giving views of global scale weather systems. These imagery give the meteorologists in particular an opportunity to view the country's weather in the context of the surrounding area's conditions.

In the field of remote sensing, Landsat imagery has also been found to be a useful technique for identifying agricultural land use in the Sudan. It is particularly useful in monitoring agricultural areas covered as well as in discriminating vegetation from soil. Ground truth check points are needed to enhance the results obtained from the imagery. The usefulness of such a technique can be viewed through its integration with conventional areal photography, ground surveys, and reports of the areas under consideration.

Digital satellite imagery data, together with the more automated processes such as those used in density analysis, can be drawn upon for more accurate results. From the experience in this study of the monitoring of agricultural areas, the techniques used for enhancing the satellite imagery (i.e. using the colour additive viewer and the densitometer) are useful to identify the cropped areas, vegetation cover, drainage systems, soil and general terrain cover patterns. As mentioned earlier, this imagery, accompanied by ground checking points, can also be used for general survey purposes.

10.2 Climate-crop yield relationships

10.2.1 Nature of the data

The data collected for the study of climate-crop yield relationships have some characteristics which make for difficulty in their use. The sample sizes were in most cases less than 20 years. The reasons for this are the differences in periods covered by different meteorological stations and how those periods were internally covered. The samples are restricted to the period mutually covered by both meteorological and crop yield data. There are many difficulties in obtaining more and better quality data for this study. Considering the meteorological data first, it was difficult to obtain original, daily readings for the different areas under study because they were summarized at the stations before they were sent to the Meteorological Department in Khartoum. Some of the variables (e.g. radiation) were not measured at the majority of the stations and some other variables (e.g. sunshine) were either not measured at all or have only recently been introduced at meteorological stations. There were also gaps even in the monthly published data, for example 1968 to 1972, and after 1975.

In relation to the agricultural data the situation is worse. Crop yield data were available only in a few centres and the data set was distorted by gaps in the records. In many cases the crop yield figures were estimates, and in many other cases they were only averages for large administrative regions (Provinces). Another aspect of the agricultural data problem is the disappearance of the figures for some schemes as they were integrated into new, large combinations (e.g. under Agrarian Reform Corporation schemes). In addition, some of the old statistical, agricultural publications were missing from the authorities archives. In the well established schemes (e.g. Gezira) good records were only found for cotton. In the private sector poor data were obtained because they were not scientifically oriented sections and because of the fact that many of the investors try to reduce taxation and administration control. Another type of data problem is the replacement of some crops by others, as happened in the Gash area (Aroma; Fig. 6.10) where cotton was completely replaced by castor oil plants. These replacements deprived us ~~from~~ of long records for the crop yield-climate relationships analysis.

Factors other than climate could be included in the crop yield modelling. Amongst these are soil moisture and water balance, mechanization efficiency, fertilizer use (amounts and types), pest and disease control (amount and type of pest control sprays), dates of sowing, irrigation and picking efficiencies. These could not be included in this study because of the absence of reliable and consistent data. Related to this, it is recognized that technological change has occurred in the Sudan during the study period. Technological change in terms of the previously mentioned agricultural management and soil conditions (e.g. fertility and salinity) happen gradually and probably can be noticed in periods longer than that selected for the present study. Technology in general and many of its related variables were assumed to be constant in the year to year variations in any one locality under consideration.

Two other problems are related to the data measuring such a change :

i) they are very limited, and

ii) they are very difficult to build into the models.

In addition to the problem of the reliability of the agricultural data, there was also the problem of whether the records of the individual meteorological stations were representative of the agricultural areas. The western and south western parts of the Gezira scheme have no meteorological stations and the nearest ones which could be taken to represent them were Dueim and Kosti on the west bank of the White Nile. Singa and Abu Naama meteorological stations were taken to represent the Dali and Mazmum areas lying to the west of them. Gedaref, Kadugli, Aroma and Tokar were also taken to represent areas other than the immediate vicinity of the stations. Although this situation was not the ideal it was the practical way to tackle the problem of complete absence of data. However, in relation to the quality of the existing data and the length of periods, the meteorological records were more reliable than the agricultural ones. Matching the two pairs, as mentioned before (p. 263), reduced the sample size and showed the period from 1960 onward to be the best for the present study because it contained the minimal gaps in both agricultural and meteorological data.

The ideal data for the examination of crop-weather relationships in the Sudan would include daily measurements of photoclimatic, thermoclimatic and hydroclimatic parameters. The phenological events such as germination, flowering, earing and ripening as related to the meteorological parameters are essential for ideal results. The successful establishment of such an approach depends on the choice of representative data and the integration of physical environment elements such as the joint effect (or relationship) of temperature and rainfall at a special stage of plant development. In the study area, with its poor available data such an approach could not be undertaken. Thus the type of approach taken was largely determined by absence of ideal data, especially when the size of the data set that will be statistically significant is considered. The weather data are measured in the normal meteorological routine for the normal calendar period (see Chapter 3). On the agricultural side there are no publicly available records of phenological events. In the present study a simple route was followed by combining the climatic data of the early growing season and relating them to the crop yield. Such combinations are of July and August, September and October, and July to September.

The reason behind selecting the regions used in the present study can be tested as follows :

i) The whole region includesthe most important agricultural schemes, irrigated and rainfed, commercial and subsistence, and governmental and private.

ii) The original agricultural data are related to administrative regions such as the planned agricultural blocks of the Gezira scheme.

iii) The regions considered are those which have meteorological stations inside or as near as possible to them.

iv) These regions include the areas with the best records in the Sudan.

The main purpose of treating the whole area selected for the study as a unit and in large groups was to test the assumption that local climatic conditions have their effect on the crop's response, and the large area integration with its inherent differences in weather conditions will present poor results. This study took another dimension where the whole area was split into regions of similar methods of watering and agricultural management. The regions were expected to show better results than the whole area because of the diversity in agricultural practices which may result in different correlations were reduced by such groupings.

Parts of the agricultural area in the study are irrigated. One of the objectives of including those areas was to explore the response of a crop to climatic variables when water supply is no limiting factor. In this way the correlations between the crop yield and the other variables could be compared in the same irrigated area or between the irrigated areas studied. These areas, in fact, lie in different climatic regions (see Fig. 4.8, A.3). While Wad Medani lies in region 6a (Factor analysis regions), Kosti and Dueim lie in region 6b. The various climatic differences would reflect different environments for the crops. Including the irrigated areas in this study gives an opportunity to make suggestions for the experimental work in agronomic stations (e.g. the Gezira Research station) about which variables seem more important than others and which can be taken first for further test.

10.2.2 Methods of weather-crop yield relationship assessment

The weather-crop yield relationship can be approached from an angle different from the statistical approach adopted in this study. Crop growth simulation models can be adopted aiming at the representation of the physical, chemical and physiological mechanisms underlying plant and crop growth processes. The proper understanding and modelling of the basic plant processes will make it possible to simulate the overall response of the plant to its environmental conditions. Simulation models can be made on the bases of various time intervals down to hourly periods which are preferable for their practical representation. This method is very useful for it provides clues for identifying and explaining the factors which are more important than others in the crop-weather relationships. This method also suggests a basis for further experimental work on the processes which are important but not fully understood. However, this experimental work has not yet been well established in the study area. Such experimental work can be witnessed in part of the Gezira scheme for cotton, while for other crops in other areas experiments are limited to short periods. The models, as maintained by Baier (1977), should be thought of as complementary to the statistical model rather than a replacement of it.

Another approach to the question of crop-weather relationships is the use of crop-weather analysis models. One type of model aims at analysing the daily contributions of those selected agrometeorological variables (e.g. solar energy, temperature and soil moisture) to the crop yield (Baier,1973). A fourth power polynomial is used for fitting daily weighted factors related to the daily contribution of each variable to the final yield. It should be said here also that the absence of the necessary data prevented the integration of this method with that adopted in this study. The polynomial method has some elements in common with the multiple regression model used in the present study. The Fisher's polynomial model included in the study was used to investigate the effect of the change (increase or decrease) of pentad rainfall on the change of the final crop yield. The argument related to this is that the crop response to weather variables occurs in a gradual manner. The joint effect of climatic variables (e.g. rainfall and temperature)could have been used for better results if the proper data were available.

The empirical models adopted here aim at describing, explaining and predicting relationships. The statistical methods are particularly helpful in drawing valid conclusions and making reasonable decisions (e.g. in agricultural management) on the basis of this analysis. One of the reasons for choosing the purely empirical approach is to quantify the phenomenon selected for the present study, variation in crop yield, which is well known and generally observed in the area. The reasons behind those variations are known to be complex. There has been a real need to measure in a quantitative form, the degree to which each factor affects crop yield. The models built on statistical bases are important to bridge the gap between observed and theoretical studies.

10.2.3 Statistical methods

Characteristics

The statistical approach adopted for the study of climate-crop relationships is believed to be valid for the Sudan for two main reasons :

i) There is a lack of experimental and field measurements of crops and weather elements in many areas of the Sudan.

ii) The data available are poor and in many cases their gaps have been closed by simple averaging and in many areas they depend on unspecialized reports and general assumptions. The present study presents a better alternative for such procedure.

The data collected from the centres of agricultural production within the study area were first explored by scatter plots for the purposes of inspecting the form of any relationships. This step showed that the scatter plots did not imply any nonlinear relationships. Transformations such as the logarithm, the square root and the selection of certain limits of different climatic variables were also tried. These transformations did not reveal significant correlations. From these preliminary steps, linear correlations and linear regressions were chosen for the study using the data in their original form.

The correlation and regression methods have many advantages, some of which are:

i) bivariate and multiple regression are useful in explaining the relationship(s) between the independent and the dependent variables;

ii) the bivariate correlation has the advantage of showing the relationship between two variables in isolation;

iii) this approach is a practical one for the identification of important variables in the context of climate-crop relationship;

iv) the models give general summaries for the climate-crop relationships which can be taken as a step for detailed inspection of those relationships.

Several problems are related to the statistical methods used which affect the results obtained from them :

i) Attempts made to express the relationships between climatic variables and crop yield in mathematical terms will be faced with difficulties. The crop in its different stages of growth responds to a large variety of factors as well as the combination of those two factors.

ii) The relationships found statistically between climatic variables and crop yields do not imply cause and effect relationships.

iii) In the regression procedures the controlling variables are assumed to be independent where in fact they are often not so, because of the interactions between those variables and the influence of each of them on the other. An example for this is the July rainfall and temperature variables where they have strong negative correlation with each other, i.e. -0.92 (see Table 3.2). This relationship was reflected on the relationship of each variable with crop yield such as those of Wad Medani-Dueim cotton and Dueim sesame (see Tables 7.5, 7.6 and 9.2).

iv) The multicollinearity problem in the multiple regression analysis occurs when one of the controlling variables is a function of another one. This problem may result in unstable estimates or predictions.

v) The statistical method is described by Monteith (1981) as very uninstructive when it is used to analyse crop weather relations because it ignores the interactions of physical and physiological mechanisms. Although this criticism is recognized, the statistical method is known to be a very pragmatic approach for the assessment and the prediction of crop yield. In this study where the statistical models were mainly designed for the purposes of explanation and prediction, a special need was true because of the quality of the data available. In addition, the models were not designed to solve the agronomic or agrometeorological problems.

In spite of their several disadvantages, the statistical models are believed to be useful for their capability of presenting good estimations and predictions. It can be observed from Figures 7.4, 8.3, 9.2 and 9.4 that estimations and predictions for different crops are good and they generally match the observations either in real values or in the trends of yield variations.

The models and the results obtained from them were assessed on the following bases :

i) they were compared with the observed yield and the degree of the associations between the observed and estimated yield were statistically measured.

ii) The results were compared with the general literature about the specific crop under consideration as well as about the plant environment.

iii) The results were compared with the results obtained from similar models used elsewhere in the world.

Climate-crop yield relationships

In the study of the climate-crop yield it has been found that poor results are expected from considering the whole country in a single analysis.

1. Cotton

Rainfall

In the whole area, as can be seen from Table 7.2, cotton-rainfall correlations were below r = 0.2. Reasons for this seem to be:

i) the differences between places in patterns, densities and incidence of rainfall;

ii) the different methods of irrigation technique;

iii) the different types of cotton and methods of cultivation;

iv) the different timing of cultivation in relation to rainfall incidence.

These differences result in different correlations and even with different signs which affect each other. July and August correlations are 0.16 and in October no relationship is found (r = 0.0).

In the irrigated area weak correlations between cotton and rainfall were obtained. However these relationships are clearer than in the case of the whole integrated regions. For June and the annual rainfall r = 0.34 each. This is probably because there is a need to supply water to the soil in the pre-sowing season. In the rainfed area cotton-rainfall relationships became significant in the pre-season period (r = 0.36), in the flowering and bolling period (r = 0.55) and for the year total (r = 0.43). These results show better relationships if compared with the irrigated area because rainfall is the major source for watering cotton.

The Wad Medani-Dueim area in 1951-1960 showed strong cotton-rainfall relationships (annual, r = 0.65; September - October, r = 0.6; July, r = 0.56). This positive relationship was particularly noticed with the rainfall of the pre-season and the vegetative periods. Weak relationships in the sowing and emergence period are noticed (August, r = 0.23). At this stage watering is not as critically needed as the period before and after it. In the 1961-1970 period no similar strong relations of the cotton yield are noticed although the pre-sowing, flowering and the year totals resulted in r = 0.35, 0.31 and 0.4 respectively. Many reasons may be attributed to such differences between the two periods studied:

i) The application of widescale irrigation of fallow (SGB, 1966);

ii) The introduction of new methods of pest control and spraying (SGB, 1963);

iii) The adoption of new sowing techniques of cotton plant;

iv) Salt in the soil, especially sodium carbonate, in Gezira is known to be a problem in cotton cultivation. Experiments on the soil have positively reflected on the yield in terms of applying new methods of fertilizers.

In the Wad Medani area (irrigated) a weak negative relationship with rainfall in August was revealed (r = -0.10). Although this is not significant it can be generally said that rainfall was not beneficial to the crop for two reasons :

i) there is a danger of inundation and waterlogging;

ii) there may be a delay in cotton sowing from August which is the optimum period (Razaux et al., 1967; Jackson, 1969b).

In the Kadugli area (rainfed) similar negative relationships occur in the sowing period (July, r = -0.36). The weak rainfall-cotton relationship may be related to several reasons:

i) rainfall in part of the study areas is sufficient and the plant may not suffer from moisture stress

ii) variation of rainfall during the seasons of the sample might have fallen within the optimum requirements of the crop;

iii) the relationships of rainfall with soil moisture and water balance affect the response of the crop to the variation of rainfall.

In the Aroma area (flood irrigated) weak relationships were noticed (Table 7.12) and there were negative relationships for July and the year's total rainfall. The flood water seems generally sufficient for crop watering and this may be behind these results.

Temperature

The temperature-cotton relationship, particularly minimum temperature, showed negative coefficients. If the whole area is considered the average temperature showed negative correlations throughout the growing season, particularly between November and January (r = -0.37). Maximum temperatures had significant negative relationships early in the season (August and September, r = -0.29) and significant positive correlations during the picking period (February, r = 0.22; March, r ≟ 0.33). The minimum temperatures were negatively correlated with cotton throughout the season, especially between November and January (r = -0.46). In the irrigated area there is a general agreement with the results of the whole area with special stress on the negative relationships in December and January (r = -0.56) and on the strong positive relationships in the picking period (February, r = 0.72; March, r = 0.60). In the rainfed areas similar results were obtained where strong negative relationships in the flowering and bolling periods were reflected (October, r = -0.74; November, r = -0.68). Support for these results came from the following sources:

i) From experimental work in the Gezira scheme (Cowland, 1947; quoted in Jackson, 1969a) where the studies showed that a drop in temperature helps to control insect reproduction. Insect and pest control is a serious problem in crop cultivation. Serious damage and great losses are witnessed frequently in different parts of the study area. It is stated that the incubation period of the egg and larval stage of thrips were shortened by a rise in temperature and the jassids were much less prolific and had longer immature stages during cold, dry weather.

ii) Eaton (1955) maintains that boll production and maturity are inversely related to mean daily temperatures.

iii) Gipson and Joham (1968) confirmed Eaton's (1955) findings and observed that the relationships existed with both day and night temperatures.

iv) Powell (1969) maintained the negative relationship with minimum temperature in particular.

v) Hesketh and Low (1968) stated that the optimum temperature for boll production was lower than that for the vegetative period.

<u>Other variables</u>

Sunshine-cotton relationships were related to those of temperature. These relationships were always negatively related to cotton (r = -0.44). In the Sudan sunshine is always sufficient for plant growth. Intensive sunshine (hot conditions) help extra water losses from the soil and from plants through evapotranspiration mechanism. More data than the available are needed to measure these rates at the different places of the study area. As the decrease in temperature is suggested to be beneficial to cotton, so is the decrease of sunshine is expected to be beneficial also. Relative humidity generally resulted in similar relationships as rainfall and opposite to those of temperature and evaporation.

2. Sorghum

Considering climate-sorghum yield relationships it can be generalized that the crop had positive relationships with rainfall and negative ones with temperature before the ripening stage.

Rainfall

From the results reached in this study it is shown that a decrease in rainfall is harmful to sorghum in the flowering stage. Rainfall in the irrigated area (Wad Medani-Dueim-Kosti) was significantly related to the yield only in the yearly totals ($r = 0.42$). In the rainfed area (Gedaref-Abu Naama-Kadugli) and the flooded area (Aroma) strong positive relationships occurred at different periods. They were strong in July at Singa ($r = 0.5$), in August at Abu Naama ($r = 0.55$) and Aroma ($r = 0.75$), and in October and Gedaref ($r = 0.65$). This confirms the strong relationships between rainfall and sorghum early in the rainy season with different stresses in the period due to differences in sowing dates and local environments. At Gedaref the strong relationship with October rainfall suggests that the moisture balance in relation to the local environment are in favour of rainfall increase. However, the weak correlations between sorghum and rainfall in the rest of the rainy months may be related to the fact that sorghum is known to be less sensitive to a shortage of water especially towards the ripening period. The weak relationships of the different climatic variables with sorghum yield, such as those of Gedaref (Table 8.4) and Singa (Table 8.5), may be related to the following reasons :

i) The adaptability of the sorghum to the area it was grown in. This may result in modification of the same sorghum species response to the different climatic variables.

ii) The decreasing effect of climatic variables on the crop in its final stages of development.

Temperature

In the irrigated area temperature had a negative correlation with sorghum throughout most of the growing months. Temperatures-sorghum relationships were relatively stronger in August. For maximum temperature in this month r = -0.43 and for the average temperature r = -0.39. In the rainfed area these results were restored, where in August the relationships between sorghum yield and maximum and minimum temperatures were r = -0.42 and -0.41 respectively. In addition, September showed stronger negative correlations for the same variables (maximum temperature, r = -0.65; average temperature, r = -0.63). These findings are supported by studies in different areas in the world :

i) Downes (1972) showed that high temperatures between germination and initiation resulted in low grain yield of sorghum.

ii) Thompson (1963) maintains that higher than average temperatures early in the season appear to be detrimental to sorghum.

iii) Sorghum is susceptible to drought before or at head emergence (Kowal and Andrews, 1973).

iv) High temperatures, by increasing the rate of evaporation, may result in plant stress (Curtis, 1966; Pasternak and Wilson, 1969).

Sorghum-temperature relationships became weaker in the ripening period where, due to its nature as it needs a drier period for the process of ripening, the crop became less sensitive to the increase of temperature or decrease in moisture. In the irrigated area in this period (October) rainfall showed a negative, though weak, relationship with the yield (r = -0.21). Temperature showed weak relationships (e.g. minimum temperature, r = -0.14). This relationship sometimes became positive (e.g. days with temperature > 35 °, r = 0.22). In the rainfed area rainfall also has no relationship with yield in the ripening period (r = 0.04). Temperature relationships became also weaker in this period than in the pre ripening period. The highest correlation for the whole area occurred between the minimum temperature and sorghum yield (r = -0.48).

3. Sesame

Rainfall

The results obtained from the climate-sesame relationship study showed an agreement with the general environmental requirements of the crop as suggested by different authors. The crop generally requires moderate amounts of rainfall and well drained soil. Heavy rain or high humidities, especially after sowing, may seriously affect the crop (Macmillan, 1956; Ochse et al., 1961; Kumar, 1963, Irvine, 1969). In the Dueim area rainfall is 270 mm p.a. which is less than half the amount of each of the other two areas (Gedaref, Abu Naama) and it is more variable. This can be related to the very strong positive relationship between rainfall and sesame yield. July rainfall as well as the distribution through the month (Pentad totals) showed correlation coefficients of 0.72 and 0.80. In the Gedaref area rainfall early in the season (July) showed significant correlations with sorghum yield (r = 0.49), but it was far less significant than at Dueim. In the Abu Naama area a negative correlation, though not reaching a level of statistical significance between rainfall and sesame occurred in July (r = -0.20). The negative relationship implied here may be related to the problem of drainage which is known to exist in the Abu Naama area.

Temperature and other variables

In the Dueim area temperatures, particularly minimum temperatures, had strong negative correlations with sesame yield. In July, August and October, correlation coefficients were -0.77, -0.57 and -0.73 respectively. This can be related to the contribution of temperature to evaporation which may lead to plant stress. In the other two regions neither temperature nor other climatic variables showed significant relationship (see Tables 9.3, 9.4). The reasons for this situation can be related to the following :

i) the moisture supply variable is crucial for the sesame plant and it is satisfactory at Gedaref and Abu Naama.

ii) the variations within each climatic element in the sample are not large enough to have a considerable effect on the crop yield, and the crop is less sensitive to those variations than those of moisture.

4. Groundnuts

Rainfall

In the groundnut yield-climate relationship assessment it is observed that both areas selected for the study (Wad Medani, Kosti; irrigated) agreed on negative relationships for October rainfall (Wad Medani, r = -0.42; Kosti, r = -0.5). July showed insignificant relationships. In August there was a contradiction as Wad Medani showed a negative correlation (r =-0.57) and Kosti showed a positive one (r = 0.45). This result could be accepted when looking at the drainage efficiency at each area. The Wad Medani area has an almost flat landscape, whereas at the Kosti area (south western Gezira) the slope of the land is steeper. The waterlogging and inundation are most likely to occur at Wad Medani than at Kosti. Kosti showed a strong positive correlation between the yield and the year total rainfall (r = 0.69). In both areas there were alternating periods of strong and weak as well as positive and negative relationships which could be put in the context of the moderate distribution of rainfall required by the plant. The negative relationships in particular may be due to :

i) the delay of sowing and the danger of waterlogging which will be reflected in the final yield

ii) the excessive rainfall (or water supply) in October could be harmful for it may result in the promotion of extravegetative growth during the normal period of pod development (Ochse et al., 1961; Holford, 1971).

Temperature

At Kosti there were generally negative relationships between temperatures and groundnut yields, but these relationships became significant only in September (r = -0.55). At Wad Medani temperature was negative in July (r = -0.52) and positive in most of the growing season months but they did not reach significant level. For the other variables, both areas showed positive relationships with relative humidity in parts of the growing season. Evaporation showed a negative relationship early in the season at Kosti, while this was only reflected in July at Wad Medani. These results appear logically related to the reasons provided in the case of the moisture situation in each of the areas.

10.2.5 Applications of the statistical models

The Barrett model for rainfall estimation which has been modified in the present study for the Sudan could be used by the Sudan Meteorological Department provided that wind speed and wind direction be included as variables in the model. The Meteorological Department can then apply the equations obtained at the longitude/latitude raingauge cells (gacells) to those cells without raingauges (satcells).

The potential use of the results obtained from the study in connection with climate-crop yield relationships based on statistical models can be achieved in many areas. The estimations and predictions of crop yields produced by the regression models at different localities are to some extent satisfactory. The regression formulae can be used for prediction and assessment at the localities as well as at their surroundings. Another dimension of the use of these models is that the formulae produced for a crop production centre can be taken as representative of the climatic region identified by factor analysis (Fig. A.3) because of the proposed similarity between places within the region. This seems more realistic than averaging for administrative regions (provinces and districts). In the case of the occurrence of several formulae from source stations within the same region then the nearest of those stations to the place under consideration should be taken. A very important application of the models is that estimations of yields at the centres within the same climatic region (see Figs. 4.8, A.3) can be made, and the productivity of each region can be estimated by averaging those estimations. This is believed to give better results than estimations and averages from the large administrative regions (i.e. Provinces).

From the study of crop-climate relationships at the different places in the study areas, plans from the Mechanized Farming Corporation and the Agrarian Reform can be carried out to introduce similar crops to other areas of similar climatic regions. Private or association investments can be directed to those areas with the help of the Ministry of Planning. An example of this is that the type of cotton grown at the Kadugli area will be more successful at the Abu Naama area than at the Singa area. This is due to the fact that both Kadugli and Abu Naama lie in the same climatic region, 7a (Figs. 4.8, A.3) while Singa lies in region 6b. This would only occur of course if other factors (e.g. type of soil, level of technology) are not largely different.

In the irrigated areas (see Table 7.1) the curves constructed for the effects of changes of rainfall through short periods within the growing season provide an opportunity to calculate the overall expected effects on the crop. Modifications and adjustments of management plans can be made by the SGB and the Agrarian Reform authorities to counterbalance any negative effects of rainfall, or to prepare for the increase of productivity (e.g. cotton picking plans, labour recruitment or securing other water supplies and transport of crop from farms to marketing centres). The adjustments of the Mechanized Farming plans could also be made at earlier stages in the rainy season according to the trends of the effects suggested by the curve. In the rainfed areas (Table 7.1) harmful effects might be hinted at early in the season and plans to tackle those harmful effects could be started. Activities in, for example, draining surplus water, weeding and thinning could be increased accordingly.

The national development plans executed through coordination among the Ministries of Planning, Agriculture and Economics and Finance can make use of the regions identified by the factor analysis classification in selecting the areas of optimum climatic conditions for new agricultural schemes. The models built in this study can be integrated in this context to help make the right choice.

In general terms, if a newly introduced crop flourishes in (or near) the production centres used in this study then areas of similar climatic conditions (Figs. 4.8, A.3) are recommended for the same crop provided that nonclimatic variables are not of great diversity. The correlations between crop yields and the many climatic variables shown in this study can help to understand the nature of crop responses to climatic conditions at the local areas studied and their surroundings. These results suggest that these relationships can be taken for further examinations at agronomic stations (e.g. Gezira). The estimations and predictions reached by applying the statistical models show the potential yields based on climatic variables alone. This knowledge is important for it helps in good assessment of crop productivity and evaluation of other reasons for crop yield deviations from the estimated ones. The models can also be used to close data gaps at the localities where they are developed or for their surroundings. This will provide agricultural planners, e.g. of the Mechanized Farming Corporation and the Agrarian Reform with a better view of the productivity records at those areas.

The crop yield assessment models used in this study could be used at national level as well as in the Early Warning System on Food and Agriculture (operated by FAO). The improvements of estimations and predictions will help in the collection of good information at the national scale which can then be transmitted to the FAO. This is particularly important because the area selected for the study is of great importance for the Sudan in terms of cash and food crop production. The improvement of estimates and assessment of crops will aid better management decisions at a global level in relation to agricultural production, storage, marketing and food distribution.

10.3 Summary

The difficulties faced in the study of the climate-crop yield relationships in the Sudan caused by the different factors previously discussed can be summarized as follows:-

1) There is a need to improve the meteorological station network over the Sudan, together with raising the status of those stations to measure as many climatic elements as possible for a better understanding of the weather and climate of the Sudan.

2) There is also a need for increasing the number of agrometeorological stations over different crop production areas.

3) Coordination must be developed between activities at agricultural research stations and agrometeorological stations in relation to the measurement of the variables needed for the crops under consideration. Field crop microenvironment measurements must go hand in hand with laboratory controlled experiments.

4) The fulfilment of the previous suggestion would help to provide much information about the development of crops through the growing season, with more specification of the phenological stages of the crop, which will reveal more concrete information about weather/climate-crop relationships through integrating empirical and experimentally-based models.

5) Agricultural management information based on scientific assessment and statistically prepared data in many of the agricultural areas will be helpful in providing more reliable data. This information gives an opportunity of integrating new quantitative information into the model for better results or even for modification of the models.

It can be concluded from this study that the problem of the climate-crop yield relationship study is a vital and a complex problem which needs an integration of approaches and the use of a variety of techniques to assess the influences of climate on crops in general and crop yields in particular.

To obtain ideal results special types and sizes of data are required. In the Sudan work over a considerable time period is needed to establish such flawless situations. These ideal requirements for climate-crop relationship evaluation have not been reached yet in any part of the world; equally there is no full agreement about the best approach to this problem. So in this context the present study aims to be immediately useful in making the best of the available information about climate-crop yield relationship in the Sudan.

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TABLE A.1 LIST OF CLIMATOLOGICAL STATIONS, THEIR GEOGRAPICAL LOCATIONS, ALTITUDES AND YEARS OF RECORDS WITHIN THE PERIOD 1941-1970

NO	NAME	LAT.	LONG.	ALT.	YEARS
1	WADI HALFA	21.8	31.4	188	26
2	STATION 6	20.8	32.6	470	18
3	PORT SUDAN	19.9	37.2	5	30
4	ABU HAMAD	19.5	33.3	315	28
5	DONGOLA	19.2	30.5	228	26
6	GEBEIT	19.0	36.9	795	21
7	KARIMA	18.6	31.9	250	30
8	TOKAR	18.4	37.7	20	21
9	HAIYA	18.3	36.4	620	21
10	ATBARA	17.7	34.0	345	30
11	DERUDEIB	17.6	36.1	510	21
12	SHENDI	16.7	33.4	360	21
13	AROMA	15.8	36.2	430	21
14	SHAMBAT	15.7	32.5	380	30
15	KASSALA	15.5	36.4	500	30
16	HALFA EL GEDIDA	15.3	35.6	450	7
17	ET TURABI	15.1	33.1	390	21
18	ABU QUTA	14.9	32.7	390	21
19	QURASHI	14.8	33.3	400	21
20	SODIRI	14.4	29.1	540	5
21	WAD MEDANI	14.4	33.5	405	30
22	EL MANAQIL	14.3	33.0	410	8
23	KUTUM	14.2	24.7	1160	12
24	GEDAREF	14.0	35.4	600	30
25	DUEIM	14.0	32.3	380	21
26	HAGABDALLA	14.0	33.6	415	21
27	EL FASHER	13.6	25.3	730	30
28	SENNAR	13.6	33.6	420	21
29	GENEINA	13.5	22.5	805	30
30	EL OBEID	13.2	30.2	570	30
31	KOSTI	13.2	32.7	380	30
32	SINGA	13.2	34.0	430	21
33	ZALINGEI	12.9	23.3	900	28
34	ABU NAAMA	12.7	34.1	445	14
35	EN NAHUD	12.7	28.4	565	29
36	NYALA	12.1	24.9	675	21
37	RASHAD	11.9	31.1	885	8
38	ROSEIRES	11.9	34.4	465	18
39	ED DAMAZIN	11.8	34.4	470	9
40	ER RENK	11.8	32.8	380	18
41	GHAZALA GZT.	11.5	26.3	485	14
42	KADUGLI	11.0	29.7	500	21
43	KURMUK	10.6	34.3	690	21
44	MALAKAL	9.6	31.7	390	30
45	AWEIL	8.8	27.4	415	15
46	NASIR	8.6	33.1	400	18
47	RAGA	8.5	25.7	545	19
48	AKOBO	8.3	33.0	400	18
49	WAU	7.7	28.0	435	29
50	TONJ	7.3	28.8	430	18
51	SHAMBE	7.2	30.8	415	14
52	PIBOR	6.8	33.1	410	5
53	ROMBEK	6.8	29.7	420	16
54	BOR	6.2	31.6	420	18
55	LI YUBU	5.4	27.3	715	14
56	MARIDI	4.9	29.5	750	13
57	JUBA	4.9	31.6	460	30
58	YAMBIO	4.6	28.4	650	18
59	TORIT	4.4	32.6	625	16
60	NAGISHOT	4.3	33.6	1980	10
61	YEI	4.1	30.7	830	5

*RAINFALL AVERAGES FOR 30 YEARS ARE AVAILABLE FOR ALL STATIONS

SOURCE: SUDAN METEOROLOGICAL DEPARTMENT

(1) 1941-71 CLIMATIC NORMALS
(2) 1941-70 RAINFALL AVERAGES
(3) 1950-1970 ANNUAL METEOROLOGICAL REPORT

Table A.2 Relief and temperature of different localities in the Sudan

Locality		Relief m	Temperature ^{0}C
Red Sea	Tokar	20	29.9
	Haiya	640	28.3
	Gebeit	795	25.3
West	El Fasher	730	25.7
	Zalingei	900	24.0
	Kutum	1160	23.3
Centre	Kadugli	500	28.1
	Renk	576	27.5
	Rashad	885	26.7
South	Juba	460	27.5
	Yambio	650	25.0
	Yei	840	24.6
	Nagishot	1980	18.0

Source : Sudan Meteorological Department :

(1) 1950 - 1970 Annual meteorological Reports

(2) 1941 - 1970 Climatological normals

Table A.3 **August rainfall at selected places along longitudes 31° - 34°E**

Latitude \ Longitude	31° - 32° E	32° - 33° E	33° - 34° E
18°- 20°N	0	0	4
14°	-	94	119
13°	134	142	125
12°	143	145	160
11°	156	-	203
			227
10°	178	194	193
9°	225	202 194	182 185
8°	-	225	194
	175	198	224
7°	155	141	162
6°	132	142	144
5°	125	121	-
4° N	150 169	140 141	176

Source : Sudan Meteorological Department :

(1) 1950 - 1970 Annual meteorological report.

(2) 1941 - 1970 Climatological normals

TABLE A.4 CLIMATIC DATA USED IN THE FACTOR ANALYSIS CLASSIFICATION OF THE SUDAN

		TA	T1	T1MA	T1MI	T7	T7MA	T7MI	TR	PA	P1	P7	PN	RH A	RH 1	RH 7
1	WADI HALFA	26.2	16.5	24.8	8.2	32.9	41.4	24.3	16.4	3	0	1	1	17	23	15
2	STATION 6	26.4	18.0	25.8	10.2	31.3	38.9	23.7	13.3	7	0	3	1	20	25	16
3	PORT SUDAN	28.4	23.6	27.3	19.9	34.3	40.6	27.9	10.7	122	23	10	13	59	67	45
4	ABU HAMAD	29.3	21.0	28.8	13.1	34.4	41.7	27.1	13.4	15	0	6	3	16	22	16
5	DONGOLA	27.6	18.6	27.8	9.3	32.7	40.2	25.1	14.1	21	0	6	3	19	25	18
6	GEBEIT	25.3	19.5	24.0	15.0	30.3	36.8	24.7	10.8	122	2	37	12	41	57	31
7	KARIMA	29.1	20.7	28.8	12.6	34.2	41.4	26.9	13.5	41	0	13	5	16	20	17
8	TOKAR	29.9	24.5	28.6	20.3	34.4	40.3	28.5	9.9	87	18	9	12	47	63	27
9	HAIYA	28.3	22.9	29.8	15.9	31.1	37.5	24.7	8.2	87	0	23	12	28	32	28
10	ATBARA	29.8	22.6	30.5	14.7	33.8	40.4	27.2	11.2	69	0	27	9	18	23	21
11	DERUDEIB	29.3	24.5	32.7	16.3	31.3	37.4	25.1	6.8	115	0	33	12	26	30	34
12	SHENDI	29.7	23.0	31.0	15.0	32.9	39.0	26.8	9.9	117	0	37	10	21	24	27
13	AROMA	29.0	24.1	33.9	14.3	30.1	35.3	23.8	6.0	227	0	65	21	28	29	37
14	SHAMBAT	28.6	22.7	30.7	14.6	31.4	37.6	25.1	8.7	165	0	50	16	21	21	31
15	KASSALA	29.2	25.2	34.3	16.0	29.5	35.6	23.4	4.3	314	0	97	30	28	27	41
16	HALFA EL GEDIDA	28.7	23.7	33.3	14.1	29.9	35.8	22.9	6.2	358	0	118	26	27	25	34
17	ET TURABI	28.4	23.0	32.8	13.1	30.3	36.9	23.7	7.3	257	0	85	22	23	20	36
18	ABU QUTA	28.4	23.0	32.6	13.6	30.3	36.6	24.0	7.3	242	0	79	21	23	20	36
19	QURASHI	28.3	23.0	33.0	12.9	29.9	36.4	23.4	6.9	265	0	77	23	23	20	36
20	SODIRI	26.0	20.3	29.4	11.1	29.9	35.5	24.3	9.6	202	0	73	15	20	15	34
21	WAD MEDANI	28.3	23.8	33.6	14.0	29.3	35.8	22.8	4.3	362	0	116	37	24	18	39
22	EL MANAQIL	28.3	23.4	32.8	14.0	29.4	35.7	23.0	6.0	262	0	85	18	28	25	39
23	KUTUM	23.3	17.9	28.6	7.2	26.5	32.9	20.1	8.6	316	0	86	31	24	19	35
24	GEDAREF	28.5	26.1	34.9	17.3	27.2	32.8	21.5	1.1	579	0	154	48	31	23	47
25	DUEIM	28.7	24.3	31.9	16.7	29.7	36.1	23.2	5.4	276	0	75	20	27	24	37
26	HAGABDALLA	27.8	23.2	34.0	12.3	28.5	34.9	22.1	5.3	430	0	122	33	30	24	44
27	EL FASHER	25.7	20.1	30.6	6.5	28.6	34.8	22.4	8.5	286	0	86	32	23	18	37
28	SENNAR	28.4	24.8	34.3	15.2	28.3	34.4	22.1	3.5	472	0	138	38	29	23	42
29	GENEINA	25.7	22.0	32.2	11.7	26.4	32.0	20.8	4.4	559	0	168	54	24	11	48
30	EL OBEID	27.0	22.1	30.6	13.5	28.2	33.4	22.9	6.1	386	0	113	36	25	16	47
31	KOSTI	28.7	24.8	32.9	16.7	29.0	34.6	23.3	4.2	396	0	111	40	29	23	46
32	SINGA	28.5	25.4	34.1	16.6	27.8	33.3	22.2	2.4	582	0	116	43	31	25	48
33	ZALINGEI	24.0	20.2	34.0	6.3	25.1	30.9	19.3	4.9	665	0	189	62	27	14	52
34	ABU NAAMA	28.1	25.0	35.0	15.0	27.1	32.5	21.7	2.1	574	0	123	54	31	17	54
35	EN NAHUD	27.2	22.7	31.8	13.5	28.0	33.2	22.8	5.3	406	0	112	39	26	15	48
36	NYALA	27.1	23.5	31.5	15.5	26.8	32.1	21.4	3.3	470	0	138	43	25	13	49
37	RASHAD	26.5	24.0	31.2	16.8	25.0	30.0	19.9	1.0	781	0	159	63	40	32	59
38	ROSEIRES	28.1	26.1	36.0	16.2	26.3	31.0	21.5	0.2	732	0	152	65	35	21	58
39	ED DAMAZIN	28.1	26.1	35.5	16.7	26.6	31.7	21.5	0.5	730	0	181	67	33	18	57
40	ER RENK	27.5	24.1	33.2	15.0	27.4	32.7	22.0	3.3	519	0	117	42	36	26	53
41	GHAZALA GZT.	27.5	23.3	32.4	14.1	27.5	32.5	22.5	4.2	473	0	108	42	31	18	55
42	KADUGLI	28.1	26.2	35.6	16.7	27.0	32.4	21.5	0.8	735	0	139	60	37	23	54
43	KURMUK	27.3	28.7	36.4	21.0	24.8	29.5	20.1	3.9	982	0	165	73	39	20	63
44	MALAKAL	27.9	26.9	35.4	18.4	26.2	30.7	21.6	0.7	787	0	149	67	39	18	63
45	AWEIL	27.5	25.8	34.7	16.8	26.2	31.0	21.4	0.4	875	0	192	67	43	24	65
46	NASIR	27.3	26.7	34.4	19.0	25.5	29.9	21.3	1.1	791	0	151	59	48	30	68
47	RAGA	25.8	23.1	34.7	11.4	25.2	30.3	20.1	2.1	1188	0	210	86	41	22	64
48	AKOBO	28.1	28.2	36.5	19.8	26.1	31.0	21.2	2.1	997	3	198	72	46	28	62
49	WAU	27.7	26.8	35.8	17.8	26.2	30.9	21.4	0.6	1175	1	205	88	38	17	60
50	TONJ	27.4	26.7	35.4	17.9	25.6	30.9	20.3	1.1	1076	3	230	78	49	27	66
51	SHAMBE	26.8	25.7	33.5	17.9	26.3	32.0	20.5	0.6	729	1	153	45	47	27	66
52	PIBOR	27.9	28.7	36.8	20.5	26.3	31.2	21.3	2.4	953	9	179	59	45	33	62
53	ROMBEK	27.5	26.7	35.3	18.1	25.9	30.9	20.8	0.8	953	1	163	73	46	26	63
54	BOR	27.4	20.1	35.7	20.4	25.9	30.8	20.9	5.8	905	5	142	67	50	32	65
55	LI YUBU	25.3	26.2	33.2	19.2	23.9	28.4	19.3	2.3	1476	10	178	104	52	33	66
56	MARIDI	24.7	25.1	34.2	16.0	22.6	28.3	16.9	2.5	1411	11	194	110	56	28	69
57	JUBA	27.5	28.2	36.7	19.7	25.6	30.4	20.7	2.6	988	4	136	95	45	24	62
58	YAMBIO	25.0	25.3	33.7	16.9	23.7	28.8	18.6	1.6	1464	12	157	117	54	34	68
59	TORIT	26.6	27.6	36.6	18.5	25.0	30.5	19.4	2.6	1022	7	174	100	44	25	60
60	NAGISHOT	18.0	19.0	24.3	13.7	16.2	20.5	12.4	2.8	1184	15	201	99	62	46	79
61	YEI	24.6	25.2	34.5	15.9	23.1	28.4	17.7	2.1	1373	10	184	105	48	27	62

1=JANUARY,
7=JULY,
A=ANNUAL,
MA=MAXIMUM,
MI=MINIMUM,
T=TEMPERATURE (°C),
RH=RELATIVE HUMIDITY (%),
P=RAINFALL (MM),
PN=NUMBER OF ANNUAL RAINDAYS

TR=RANGE OF TEMPERATURE, JUL.-JAN. (°C)

SOURCE: (1) SUDAN METEOROLOGICAL DEPARTMENT (1973) CLIMATOLOGICAL NORMALS 1941-1970,
(2) SUDAN METEOROLOGICAL DEPARTMENT (1950-1975) ANNUAL METEOROLOGICAL REPORTS, KHARTOUM, SUDAN.

Table A.5 Correlations between cloud amount, cloud type and synoptic condition as calibrated from satellite images

No.	Station	July			August			September		
		AM/TY	AM/SY	TY/SY	AM/TY	AM/SY	TY/SY	AM/TY	AM/SY	TY/SY
1	Shambat	0.78	0.90	0.90	0.92	0.82	0.87	0.97	0.94	0.99
2	Kassala	0.77	0.87	0.74	0.78	0.69	0.77	0.97	0.94	0.93
3	Wad Medani	0.91	0.88	0.89	0.92	0.77	0.70	N.P.	N.P.	N.P.
4	Gedaref	0.93	0.87	0.79	0.89	0.79	0.80	0.84	0.94	0.66
5	El Fasher	0.75	0.79	0.84	0.84	0.66	0.77	0.70	0.82	0.72
6	Geneina	0.69	0.82	0.73	0.77	0.68	0.74	0.85	0.78	0.81
7	El Obeid	0.90	0.81	0.85	0.84	0.73	0.77	0.80	0.89	0.76
8	Kosti	0.86	0.82	0.85	0.68	0.73	0.57	0.86	0.83	0.85
9	Ed Damazin	0.86	0.59	0.73	0.75	0.79	0.74	0.86	0.76	0.63
10	Kaduglie	0.86	0.76	0.78	0.86	0.80	0.89	0.61	0.76	0.75
11	Malakal	0.86	0.81	0.70	0.77	0.63	0.87	0.11	0.79	-0.03
12	Wau	0.76	0.77	0.81	0.89	0.80	0.86	0.83	0.82	0.80
13	Juba	0.72	0.73	0.68	0.69	0.82	0.60	0.91	0.29	0.31
No. of Cases		29			30			30		

N.P. = Calculations were not possible (invariable figures)

AM = Cloud amount (%)

TY = cloud type (Table 5.1)

SY = synoptic condition (Table 5.2)

TABLE A.6

FORMULAE USED IN DAILY JULY RAINFALL ESTIMATIONS(RF)**

```
SHAMBAT
 RF= 0.00113526*AM +0.0000201*SW -0.000025328*EA
 -0.0251915*SY +0.004321642*TY -0.00001308509*WE
 -0.00004445453*DS +0.03542263

KASSALA
 RF= 0.4101201*AM -7.252984*SY +0.009415704*DS
 -0.3679165*TY 0.007972373*SO -0.00270618*SW
 +0.001992488*EA +9.850607

WAD MEDANI
 RF= 3.43008*SY +0.004969140*SO -0.09462064*AM
 -0.00601967*EA +0.0174390 4*DS +0.00330248*SW
 -0.1479549*TY +0.000481402*WE -2.902557

GEDAREF
 RF= 0.009805355*DS +4.980735*SY -0.4224718*AM
 +2.153557*TY -0.004032638*EA -0.001431851*WE
 -0.001633915*SW +0.002660173*SO -2.983705

EL FASHIR
 RF= 0.01352904*WE -0.01523843*EA -0.008508*SO
 -3.45524*SY +0.7546648*TY -0.09830954*AM
 +0.001442287*SW -0.001653965*DS +12.32495

GENEINA
 RF= 0.00831575*DS +0.01061035*EA -0.0119331*SW
 +0.008849926*SO -0.002581581*WE +0.1431597*TY
 -0.01298248*AM +2.9606336

EL OBEID
 RF= -0.009928824*EA -0.05676259*DS +0.0233736*TY
 -0.00688069l*SO +0.1083161*AM +0.003508671*WE
 -0.001567969*SW +5.765558

KOSTI
 RF= 0.1396725*AM -0.01206631*DS -0.572034*TY
 -0.005688235*SO +2.103703*SY +0.001627814*WE
 +0.001947948*EA +0.001230876*SW -2.562995

ED DAMAZIN
 RF= -0.01262598*WE -0.02404912*SO -0.00071666*EA
 +0.008347751*SW +0.1398584*AM -1.111963*TY
 +0.007709019*DS +0.6318207*SY +6.320224

KADUGLI
 RF= 0.01692578*EA -0.02592903*SO +0.01115521*SW
 -0.5108127*TY -0.00743427*DS -0.005317281*WE
 +0.7519366*SY +4.609426

MALAKAL
 RF= 0.003409459*SW -0.03839097*EA -0.05410739*WE
 -0.06883595*DS -0.04861991*SO +0.3868052*AM
 -1.434459*TY -1.713941*SY +34.32852

WAU

 RF= 0.009155934*EA +1.11147*TY -0.09136765*AM
 -0.007915974*SO -5.70658*SY +2.01023372*DS
 +0.004631646*SW +0.002537411*WE +10.74868

JUBA
 RF= 5.47403*SY -0.03621678*SW +0.02072276*DS
 +0.01623287*SO -0.275645*AM +1.626545*TY
 -0.01189907*EA -5.668409
```

```
*  MULTIPLICATION SIGN
** AM=CLOUD AMOUNT  TY=CLOUD TYPE  SY=SYNOPTIC CONDITION,
   DS=DISTANCE INWARD INTER TROPICAL CLOUD BAND,
   DISTANCES OF THE NEAREST CLOUD FROM: WE=WEST SO=SOUTH
           SW=SOUTHWEST EA=EAST
```

TABLE A.7

FORMULAE USED IN DAILY AUGUST RAINFALL ESTIMATIONS(RF)**

```
SHAMBAT
 RF= 2.197867*SY -0.02036137*SO -0.1259766*DS
 -0.01962917*EA -0.01797047*WE +0.1904271*AM
 -0.005431158*SW +0.5660242*TY +20.15212

KASSALA
 RF= -0.005606144*WE +0.3454693*TY +0.02080738*SO
 +0.04103196*AM -0.005901407*EA +0.008034376*DS
 +0.001998981*SW -0.2523207*SY +0.003052372

WAD MEDANI
 RF= 0.05762179*DS -0.0241372*SW -5.270383*SY
 -0.005823877*SO +0.08859011*AM
 -0.0031296*EA +13.99137

GEDAREF
 RF= 0.03257362*DS -0.03307711*EA -0.01865946*SO
 -8.670696*SY +0.4587980* AM -1.248993*TY
 -0.004602510*WE +29.09021

EL FASHIR
 RF= -0.01319143*SO -0.009071297*EA +4.935691*SY
 -0.5239319*TY -0.009923537*SW -0.01726195*DS
 -0.005973589*WE +0.02575029*AM +5.441668

GENEINA
 RF= -0.02686306*SO +0.08510368*AM +0.01200597*WE
 +5.742613*SY -0.01095388*SW -0.006002078*EA
 -0.3500965*TY -0.008586542*DS -2.191547

EL OBEID
 RF= 0.1007293*DS +0.02098046*EA +0.2534455*AM
 -5.197279*SY -0.008949651*SO +0.01308721*WE
 -0.2532481*TY -0.00273503*SW -0.7176772

KOSTI
 RF= -0.03166592*SW +0.005415546*WE -0.008469*SO
 +1.32625*TY -4.731995*SY +0.020939*EA
 +0.1262704*AM -0.040955*DS +9.282443

ED DAMAZIN
 RF= -0.04730569*EA +0.01696365*SO +10.20347*SY
 -1.384352*TY -0.2029481*AM -0.007459479*WE
 +0.2027967

KADUGLI
 RF= 0.2629958*AM +0.05035994*SO -0.0362249*SW
 +0.02189862*WE +8.531712*SY -0.0368159*DS
 -0.855964*TY -0.00271053*EA -20.72092

MALAKAL
 RF= 0.3208896*AM -0.03364347*WE -0.01651329*SO
 +0.02606104*SW -0.06989484*DS +8.23346*SY
 -1.639182*TY -7.233912

WAU
 RF= 0.00951563*SW -0.00500154*WE +0.0106279*DS
 +0.1598913*EA +1.938287*TY -8.453041*SY
 -0.05902151*AM +13.59915

JUBA
 RF= 0.05043944*SO -0.01585813*EA +0.1534602*TY
 -0.006549818*WE +0.1027003*AM -3.105719*SY
 -0.002612386*SW +20.23743
```

```
*  MULTIPLICATION SIGN
** AM=CLOUD AMOUNT  TY=CLOUD TYPE  SY=SYNOPTIC CONDITION,
   DS=DISTANCE INWARD INTER TROPICAL CLOUD BAND,
   DISTANCES OF THE NEAREST CLOUD FROM: WE=WEST SO=SOUTH
            SW=SOUTHWEST EA=EAST
```

TABLE A.8

FORMULAE USED IN DAILY SEPTEMBER RAINFALL ESTIMATIONS(RF)**

```
SHAMBAT
 RF= 0.000041899*SO -0.000052114*EA +0.000013053*WE
 -0.02705517*SY -0.003488349*AM +0.02767881*TY
 +0.000370134*DS -0.000002752733*SW +0.04393879

KASSALA
 RF= 0.9254097*AM -16.81484*SY -0.009027275*SO
 -0.1.907162*TY0.004266907*EA -0.003094266*SW
 -22.46795

WAD MEDANI
 RF=0.003189748*SW -0.002758366*SO -0.1420438*AM
 -0.001361332*EA -0.0007818096*WE +0.7998571

GEDAREF
 RF= -0.009201872*EA -0.006997384*SW -0.1507791*DS
 +1.503562*AM -22.60371*SY -3.777231*TY
 -0.004791967*WE +0.008011603*SO +29.78951

EL FASHIR
 RF= 0.925129*TY -0.003635307*SW +0.004121904*EA
 +0.002811532*DS +0.0007355799*SO -0.208761*SY
 -0.0005247259*WE -0.007266142*AM -0.7404278

GENEINA
 RF= 0.07527262*AM -1.747192*SY -0.00298934*EA
 +0.006114514*DS +0.002648507*WE +0.00225677*SO
 +0.190573*TY -0.0006984092£SW +1.599995

EL OBEID
 RF= 0.01637498*DS -0.6057681*SY +0.3962402*TY
 -0.4121886*AM -0.00193094*EA +0.000615715*SW
 -0.0002296667*WE +1.41201

KOSTI
 RF= 0.01079153*SO +0.002579744*WE +0.5019516*TY
 -0.003907358*EA +0.00276074*SW -0.05852347*AM
 +0.01875248*DS -2.059097

ED DAMAZIN
 RF= 1.245852*TY -0.006245809*DS -0.005807906*EA
 -0.001894629*SW -0.8957421*SY +0.05534161*AM
 +0.002719306*SO -0.001231092*WE +4.467666

KADUGLI
 RF= -0.01329147*EA -0.06601318*DS +0.2223561*AM
 -1.11046*TY -0.00870075*SO +0.006278385*SW
 +1.60862*SY -0.001736116*WE +8.065775

MALAKAL
 RF= 0.4692103*AM +0.02116419*WE -7.734707*SY
 +0.03832397*SO -0.03781413*EA -0.0249561*SW
 -0.3914161*TY +0.01563365*DS +10.54736

WAU
 RF= 0.02795699*SW -0.02825667*WE -0.05976882*DS

 +0.03066077*EA +1.969166*TY +0.01975789*SO
 -3.462365*SY +0.1306535*AM -7.239675

JUBA
 RF= 2.713444*TY +0.03266937*WE +0.03175167*DS
 +0.017877892*SW +0.0009508190*EA -1.209470*SY
 +0.005802211*SO -17.54158
```

```
*  MULTIPLICATION SIGN
** AM=CLOUD AMOUNT  TY=CLOUD TYPE  SY=SYNOPTIC CONDITION,
   DS=DISTANCE INWARD INTER TROPICAL CLOUD BAND,
   DISTANCES OF THE NEAREST CLOUD FROM: WE=WEST SO=SOUTH
            SW=SOUTHWEST EA=EAST
```

Table A.9 Cotton yields(kantar/fd) in 5 Areas in the Sudan

1950 - 1959				1960 - 1978					
	Wad Medani	Dueim	Aroma		Wad Medani	Dueim*	Aroma	Kosti**	Kadugli
1950/51	7.09	5.98	1.41	1960/61	4.01	2.30	1.50	2.55	2.73
1951/52	2.66	2.83	1.74	1961/62	7.07	4.45	0.67	6.01	3.59
1952/53	4.57	4.53	1.48	1962/63	5.75	1.82	0.47	4.14	2.75
1952/54	5.72	3.91	1.07	1963/64	1.93	1.98	0.44	3.22	4.10
1954/55	4.93	4.77	1.39	1964/65	5.53	2.66	-	5.16	2.93
1955/56	5.80	3.16	2.20	1965/66	3.26	3.20	0.60	3.75	3.48
1956/57	7.81	5.64	1.13	1966/67	4.45	3.66	0.30	4.58	2.58
1957/58	1.90	1.50	1.96	1967/68	4.96	3.92	1.00	4.54	2.80
1958/59	5.85	3.60	2.19	1968/69	6.71	4.64	1.69	6.51	2.54
1959/60	4.84	3.59	0.88	1969/70	5.58	3.31	-	6.50	2.47
				1970/71	6.36	5.35	0.96	6.68	2.80
				1971/72	7.40	5.02	0.81	6.88	2.08
				1972/73	6.17	3.55	-	5.65	2.60
				1973/74	6.20	4.61	-	6.42	3.66
				1974/75	4.76	3.67	-	5.06	1.68
				1975/76	4.10	1.64	-	2.43	2.29
				1976/77	5.34	2.18	-	2.44	1.98
				1977/78	6.80	3.66	-	-	0.88

* Represents West Gezira scheme

** Represents southwest Gezira scheme

Source : (1) Ministry of Agriculture (1970; 1977; and files)

(2) SGB Agricultural files

Table A.10 Comparison of two decade rainfalls at the Wad Medani-Dueim area

Rainfall variable	Mean (mm)		Standard deviation		Coefficient of variation (%)	
	1951-1960	1961-1970	1951-1960	1961-1970	1951-1960	1961-1970
Annual	368.6	292.7	136.8	75.9	37	25
July	98.6	86.8	52.4	59.9	53	70
August	149.2	122.4	83.3	59.7	56	49
September	67.8	33.9	35.5	23.6	52	70
October	6.5	13.1	7.0	14.2	107	108
Jul.+ Aug.	246.4	209.3	104.7	71.1	42	34
Sept.+ Oct.	73.9	52.9	33.9	34.8	45	65

Source : Sudan Meteorological Department : Annual meteorological reports 1951-1970.

TABLE A.11 ALTERNATIVE REGRESSION FORMULAE FOR ESTIMATING COTTON YIELDS

1- WAD MEDANI

$$Y = -21.30958 + 0.0088042 I11 - 0.1089527 W1 + 0.0037396 I15 - 0.0020542 I19$$

2- KOSTI

$$Y = -0.8730897 - 1.861643 V12 - 0.0132804 RF7 + 0.4070269 MI3 + 0.3969624 MA4$$

3- AROMA

$$Y = -0.2206296 + 0.2206658 V10 + 0.0522098 H11 - 0.0358804 H7 - 0.0322243 R8$$

SYMBOLS

H7=JULY NO.OF DAYS WITH TEMPERATURE >35°C
H11=NOVEMBER DITTO
I9=PENTAD 9(TABLE 7.9) RADIATION (CAL./SQ.CM)
I11=PENTAD 11 DITTO
I15=PENTAD 15 DITTO
MA4=APRIL MAXIMUM TEMPERATURE (°C)
MI3=MARCH MINIMUM TEMPERATURE (°C)
R8=AUGUST AFTERNOON RELATIVE HUMIDITY (%)
RF7=JULY RAINFALL (MM)
V10=OCTOBER EVAPORATION (MM)
V12=DECEMBER EVAPORATION (MM)
W1=JANUARY NO.OF DAYS WITH WIND FORCE 4-7 (BEAUFORT)

Table A.12 Sorghum yields(kg/fd) in 5 areas in the Sudan

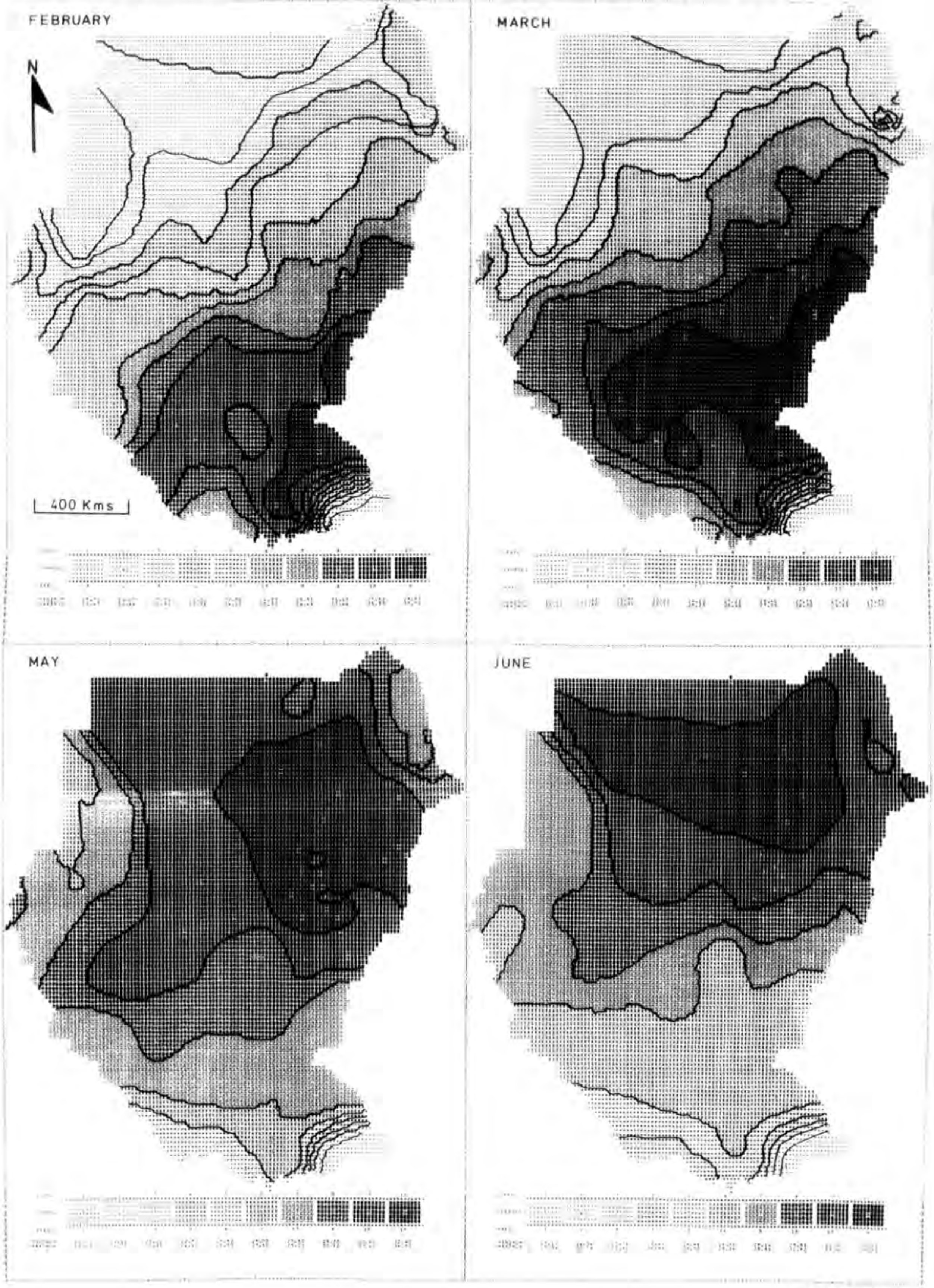
	Kosti	Singa	Abu Naama	Gedaref	Aroma
1960	-	-	-	258	-
1961	1121	406	-	404	1349
1962	1316	530	-	406	712
1963	906	450	-	323	302
1964	472	290	-	357	354
1965	442	360	364	313	500
1966	754	260	292	208	438
1967	505	305	363	400	568
1968	851	166	383	286	720
1969	219	453	344	286	511
1970	228	485	569	258	365
1971	189	315	562	308	438
1972	375	209	245	100	365
1973	363	182	273	454	290
1974	596	273	273	273	378
1975	636	391	278	40	250
1976	440	406	212	300	240
1977	216	396	299	231	250
1978	-	-	455	-	-

Source: (1) Ministry of Agriculture (1970) Bull.agr.statistics of the Sudan, No.10, Khartoum.
(2) Ministry of Agriculture (1977) Sudan yearbook of agricultural statistics, Khartoum.
(3) Ministry of Agriculture files.

Table A.13 Sesame and groundnut yields(kg/fd) in 5 areas in the Sudan

	Sesame			Groundnuts	
	Dueim	Gedaref	Abu Naama	Wad Medani	Kosti
1960	-	-	-	700	-
1961	587	102	-	640	1500
1962	186	274	-	630	1250
1963	178	236	-	590	700
1964	186	135	42	500	700
1965	236	125	130	500	800
1966	300	151	238	330	900
1967	119	135	207	-	600
1968	175	124	180	900	900
1969	180	158	70	350	300
1970	145	149	103	750	300
1971	145	139	145	608	1200
1972	118	163	99	750	1275
1973	-	180	90	-	1250
1974	145	67	90	1500	1250
1975	-	90	91	767	1500
1976	-	135	175	1200	1125
1977	-	-	81	-	-
1978	-	-	91	-	-

Fig. A.1 THE DISTRIBUTION OF TEMPERATURE OVER THE SUDAN IN EACH OF EIGHT MONTHS



(CONTINUED)

Fig A.1 (CONTINUED)

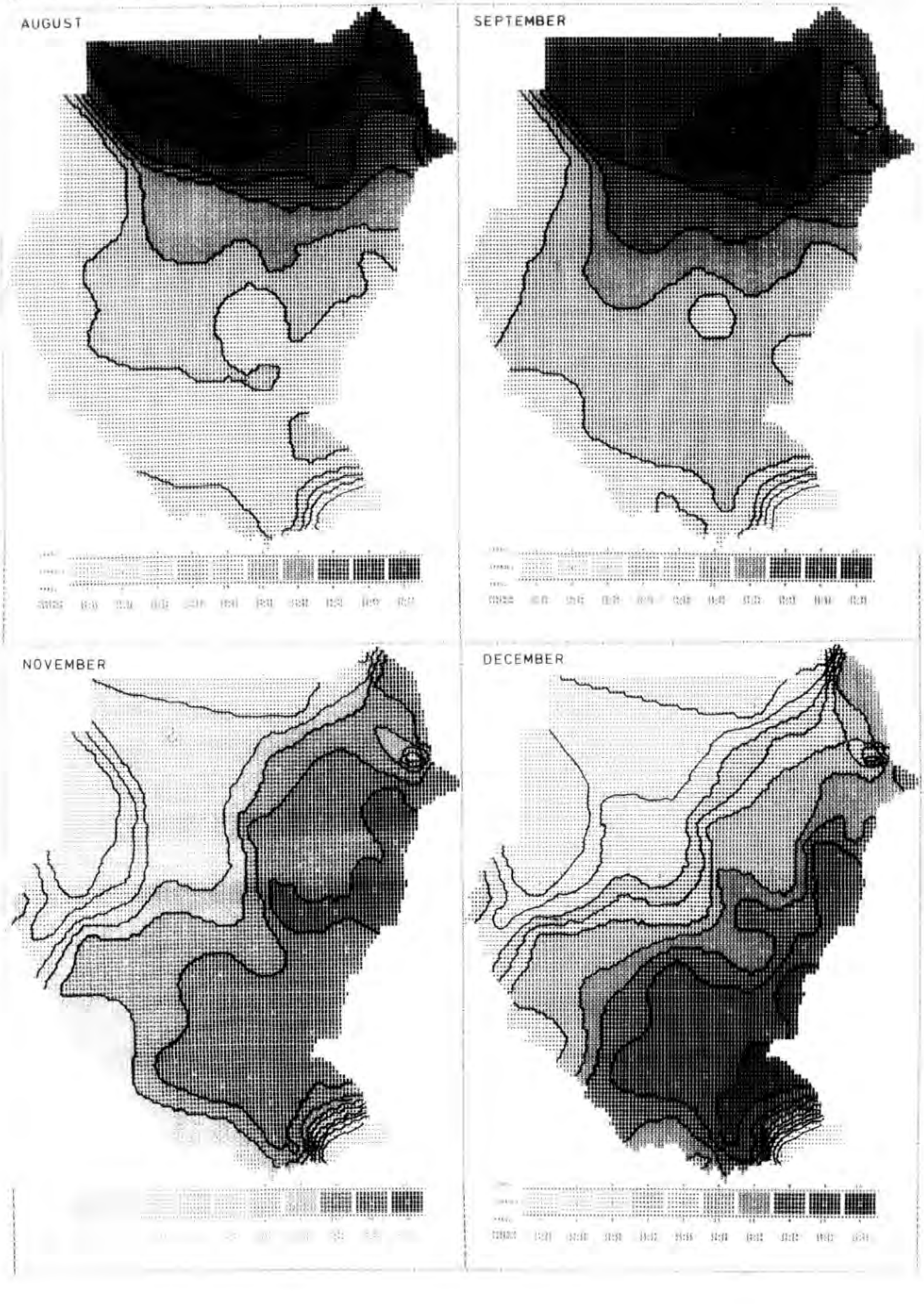
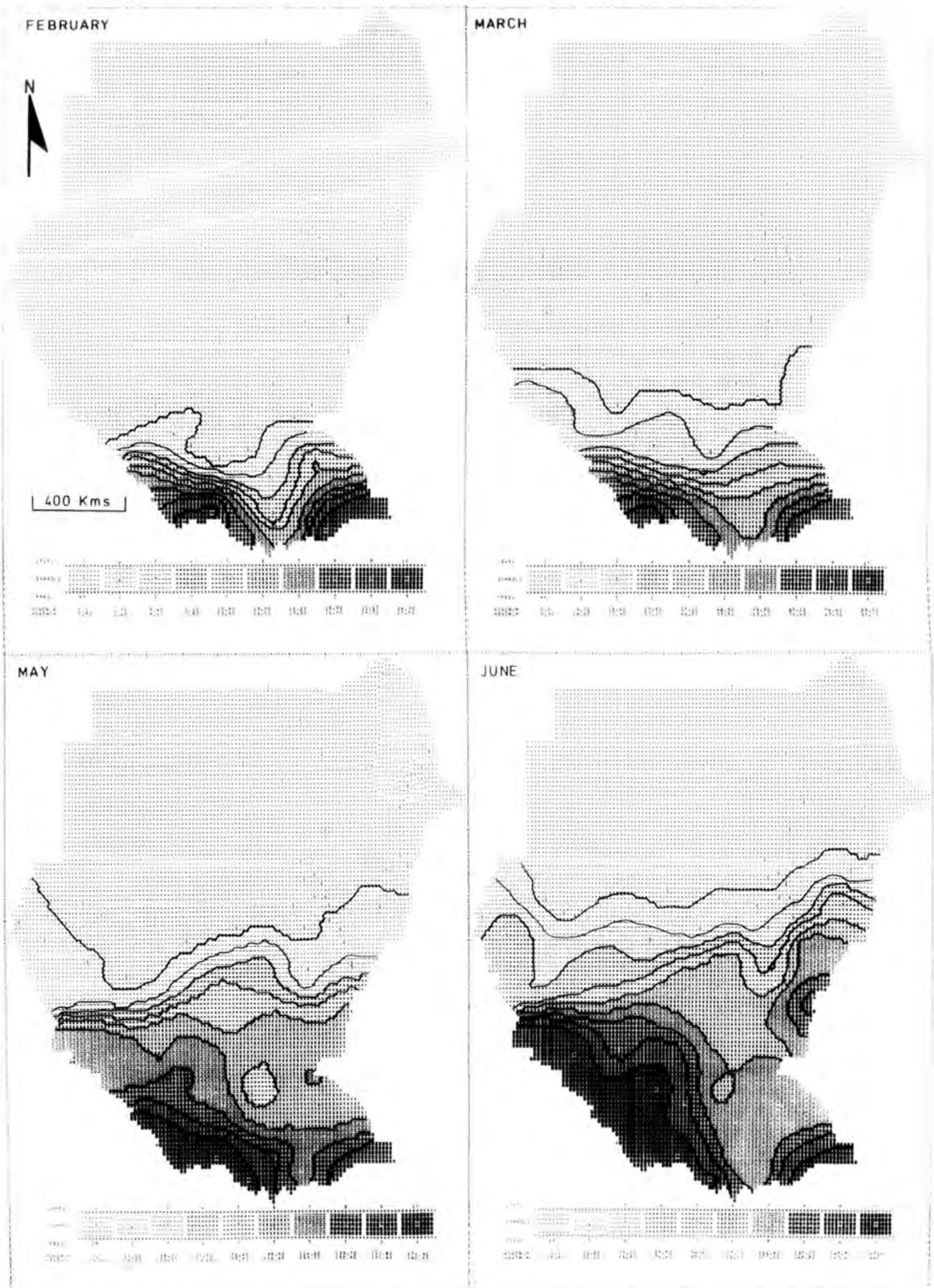


Fig. A 2 THE DISTRIBUTION OF RAINFALL OVER THE SUDAN IN EACH OF EIGHT MONTHS



(CONTINUED)

Fig. A.2 (CONTINUED)

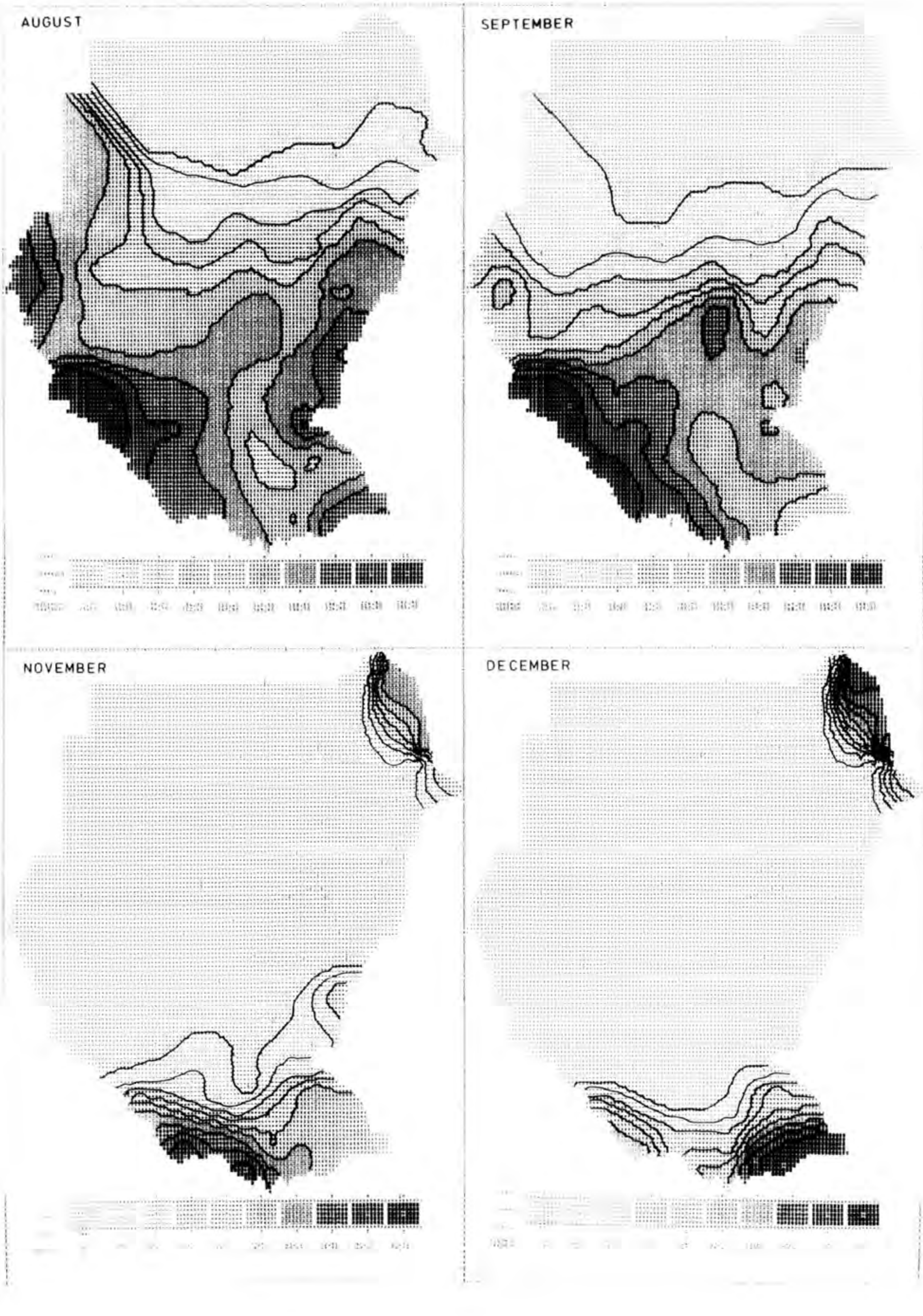


Fig. A.3 ELEVEN CLIMATIC REGIONS PRODUCED BY FACTOR AND CLUSTER ANALYSIS