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AFRICAN MONSOON METEOROLOGY

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Monsoon Meteorology - Africa

Approach

There are three lectures on Monsoon Meteorology - Africa. Lecture 1 is on the Climatology of Monsoon in Africa and it deals essentially on a general discussion on the prevalence of the Monsoon in Africa. Subsequent lectures (i.e. Lecture 2 and Lecture 3) will deal with the structure and forecasting models in current use in Africa (West and East Africa respectively) for the onset and cessation of the monsoon.

Lecture 1 : Climatology of Monsoon over Africa

1.1 Introduction

The Monsoon, a term which is used to describe a wind system in the tropics in which there is a persistent seasonal reversal of the mean winds in an area, is derived from the Arabic word Mausim, which means season (Neiburger *et al.*, 19[illegible]). It was originally used by the Arab traders to describe seasonal winds which blew steadily for six months from the north and six months from the south (Ramage, 1971).

A peculiar feature of this terminology is that there is a seasonal reversal of the prevailing winds over an area (Walker, 1960; Ramage, 1971), which, strictly speaking, implies the operation of two distinct climatic regimes, depending on whether in one season the mean wind is on-shore and off-shore in another and vice versa.

2. Monsoon Components and Research Emphasis

Although most writers on the monsoon climate in all parts of the tropics where the monsoon climate is observed, have tended to concentrate on the summer rain-bearing component of the monsoon, recent works in tropical meteorology reveal that the winter component of the monsoon is equally important. This one-sided emphasis, which had in the past pervaded discussions on monsoons of the world, is gradually dying out, thereby giving room for a more well balanced treatment on the two components of the monsoon climate which we designate as:

(a) The South-west Summer Monsoon (SWSM)
(b) The North-East Winter Monsoon (NEWM).

A more comprehensive understanding of tropical climate in both West Africa and East Africa, where the Monsoon system is observed in Africa in different degrees, demands a good knowledge of the monsoon climatic pattern in these regions.

As a result of the prominence and interest which the Indian primary monsoon system has generated among early tropical meteorologists, the SWSM has been unnecessarily emphasized by several researchers on the monsoon system, with the result that sometimes, only sketchy treatments have been given to its winter counterpart. It is this very much restricted attention on the monsoon climate which had hindered an early recognition of the significant role of the NEWM in the African Monsoon system.

This one-sided treatment of monsoon climatology is also evident in the planning and implementation of large-scale research experiments in Africa. For example, the recent West African Monsoon Experiment (WAMEX), conducted in summer of 1974, considered only the summer component of the West African Monsoon. Perhaps, hopefully, phase II of the monsoon research programme in West Africa may involve the NEWM.

This is primarily because in terms of the energetics of the tropical atmosphere, the winter monsoon is very important in a proper understanding of the climatology of West Africa, for example, especially in terms of heat sources of the tropical atmosphere in winter. As Chang *et al.*, (1979) have discussed, the northern winter monsoon is one of the most energetic systems of the tropical atmosphere.

Consequently, therefore, these lecture series will emphasize the NEWM in our discussions for both the West Africa and East Africa monsoon systems.

3. Establishment and Maintenance of the Monsoon Circulation

In the literature on monsoon meteorology, frequently, one finds an explanation in terms of differential heating between adjacent land sand sea (e.g. Flohn, 1960). However, on a careful examination of the monsoon concepts - its extent and intensity in the context of tropical meteorology and present day knowledge of the structure and mechanisms of the tropical atmosphere of which the monsoon is an important circulation system, one finds that this differential heating is itself not a causal factor for the monsoon, but somehow an effect of the monsoon phenomenon.

This view is based on the fact that temperature gradient arising from a difference in the heat capacity of land and water bodies is insufficient to generate and sustain the intensity of the monsoon circulation. This is primarily because the 'sea-breeze effect', as the atmospheric process of air motion emanating from the existence of a temperature difference between land and sea is usually called (Neiburger *et al.*, 19[illegible]), can also occur in both seasons, even on a daily basis. What causes and maintains the African Monsoon is, in fact, more dynamically involved than this simple heat capacity concept.

Further, a close study of the monsoon dynamics as an important component of tropical general circulation reveals that the African Monsoon, including the Indian Monsoon system, is dynamically induced. The writer is therefore in perfect agreement with Krishnamurti and Bhalme (1976) in stating that there probably exists a natural oscillation of the broad-scale monsoon due to its own inherent dynamics.

The observed persistent seasonal turning of the prevailing winds from south-easterly to south-westerly on crossing the equator on a large-scale over a given monsoon region in the tropics in summer is not a direct result of differential heating effect between land and sea, but derives from the dynamical structure of the tropical atmosphere determined by the apperent annual movement of the sun across the equator. The dynamical controls on the monsoon may be of the same degree as that produced by the Coriolis force - a force which is capable of deviating the powerful south-easterly trades into a south-westerly monsoon current on crossing the equator intc West Africa over the Gulf of Guinea (see Fig. 1). This same effect occurs in the Indian subcontinent and also in Eastern Africa in summer. The writer, does not believe that this soft of 'sea-breeze effect' explanation for the existence of the monsoon actually tells the whole story of the evolution and maintenance of the monsoon circulation.

For example, in West Africa, the prevalence of the highly stable dry dust-laden North-East Trade winds during the northern winter and their reversion, on a continental scale, to an unstable moist on-shore south-westerly winds in summer is determined principally by changes in the dynamical structure of the tropical atmosphere, especially in the meridional direction in which the apparent movement of the sun across the equator in the course of a year is the prime motivator of the monsoon system.

It is usually constitutes an interesting and intriguing spectacle to observe on synoptic weather maps the highly organized flow of air on a large-scale from the South Atlantic in northern summer arriving West Africa as a south-westerly wind on crossing the equator. The south-westerly winds which cover most parts of the subregion as far north as 25°N by mid-August is completely replaced in winter, say, January, by a dry north-easterly wind called the Harmattan which is of a different thermodynamic characteristic when compared with the moist south-west monsoon current. This observation may seem rather surprising, but it explains the dynamical background of the monsoon climatology in West Africa and other tropical areas where the system is observed.

4. Factors which favour Monsoon Circulation in Africa

4.1 Geographical Position of African Continent

The geographical location of the continent of Africa, which is approximately symmetrical with the equator, strongly favours the prevalence of the monsoon circulation in Africa. This, together with the presence of a continental land mass to the north of the equator in West Africa and the presence of two oceans to the West and eastern sectors of the continent, are highly condusive for monsoon circulation.

4.2 Meridional Seasonal Displacement of Pressure Systems

A second factor which favours the monsoon circulation in Africa is the characteristic meridional displacement of major climatological pressure systems. The latter for the West African subregion are the Saharan anticyclone and the Equatorial trough (ET), referred to in this lecture as Monsoon Trough (MT). These systems are known to generally move polewards in northern summer and in the reverse direction in winter as if connected by a spongy loop (Kalu, 1985) See Fig. 2.

This meridional movement is astronomically determined with the annual north-south migration of the sun across the equator being the principal motivator of the oscillation of these pressure systems. It is a known fact that it is the direct interaction of solar radiation on the equatorial region that creates the permanent low pressure area observable all over the tropics in the equatorial area. The trough therefore moves in sympathy with the sun in the course of a year and this is an integral part of the general circulation of the tropical atmosphere. That is why in northern summer the MT is located to the north of the Equator about 20 - 25°N in mid August during high sun period while it is found as far south as 5°N during low sun period in West Africa. Although the MT is permanently north of the equator all the year round in West Africa, this is not the case in Central and Eastern Africa where in winter the position is found south of the equator (See Fig. 3).

5. Influence of Topography

Adefolalu (1979) has divided Africa topographically into two distinct relief categories, namely : (a) Low Africa and (b) High Africa. This type of consideration is relevant in studies involving the monsoonal flow in Africa especially as it is known that topography does exert some significant impact on the intensity, bursts and persistence of the monsoon, especially in creating the shear-lines which are favourable weather development areas of the Easterly wave. See Fg. 4.

While the monsoon circulation is well pronounced in the areas described as Low Africa, e.g. West Africa (Udo, 1978) this is not the case in the High Africa. Topography distorts significantly the organisation of Easterly wave synoptic systems (e.g. the Inter-Tropical Discontinuity (ITD), cyclonic vortices, the Easterly waves themselves). The restricted application of the Easterly wave concept to forecast weather development in East and Central Africa is primarily attributable to the complex relief features of these areas.

Perhaps, the greatest influence of topography on monsoon circulation in Africa is in the low-level Easterly windfield. The impact of topography on low-level Easterly Jet of East Africa has been discussed by Findlater (1969, 1972) while Kalu (1983) has described the role of topography (See Fig. 5) as an enhancement factor to the strengthening of the Easterly windfield which is important for dust transport in the area.

The influence of topography on the monsoon system of West Africa is also recognized because it was designated as a third phase of the WAMEX programme for the tropical atmosphere over West Africa (GARP Publications).

6.$ Major Monsoon Pressure Systems

On a climatological basis, the principal pressure systems which are important in the generation and maintenance of monsoon system in Africa are the subtropical anticyclones - the so-called hemispheric anticyclone and Equatorial trough. The prevailing winds and weather pattern observed in Africa are linked with the meridional oscillation of these two pressure systems based on the astronomical activity of the sun in the course of a year. Although the subtropical anticyclones are semi permanent, their influence shifts slightly polewards and equatorwards owing to the pronounced movement of the Equatorial trough. See Fig.2.

The meridional distribution of the pressure systems is an important feature of the general circulation of the

tropical atmosphere. This is such that there is a poleward displacement of these systems during the high sun period and towards the equator in the winter low sun period.

The prevalence of low-level Easterlies and Westerlies at upper levels derives from the interaction between the two hemispheric anticyclones (the Saharan High and St. Helena High for West Africa) and the monsoon trough. The generation of weather is also dependent on the relative positions of these two climatological pressure systems.

PART I

Lecture 2: The West African Monsoon

1. Introduction

In lecture 1, we have discussed some recent ideas on the monsoon climatology in Africa. In the following lecture, we shall treat the structure of the monsoon system and a review of some current forecasting techniques for the onset, cessation and breaks of the monsoon in West Africa.

2. Structure

2.1 Flow Pattern

In order to understand the structure of the tropical atmosphere in West Africa, it is necessary, firstly, to discuss the flow pattern during the two seasons which characterize monsoon system in Africa. Thus, the structure of the troposphere in West Africa, as can be seen in Figs. 6a,b, exhibits the following typical features :-

a. Northern Winter

(i) A persistence of Easterlies at lower tropospheric levels (surface - about 650mb) with cores of maximum wind velocity which Kalu (1983) has described as low-level Easterly wind maximum (LLEWM). Some other authors have also designated this wind as a Low-Level Jet (e.g. Aina, 1972). It is located approximately between 950mb and 900mb for most parts of West Africa. See Fig. 6a.

(ii) A broad band of westerlies extending approximately over the second half of the troposphere with core forming the subtropical jet stream at approximately 200mb over North Africa.

b. Northern Summer

(iii) Weak upper westerlies and the disappearance of the subtropical (westerly) Jet stream which is then replaced by an upper tropospheric/stratospheric Tropical Easterly Jet (TEJ).

(iv) A boundary layer weak south-westerlies, sometimes known as the Equatorial westerlies (Watts, 1955, Flohn, 1960). This is represented by W in Fig. 6 and S in Fig. 4b for both the U- and V- components of the mean zonal winds, and

(v) A mid-tropospheric Easterly Jet stream which has now been called the African Easterly Jet (AEJ). (Adefolalu, 1974; Pedgley and Krishnamurti, 1976).

A significant feature of Fig. 6a is the increased depth of the Easterlies during the dry season. This is very important for an effective dust transport in West Africa (Kalu, 1983).

2.1.1 The Harmattan

The Harmattan, one of the most important low-level regional winds which are associated with the winter monsoon system in West Africa. The Harmattan, is a dry but cool and often dust-laden wind, blowing from the subtropical anticyclone across the Sahara into the Equatorial trough in West Africa during the dry season. It is an English derivative of the word "Harmata" from the Fanti language of Ghana meaning dry dusty wind from the Sahara desert during the dry season (see Longer Oxford English Dictionary). The Harmattan in West Africa is synonimous with increased turbidity of the lower atmosphere due essentially to suspended soil-dust particles from the Sahara and its equatorward fringe areas, for example, the Sahel zone. The Harmattan and its associated weather have been well documented in Nigeria (e.g. Adefolalu, 1968; Aina, 1972; Kalu, 1979, 1983).

An important feature of the West African Harmattan wind is the existence of a well defined core of maximum local Easterly wind in winter at the gradient wind level (about 950 - 900mb in most cases). This wind system has been previously described as a low-level jet (LLJ)(e.g. Adefolalu, 1968; Aina, 1972; Kalu, 1979), but Kalu (1983) has discussed the same wind under the term low-level Easterly wind maximum (LLEWM). This terminology is still maintained in our present discussion without any prejudice to the LLJ terminology which has hitherto been applied to describe this significant low-level winter windfield (see section 2.1.3).

The latest work on the Harmattan wind in West is a new forecasting model for the various prosess of the African dust plume using both dynamical principles and thermodynamical aspects of the PBL based on upper air radiosonde data for predicting the mobilization, transport, persistence and clearance of the African dust plume as has been defined by Kalu (1979).

ins 6a

2.1.2 The Equatorial Westerlies

On examination of the annual wind profile for West Africa, one will find a distinct wind system at lower levels of the troposphere in summer below the Easterlies (Fig. 6). This is Equatorial westerlies which has been described by various authors (e.g. Watts, 1955; Flohn, 1960, Kiangi, 1984).

The appearance of the low-level westerlies is due to the increased depth of the south-westerly Trade winds (originally South-Easterly Wind south of the Equator, but becomes. South-Westerly wind on crossing the Equator as a result of the Coriolis effect). The Equatorial westerlies are a significant wind field of West Africa as it represents a change in the structure of the monsoon circulation in the area. It is usually very pronounced in August when the Walker's (1960) Zone D is located over the coastal areas of West Africa.

2.1.3 The Lower Tropospheric Easterly Wind Maxima

a. Nomenclature

A significant feature in the structure of the lower tropical troposphere in West Africa, which is relevant to the dynamical feature of the tropical atmosphere in both seasons, is the existence of cores of maximum winds in the easterly windfield. These low-level wind maxima have been designated by various names. For example, in summer the terminology, the African Easterly Jet (AEJ), has been used to describe the summer mid-tropospheric Easterly wind maximum occurring at 600 - 650mb (e.g. Burpee, 1972; Adefolalu, 1974; Pedgley and Krishnamurti, 1976, etc).

Also in winter, another core of maximum wind in the Easterlies is observed, but this time at the gradient wind level (950 - 900mb) and has been designated the Low-level Easterly wind maximum (LLEWM) by Kalu (1983) as mentioned in section 2.1.1. See Fig.7.

While the AEJ has been extensively studied, its winter counterpart has received as yet very little attention. This is probably because of its direct association with the winter monsoon which has not been widely studied. Another reason may be that, being a boundary layer wind phenomenon, it is very often missed by upper level ascents based on standard pressure levels. However, as a result of its

direct association with dust transport across West Africa from the Sahara desert, the LLEWM has of recent received some attention by meteorologists (e.g. Adefolalu, 1968; Aina, 1972; Kalu, 1983).

Our discussion here is not to present a detailed treatment of the two seasonal low-level Easterly wind maxima, but to emphasize their importance in the dynamics of the monsoon circulation in West Africa.

b. Dynamical Significance

The large-scale low-level atmospheric circulation, especially with regards to the existence of wind maxima, can determine the structure of the lower troposphere in three ways. These are :

(i) They influence directly the energy and momentum budgets of the earth-atmosphere (PBL) system through horizontal and vertical advection processes, particularly the latter,

(ii) The low-level wind field controls exchange processes in the atmospheric boundary layer, and

(iii) Convection is regulated by both dynamical and thermal structures of the PBL.

Perhaps, a most important contribution of the existence of characteristic maxima in the Easterly wind field in West Africa during the two seasons is the provision of definite shears in the zonal Easterly windfield, both in the vertical and horizontal directions. These are very important and necessary factors for the various instability modes which have been found to be important for the tropical monsoon atmosphere in West Africa, for example, combined baroclinic-barotropic instability (Burpee, 1972; Rennick, 1976; Pedgley and Krishnamurti, 1976).

Furthermore, both the AEJ and the LLEWM are also important in energy exchange mechanisms of the tropical atmosphere for both seasons in West Africa as have been variously discussed by Reed (1978), Krishnamurti et al., (1978); Norquist et al.(1977), etc.

c. Possible Relationship between Winter and Summer Easterly Wind Maxima

In order to establish a possible relationship between the LLA and the two Easterly wind maxima in winter and summer, it is necessary to note the following: firstly, the observation by Adefolalu (1979) that the AEJ, whose mean level of occurrence in June through August, is 650 - 600mb, descends sharply to about 700mb in October; Secondly, the documentation by Thompson (1965) who has shown evidence that the low-level anticyclone (LLA) over West Africa is found at a lower level of the troposphere in winter than its summer position, and thirdly, the observation by Kalu (1983) that both the AEJ and LLEWM are Easterly outlows from the same subtropical anticyclone and which are located to its equatorward south-eastern periphery. On the basis of the above observational evidence, it is reasoned that these two seasonal Easterly wind maxima may, after all, be essentially the same windfield whose seasonal prevalence in West Africa is attributable to monsoonal circulation. Although the above contention is still highly hypothetical and still needs further research confirmation, observational evidence so far established are highly in favour of the existence of such a relationship between the two seasonal low-level Easterly tropospheric wind maxima.

3. Elements of Monsoon Circulation in West Africa

Although under this heading several synoptic and climatological features may be discussed as have been done by Krishnmurti and Bhalme (1976), for purposes of the present discussion, we shall restrict our attention to the following two primary monsoon systems:-

(a) The Monsoon trough
(b) The Hemispheric anticyclones

3.1 The Monsoon Trough

In this lecture, the term Monsoon Trough (MT) is synonimous with Equatorial trough, as the low pressure area in the equatorial region is generally known in the tropics. The Monsoon trough develops as a result of radiative imputs into the earth-atmosphere system such that the characteristic intense heating of the ground surface produces a persistent column of rising air in this region. This creates a condition favourable for the existence of a broad belt of low pressure region all over the tropics. It is a zone of energy maximum at ground surface

A significant feature of the MT is its meridional oscillation in the course of a year. This is astronomically controlled with the position of the earth relative to the sun at any time of the year determining the surface position of the trough. As a result the trough moves

polewards during high sun period (northern summer) and equatorwards or southwards during low sun period (northern winter). See Fig. 3.

3.1.1 The Inter-Tropical Discontinuity

In West Africa, an important weather-related feature of the MT is the Inter-Tropical discontinuity (ITD). The ITD is not a temperature discontinuity as earlier meteorologists had tried to imply by erroneously coining the term Inter-Tropical Front (ITF) which does not apply in the tropics. But it is a discontinuity in both moisture and wind fields. It describes the trade confluence zone over-land and its counterpart, the Inter-Tropical Convergence Zone (ITCZ), is used to describe the Trade confluence zone over the oceanic areas of the tropics.

The ITD is a synoptic feature which is located within the Monsoon trough and oscillations of the latter are interpretted in terms of diurnal and seasonal movements of the ITD in sympathy with the apparent movement of the sun.

3.1.2 Diurnal and Seasonal Oscillations

Although the ITD is a persistent synoptic-scale feature of the monsoon circulation in West Africa, it is found to exhibit some oscillations in the course of a year. These oscillations, which have been identified on surface weather maps, are of diurnal and seasonal nature The ITD is the most relevant feature of the MT in West Africa as far as the generation of weather, especially during summer, is concerned.

Essentially as a result of the steadiness of the ITD, a determination of its surface position on weather maps is of great forecasting interest. Apart from the delineation of West Africa into weather zones with specific reference to the mean surface position of the ITD, routine forecasting based on the north-south migration of the ITD is of more practical importance. The forecasting of weather in Nigeria is principally based on the characteristic meridional oscillation of the MT which is represented on synoptic weather charts in terms of the surface position of the ITD.

The diurnal oscillation of the ITD is non-directional but represents a daily variation in cloudiness and convective weather over a given station, while the seasonal oscillation is strictly directional - moving polewards in summer to a maximum possible position of about 22 - 25°N (Fig.8) in the longitude of Nigeria and Southwards in winter to a maximum Southward position of about $5^{o}N$. It should be pointed out that the ITD is permanently north of the equator throughout the year in West Africa. This is, of course, not always the case in all parts of Africa.

An important feature of the ITD to monsoon circulation is that it constitutes a zone of convective weather in West Africa. However, observational evidence in Nigeria reveals that surface position of the ITD does not usually coincide with active weather zone of the ITD, the latter is the Walker's (1960) zone C. Synoptic evidence shows that the surface position of the ITD as defined by the 15^{o} isopleth of dew point temperature is not necessarily convective and this may be explained by the stability influence of the continental North-Easterlies which over-ride the moist south-westerlies. In three-dimentional perspective, the ITD slopes equatorwards with height as schematically depicted in Fig. 8. Both the diurnal and meridional oscillations of the ITD should be emphasized for purposes of weather forecasting in the area.

3.2 The Hemispheric Anticyclones

The Hemispheric anticyclones which are known to influence the weather and, in fact, climate of West Africa are : (a) The Saharan High, and
(b) The South Atlantic High. See Fig. 1(b)

These are subtropical anticyclones which are located respectively to the north and south of the geographical equator. Together with the MT, they represent a complete synoptic structure of the tropical monsoon troposphere which control the generation and maintenance of weather systems in the subregion.

3.2.1 Oscillations

The hemispheric anticyclones, like the MT, also exhibit a meridional oscillation in the course of the year. It is necessary to point out that the present work does not consider the weather patterns associated with each anticyclone because such information is available in the literature, but it emphasizes on the seasonal oscillation of these pressure systems and their effects on the weather and the climatic pattern of West Africa. This line of action is adopted primarily becuase its understanding is fundamental to successful forecasting of monsoon weather systems in West Africa.

Although on a climatological consideration,the subtropical high pressure cells are semi-permanent features of the earth's atmosphere, they are nevertheless known to exhibit some significant movements, especially in the meridional

direction. Such movements have been observed on synoptic weather maps in West Africa and they may be better classified as seasonal displacements rather than oscillations - a term which is more appropriate for the Monsoon trough and its ITD.

On the basis of the general circulation of the earth's atmosphere, it appears that the three pressure systems effecting the subregion (i.e. the Saharan High to the north, the south Atlantic High to the South and the Monsoon trough in between) are connected in a form of spongy atmospheric loop. By this we mean that the intensification or weakening in one system affects the other in a chain. Thus, for example, in northern summer, there is a general tendency for these pressure systems to move polewards with the movement of the MT being most pronounced and more easily identified on weather maps in terms of the ITD. The northward displacement of these hemispheric highs are usually indicated on synoptic weather maps in the form of closed anticyclonic eddies or in some cases intense ridges in areas usually occupied by other pressure systems e.g. the polar low during the northern summer.

Similarly, during the same period the influence of Saharan High over West Africa is greatly diminished with a subsequent intensification of the Sahara High over the extratropical latitudes over Gibraltar and the Meditarranean Coast of Africa. The reverse is, of course, true in winter when, due to a southward displacement of the Saharan High, the North-Easterlies exert a controlling influence on the weather of West Africa with a relative decrease on the influence of the moist south-westerlies, originating from the southern hemispheric high over the Ascenssion Island in the South Atlantic.

3.2.2 Significance of the Oscillations

These temporal and spatial oscillations of the hemispheric anticyclones are important in many respects. Firstly, they produce the necessary drive for the monsoon system, especially by producing the necessary poleward steering for the rain-bearing south-westerly winds. Secondly, they determine the climatic pattern of the West Africa subregion. For example, during the rainy season, the thrust from the South-Atlantic high or St. Helena High over the Ascension Island, as it is sometimes called, is very much felt over West African mainland in the form of considerably increased surge of the south-westerlies. Kalu (1972) has suggested that it is because of the proximity of the South Atlantic High to the West African coast in mid-summer that produces the anomalous mid-summer monsoon break called the Little Dry Season. The high produces the observed characteristic pronounced stability of the lower troposphere inspite of high depth of moisture resulting in persistent cloudiness, but without much rain. Obasi (1964) has also discussed the anticyclonic circulation which may produce such observed stable lower troposphere over Nigeria during the Little Dry Season.

3.2.3 The Relative Strength of the Hemispheric Anticyclones

The relative strength of both the North-East and South-west Trade winds determine structurally the mean climatic pattern of West Africa in either season. A decrease in the thrust of the south-westerlies, for example, into the West African mainland, possibly due to either a decrease in the strength of the South-Easterlies, south of the equator, or the strengthening of the North-Easterlies (or both), may cause the existense of a drought condition over the semi-arid areas of West Africa. This situation has been described by Bryson (1973) as a "failure of the monsoon".

On the other hand, if the thrust of the south-westerlies into the heart of the African bulge is appreciable, then an above-average rainfall may be found to prevail over the Sahel region. This relative strength between the two Trades winds of the monsoon system in West Africa in relation to the inhibition or enhancement of tropical droughts in the rainfall-sensitive area of the Sahel has been discussed by Kalu (1983). He attributes the severe 1972/73 West African drought to a decrease in the poleward thrust of the moist south-westerlies and a corresponding increase in strength of the continental dry North-Easterlies resulting from an equatorward intensification of the Saharan high.

It is however true that, whether below-or above-average rainfall obtained in transitional rainfall-sensitive zone of West Africa, called the Sahel Region depends on the relative strength of the two Trade winds.

4. Review of Forecasting Techniques in West Africa

4.1 Introduction

Although the climatological and the frontal air-mass schools of thought in tropical meteorology may have had their merits and demerits, latest developments in tropical

meteorology which seem to fit in with actual observations of weather in the area is produced by the perturbation school. The latter is a line of thought which is based on the existence of an organized wave pattern of atmospheric motion systems in the low-level Easterlies, propagating from east to west south of the subtropical anticyclone. The ability to predict weather development with the Easterly wave concept therefore depends largely on a knowledge of the synoptic-scale disturbances associated with the Easterly waves.

Fortunately, in West Africa, unlike in the complex topographical structure of East Africa, most of the region, excepting the eastern boundary, lies within the area described as Low Africa (Adefolalu, 1979). As a result the Easterly waves are little disturbed by topography, especially west of about longitude 25°E. See Fig.9.

Since two different weather systems are observed for each of the two components of the monsoon in West Africa (i.e. the NEWM and SWSM discussed earlier); we shall consider each component separately.

4.2 The Winter Monsoon

4.2.1 Forecasting Dust Haze

As a result of equatorward displacement of the monsoon trough during northern winter, the Saharan High pressure, with its increased surge of the Harmattan over West Africa, is the dominant synoptic system during the period. A most persistent weather during the dry season is the Harmattan dust haze and this is the only weather phenomenon for which several research efforts have been made. Especially in Nigeria because of its role in Civil Aviation Operations and, perhaps, as a result of its contributory feature in air pollution during the dry season and its role in the atmospheric phenonemon of desertification in the northern fringe areas of the subregion, several meaningful researches have been carried on it.

Firstly is the pioneering effort of Hamilton and Archbold (1945) who produced the first attempt to forecast the Harmattan dust haze by means of conventional synoptic techniques of pressure field analysis and visibility. This was followed by Burns (1961) who introduced the pressure gradient technique of forecasting dust haze and further developed by Adefolalu (1968). This method was later reviewed by Aina (1972) who recognized the significance of the low-level Easterly wind maximum (or Jet) in forecasting dust in Nigeria. However, an important point against the pressure gradient technique for forecasting dust in Nigeria was that the model proved useful only for cases when dust had been visibly reported at the Bilma or Faya Largeau source area. The technique failed to forecast the mobilization of dust at the source region. This nowcasting method did not provide the forecaster with the necessary tools to predict the mobilization of dust in the form of duststorms. It is in this area that the recent work on the West African dust plume by Kalu (1979, 1983) constitutes a significant contribution in the winter monsoon meteorology of West Africa. See Fig. 10.

Kalu (1983) has applied different synoptic methods to forecast the three phases of the dust plume, namely

(a) The mobilization phase
(b) The transport phase , and
(c) The clearance phase.

For (a) he uses the genesis and subsequent intensification of the low-level anticyclone (LLA) over the Sahara and its subsequent development in the form of a blocking condition across the extratropical westerlies over North Africa and the Mediterranean.

An important synoptic feature which favours the establishment of a blocking condition in this area was the rather periodic incursion of frontal depressions and their associated cold air outbreaks into the Sahara desert. The westerly subtropical Jet Stream was identified as a steering force for the frontal depressions.

The background of the method for forecasting development of duststorms from which emanates the Harmattan dust haze over Nigeria and the rest of West Africa in winter is that whenever the LLA intensifies over Central Sahara, with its South Eastern periphery suitably orientated over the dust reservoirs and ergs, then the conditions for strong wind development - the LLEWM - are satisfied on a broad-scale. Under such synoptic situation with the strong development of the low-level Easterlies, it is most likely that duststorms will develop over the dust source region, not necessarily over established synoptic stations. The low-level Easterly wind provides the necessary instability requirements - shear-induced instability for the destabilization of the PBL over the desert ergs.

For (b) the usual Burns' (1961) and Aina's (1972) gradient wind technique is used with some modification.

But for (c) a completely different parameter is introduced in the meteorology of the Harmattan dust haze - that of using thermodynamical techniques of the low atmosphere

Table 1 Daily variation of relative humidity, temperature and visibility at the ground surface during dust outbreaks, 1200GMT, Kano.

MARCH 1977			
Date	T (°C)	R.H. (%)	Vis. (km)
1	29.4	19	1.3
2	28.3	11	10.0
3	24.7	23	0.8
4	22.2	16	0.2
5	21.9	08	0.3
6	24.6	08	0.3
7	26.9	06	0.6
8	27.8	07	0.7
9	29.0	08	0.4
10	30.0	08	0.6
11	28.9	07	1.0
12	28.6	07	0.5
13	28.7	05	0.5
14	32.2	05	1.6
15	29.8	03	0.5
16	28.5	05	0.3
17	27.5	06	0.3
18	26.6	03	0.3
19	27.2	04	0.7
20	29.0	08	0.8
21	31.1	08	4.0

FEBRUARY 1974			
Date	T (°C)	R.H. (%)	Vis. (km)
9	30.6	07	30.0
10	26.7	08	6.0
11	23.6	18	10.0
12	24.6	10	0.2
13	26.6	08	1.5
14	28.3	10	30.0

DECEMBER 1973			
Date	T (°C)	R.H. (%)	Vis. (km)
25	30.0	11	25.0
26	26.1	09	5.0
27	24.8	14	1.5
28	23.3	15	1.1
29	25.0	16	1.6
30	26.7	14	4.0
31	27.2	16	10.0

DECEMBER 1980			
Date	T (°C)	R.H. (%)	Vis. (km)
10	28.0	24	14.0
11	23.5	26	0.3
12	19.7	32	0.2
13	20.6	29	0.3
14	22.1	24	1.2
15	23.4	28	1.4
16	22.5	30	1.6
17	25.4	28	3.5
18	27.4	27	15.0

JANUARY 1975			
Date	T (°C)	R.H. (%)	Vis. (km)
11	23.8	20	25.0
12	20.3	17	0.4
13	20.0	18	0.4
14	19.9	18	0.5
15	21.7	15	1.1
16	20.0	15	1.0
17	20.1	19	0.7
18	22.9	19	5.0
19	25.6	12	4.0
20	23.9	11	25.0

based on upper air radiosonde temperatures for the dissipation of the plume and so clearance of the dust in a downwind area.

An important radiative characteristic of aeolian dust-that of absorption of solar radiation - was used to infer the concentration of the dust in terms of horizontal visibility. This was reflected in terms of dust-induced temperature inversion which was found to be related to the variation of horizontal visibility and temperature on the ground surface (See Fig. 11 and table 1).

Apart from conventional synoptic techniques, the use of satellite images in forecasting the transport phase and the clearance phase of the dust has also been discussed by Kalu (1983).

4.2.2 Forecasting Fog

a. Introduction

Another significant weather which is observed during the winter monsoon in West Africa, especially over the coastal area, is fog. This is not observed to the north of the ITD because of low humidity field in the area. But as has been discussed by Kalu (1980), it constitutes an aviation hazard in the coastal areas especially during early morning flights into and out of the various airputs located around the coast.

For this weather phenomenon, no specific model has been produced, but the use of pressure field analysis and identification of the centre of the high pressure in relation to the forecast area and the T-Ø diagrams for moisture and stability criteria of the lower atmosphere are important for forecasting the formation and clearance of fog. Forecasting of fog lifting can also be more successfully done if the radiative response of the ground surface together with the sun-rise data are considered along side with the relief features of the area of interest.

Further, external inadvertent contributions by man on the persistence of fog can also be surveyed and understood. This is because of the observation in Nigeria that increased pollution level of the PBL especially over the increasingly industrialized cities of coastal areas of West Africa e.g. Lagos (Ikeja) and Apapa industrial complexes in Nigeria affects the persistence of fog in these areas. An interesting observation in this regard is the slightly increased persistence of fog in these areas of Lagos. This is attributable to the strongly turbid atmosphere where

particulate pollutants, especially the highly hygroscopic ones, which may not have any aeolian origin, are found to enhance the growth of liquid droplets around these numerous condensation nuclei.

Present evidence in Nigeria, however, does not favour the enhancement of the microphysical process of rain formation by the presence of large concentration of dust in the lower atmosphere. What is observed during severe dust outbreaks over the coastal areas where moisture content of the air may be high, even during the dry season, is that a near-smog condition is obtained due to the simultaneous presence of large quantities of both liquid and solid (dust) particles. Kalu (1980) has discussed the significance of such a synoptic situation in Civil Aviation Operations in Nigeria and has suggested a mechanical method for clearing severe dusty atmosphere through areal flushing device.

b. Formation

1. Clear sky or little cloudiness at lower levels. This condition permits upwelling radiative transfer and cooling of the ground surface.

2. Light and variable winds. This condition does not enhance mixing of available water droplets. It also enhances nocturnal cooling. It stagnates the air and enhances concentration of available water droplets.

3. High moisture content of the lower atmosphere during early morning hours. The climatology of West Africa indicates that minimum temperature in the day is always attained at dawn, say 0400 - 0500GMT. This is also the time when fog is commonly observed in West Africa. High humidity is necessary so that only little cooling will be necessary before saturation can occur.

4. Anticyclonic circulation. Produces favourable stable atmospheric conditions for effective prevalence of the synoptic conditions discussed above.

5. Topography. Relief features (e.g. whether the forecast area is characterized by open flat fields, valleys, topographic constrictions, coastal areas, etc) are important in the enhancement of fog formation. This is the reason for the common occurrence of fog or smoke trapping in valleys.

6. Climatology. There are regions or areas which are climatological favourable for fog formation. These are areas which are characteristically affected by upwelling ocean current as over the Ca..nary Island and the Benguela Coast of Angola.

c. Clearance.

Mechanical turbulence is usually generated by strong winds. This causes mixing in the air column due to increased insolation. It is perhaps the most important synoptic feature for fog dissipation. Fog occur as a result of radiative cooling of the surface layers of the atmosphere and when insolation increases after sun rise, two things are known to happen. Firstly, the heating renders the water droplets unstable and will therefore evaporate as they will no longer maintain their thermal equilibrium. Secondly, the fog layer closest to the ground surface will be affected most and it is from here that fog lifting starts.

From studies on the formation and dissipation of fog by means of satellite images and other conventional techniques, it is known that extensive areas of fog, particularly radiation fog, start dissipating from their outer edges and from below. This is attributable to heating from below and from their outer edges. An inward mixing process is one of the strongest mechanisms of fog dissipation through inward erosion into the fog ensemble.

Another synoptic feature which can favour fog clearance is the presence of convective system in the area affected by fog. This is suggestive of a vertical motion in the boundary layer. It therefore destroys the stability of the lower atmosphere which is so important for fog formation as discussed in (4) above.

4.2.3 The Summer Monsoon

a. Introduction

Since a most significant weather type of the summer Monsoon in West Africa is squally thunderstorm, usually associated with squall-lines, our next attention will be directed towards a discussion of some procedural techniques for their prediction. Although Riehl (1954) and others have laid the foundation of weather forecasting in the tropics especially by means of the Easterly waves concept, recent observational evidence of the behaviour of weather systems during GATE (e.g. Reed, 1979), for example, appear to indicate that the classical view may be modified in order to be consistent with present observation of weather in the subregion.

An important characteristic property of the Easterly wave concept which enhances its application to weather forecasting in West Africa is that most squall-lines which

give a wide-spread rainfall are usually well organized. This condition makes it possible to predict very successfully subsequent arrival of the various wave components (e.g. the trough and ridge zones) to a given forecast area. This is only possible if some properties of the wave and squall-lines themselves are well known. The following discussion therefore goes to provide such useful information which will enable a forecaster to effectively forecast rain storms and squalls associated with organized squall-lines.

b. Origin of West African Disturbance Lines

In this section, we shall offer a brief insight into the possible origin of the violent weather systems which affect West Africa during northern summer. These systems are already well known by various names such as squall-lines or Disturbance Lines (Albignat and Reed, 1980)

The rationale in considering the possible origin of disturbance lines in West Africa before outlining the various synoptic symptoms which can be used effectively to forecast their presence in the subregion is that, from experience, one stands a better chance to predicting the future state of a weather system if he knows its origin. Thus, in order to be able to recognize and readily predict the weather associated with squall-lines, it is necessary, first, to have some insight into the dynamical as well as non-dynamical origin, as the case may be, of the synoptic systems giving rise to such distinct weather features of the summer monsoon.

Several theories have already been given as the possible origin of West African squall-line (e.g. Eldridge, 1957; Carlson, 1969a,b; Frank, 1970; Burpee, 1972;etc.). These theories will not be reviewed here, but the survey will be restricted to a treatment of an aspect of some of the motivating factors which are gradually becoming popular in the meteorology of Disturbances Lines in West Africa. This concerns the role of topography in the genesis of the lower tropospheric cyclonic vortices which form and propogate westwords within the Easterly waves from east of Nigeria.

An important requirement in this understanding is that the basic easterly wave is perturbed into discernible closed circulation centres in the form of cyclonic vortices with distinct shears in the mean zonal wind flow pattern. A consistent theory should therefore explain what dynamical and/or mechanical forces are responsible for this type of perturbation of the basic Easterly current.

[very similar to the lee-waves which have been well described by Palmen and Newton (1969). See Fig. 12.]

A careful examination of the nature of the possible mechanism which can perturb the basic zonal Easterly lower tropospheric flow into closed circulation centres reveals that such perturbation may be mechanically induced. The relief features of the eastern sector of West Africa from where emanates these vortices with the Cameroun mountain nearest to Nigeria and the Etheopian highlands further to the east, seem to confirm that the existence of such mechamically induced perturbation may be possible. Both the Cameroun mountain and the Etheopian highlands are topographic features with peaks above the mean level of maximum intensity of the Easterly waves (700mb or 3km) (Fig. 9). The situation is such that the basic easterly current on rising above the maintain peaks descends sharply on the leeward side with some mechanical force such that distinct shears in the horizontal windfield are produced in the basic zonal Easterly wind pattern. Initially closed circulation centres are not formed, but as time goes on the shears in the wind flow pattern at or below the level of the mountain peaks constitute themselves into closed vertical centres which then propagate westwards within the Easterly wave current. In this way the mountains act as a trigger point for squall-line generation.

Observations in West Africa show that not all the cyclonic vortices so-formed may energize into organized squall-lines. Some of these may die out before reaching the Eastern Nigeria border owing to lack of or weakening in the sustaining dynamical influences such as the availability of moisture for a proper development of the shears in the windfield into clear vortical centres. La Seur (1962) has noted that orography can play a vital role in the structure of shear-lines and weather systems associated with them.

The present suggestion and amplification of the role of topography in the perturbation of easterly waves into closed lower tropospheric vortices is, however, without any prejudice to existing dynamical theories for the growth and maintenance of Easterly wave disturbances in the tropics generally. However, experience in Nigeria on the frequency, emergence (always from the East of Nigeria) and the direction of movement of these vortices associated with well organized squall-lines, which produce wide-spread rainfall and squally thunderstorms along their tracks, suggest that such topographically induced perturbation can be possible.

c. Synoptic Features for Forecasting Squally Thunderstorms

An important requirement in weather forecasting in the tropics, or any other parts of the world for that matter, is an accurate analysis which is representative

of observed real-time data. Contrary to this, forecasts based on wrong analysis of synoptic data will definitely produce wrong forecasts of weather at any particular time.

It is, however, very difficult to identify one synoptic technique or model which will be suitable and also acceptable for weather development in all parts of the tropics. As a result, various National Services have developed their own specific techniques or "rule of thumb" in some cases, but the end result of these various techniques is to be able to predict, as accurately as possible, the development and movement of meso-scale cyclonic vortices usually associated with squall-lines. However, the most important requirements are, firstly, the identification of a clear synoptic system at the appropriate level and, the availability of moisture to energize such a system.

Based on the above introductory discussions, the following features need to be observed and identified:-

(i) Shear-Lines in the zonal wind flow at the appropriate levels. Such shear-lines may include features like trough-lines, ridge-lines, cols, etc.

(ii) Closed Cyclonic Vortices. The appropriate levels in West Africa for the location of these lower tropospheric vortices are the 900mb, 850mb and sometimes 700mb especially when the moisture depth is very high as during mid-August when Zone D lies over the coastal area of West Africa.

(iii) Asymptote of Convergence. This is a most favourable area of cyclonic vortex for the formation and development of squally thunderstorms. It is usually located at the confluence zone of the vortex as depicted in Fig. 13. Its counterpart the asymptote of divergence is an area of diffluent motion and is not usually found with cyclonic vortices and so not observed in squall-lines.

(iv) Lower Tropospheric Jet Stream. This is the familiar African Easterly Jet (AEJ) which has been well documented in the literature (e.g. Dhonneur, 1974; Adefolalu, 1974, Pedgley and Krishnamurti, 1976) Its significance is stressed here especially in producing the vertical and horizontal shears in the velocity field of the troposphere which are very vital in the barotopic instability model (e.g. Bumpee 1972; Rennick, 1976, etc).

(v) Precipitation Areas of the Easterly waves. As may be observed from satellite images (see Plate A), areas of most intense precipitation within the squall-line is around the south-eastern portion of the vortex - that is the asymptote of convergence as discussed in (iii) above. Although there is confluence within the vortex, but a careful examination of satellite photographs in the tropics reveals that most frequently the bright shower zones of the vortex are located most characteristically to the South-eastern periphery of the vortex and not at the centre. The shear-line analysis will show precisely the configuration of the asymptote of convergence in a particular synoptic situation.

(vi) Moisture Content. This is usually indicated from many synoptic inferrences, notably T-φ ascents, where the dew point depression may be indicated at various levels of the lower atmosphere. Apart from conventional synoptic methods, satellite water vapour (WV) channel image data are presently the most effective tracer technique in the tropics (see Plate B).

In addition to the identification of the above symptomatic synoptic features for forecasting the development and tracking of squall-lines, it is also necessarly to use these feature in close association with the geophysical features of the forecast area such as topography, nearness to water sources, etc.

Further, nowcasting may sometimes become very necessary especially when tracking the movement of the squall-line. It will be necessary to carefully examine the significant weather for the past 24 hours, 6 hours and at the time of forecast preparation. This will enable the forecaster to know the past position, the present position, and then a possible direction of movement of the squall-line. The sequence of severe weather development from Eastern to Western stations, such as squalls, rain showers and thundery activities should be clearly identified especially for well organized systems. In Nigeria, for example, it is possible to predict very successfully the arrival of squally thunderstorms in Lagos, 24 hours (or longer) ahead which had previously been located at, say, Calabar, Arochukwu, Benin and Ibadan, for example. See fig. 14.

4.3 Monsoon Breaks

a. Definition

Monsoon breaks are short periods ranging from a few days to about three weeks (or longer) during which the characteristic heavy monsoon rainfall is relaxed into a period of essentially fine weather with little rain or

none in places (Hamiton, 1979). In West Africa the most significant monsoon break is the meso-scale climatological entity known as the Little Dry Season (LDS) (Ireland, 1962) and which is sometimes locally called in Nigeria the "August break". This is because the phenomenon occurs in most years in Nigeria in July/August. Kalu (1972) has however defined it as a period of rainfall minimum, while others (e.g. Adefolalu, 1973) have considered it as a mid-summer drought. Whatever terminology may be used, the point is that the Little Dry Season is a period characterized by a definite break in the summer rainfall. See figs. 15 a-c.

b. Features

The Little Dry Season is restricted to the coastal areas and inland up to about 9^{o}N in West Africa. It is less intense in the mountainous eastern border of Nigeria. This is principally a direct result of orographic influence. Recently, it is observed that its onset and duration have varied somewhat, especially since the last peak of the on-going droughts in West Africa. It now occurs much earlier than before - sometimes in June as in the last two years (1984, 1985) - and lasts much longer thereby distorting markedly the rainfall pattern of the subregion. However, investigations in this direction are still continuing. Inspite of the high moisture content of mid-summer atmosphere, the moist instability usually associated with this condition is not released with the result that essentially the weather is characterized by a persistent cloudiness devoid of violent weather like squally thunderstorms, with only occasional slight rain and drizzle in places. This contrasts very significantly with the situation before and after this meso-climatic phenomenon.

Furthermore, an important characteristic of the LDS is the considerably stable lower atmosphere during the time when the LDS is observed. This, according to the findings of Obasi (1964), has been attributed to the pronounced low-level anticyclonic circulation which is characteristic of the lower troposphere during mid-summer over West Africa.

Nnoli et al., (1987) are still working on various aspects of the LDS for 1987 - a year of great climatological significance in the history of the LDS and, in fact, in the climatological history of West Africa - a year in which the LDS was totally absent. If this continues next rainy season, then it means that the climatological map of West Africa will have to be revised to take into consideration the new rainfall distribution pattern in the subregion. But we hope this does not happen.

c. Genesis

Although the LDS is a significant climatological feature of the annual rainfall of the southern part of West Africa, especially the Coastal areas, it has not received a proportionate research attention. Most of these researches on the phenomenon have not been published. For example, Kalu (1972) in collaboration with Obasi has investigated the cause(s) of this large-scale monsoon break phenomenon using surface pressure fields derivable from IGY 1958 Data. They related the LDS to the influence of the South-Atlantic anticyclone over the Gulf of Guinea Coast in mid-summer months of July/August, during which time pronounced pressure surges at lower tropospheric levels are observed in West Africa. This effort was directed at finding a possible forecasting model for the Little Dry Season. Adekoya (1979) has also investigated some dynamical basis for the occurrence of the mid-summer minimum rainfall phenomenon.

A most outstanding investigation which has a clue to the genesis of the Little Dry Season is by Obasi (1964) who has shown evidence that, although the total moisture flux over Ikeja is larger in August than in June, rainfall is higher in June than in August when the LDS is observed over Southern Nigeria. His computations show that the moisture field is predominantly convergent in June and divergent in August. The latter is confirmed by the finding of Kalu (1972) that the nearer presence of the southern hemispheric anticyclone over the Gulf of Guinea Coast of Africa is the possible source for the observed predominantly anticyclonic circulation in the lower troposphere. The latter produces the observed stable atmospheric condition which is associated with the Little Dry Season in West Africa.

This condition only implies that what determines the rainfall over a given station is not only the moisture flux over such a station, but primarily the convergence or divergence (as the case may be) of the moisture field. For the former, the requirement is that to enable rainfall to occur on a large-scale, the transient eddies which are rain-producing systems, must be activated significantly. In July or August the lower tropospheric circulation is found to be predominantly divergent over West Africa resulting from the prevalence of a strong anticyclonic circulation. This is not favourable for effective development of the transient systems and so dampens any convective instability which may be present by virtue of the observed high moisture depth during the period.

d. Synoptic Indications

Forecasting the onset of monsoon breaks, like the West African Little Dry Season, is essentially a climatological

prediction for which no acceptable model has so far been produced in West Africa. It is, however, possible on the basis of a good knowledge of its salient characteristics, to be able to recognize the on-set of the LDS and its cessation. This is the procedure adopted in the present treatment.

A most significant synoptic feature which indicates the on-set of the LDS is the presence of some anticyclonic eddies and ridges at lower tropospheric levels over the Gulf of Guinea and coastal areas of the subregion.

A most important characteristic of the LDS in this connection is a stable lower troposphere in the presence of a high moisture depth. For example, the LDS is observed in Zone D area (Dhonneur, 1985). The latter is the zone of highest moisture depth in view of the characteristic slope of the ITD with height towards the Equator. The stable atmosphere is usually associated with strong anticyclonic circulation which in our consideration here is the influence of the south Atlantic anticyclone. Additive to the above may be mentioned of a low-level flow with pronounced anticyclonic curvature in the streamlines. A synoptic feature which may therefore depict the above characteristics is the presence of strong closed anticyclonic eddies and/or ridges at surface and lower atmosphere at least below 700mb over Southern Nigeria, for example. The presence of these synoptic features implies, among other things, that the centre of the low-level subtropical anticyclone is close to the Guinea Coast of West Africa. Furthermore, extensive observation by the writer in Nigeria shows that these are not a feature which is associated with convective rain-bearing weather system like squall-lines.

4.4. Techniques for Forecasting Onset and Cessation of Monsoons

In sections 4.2 and 4.3 we have reviewed some of the methods which are currently applied in West Africa in forecasting major weather disturbances of the two monsoon seasons in the subregion. In the following sections, an effort is directed towards predicting the onset and cessation of the monsoon rainfall.

The forecasting of the onset and cessation of two monsoon rainfall is essentially a climatological problem and up to the present time, climatological forecasts have not been sufficiently documented in the literature. In West Africa there is at present no published model or technique on a synoptic-scale basis which has been specifically directed to this purpose.

However, in the absence of such a recognized model, the author has chosen to discuss a climatological method which has been produced as a basis for the prediction of a climatological rainfall forecast in Nigeria in the form of the onset and cessation of the rainy season. The project was initiated and organized by Prof. G. O. P. Obasi, formerly of the Nigerian Meteorological Services and the then Director, Education and Training, World Meteorological Organization Headquarters, Geneva and presently the Secretary - General of the Organisation.

Although the programme was originally meant for agricultural purposes, it is presently being used as a basis for some climatological forecasts for both the onset and cessation of the rainy season and dry season, including for example, the first monsoon rains in the year.

4.4.1 Data

The data include running pentade rainfall values for all synoptic stations as well as climatological stations in Nigeria as long as rainfall records were available. Data for the period 20 - 50 years were considered in most cases. Such data are presently available on punch cards at the Data Processing section of the Nigerian Meteorological Department, Oshodi, Lagos.

4.4.2 Method

The procedure adopted is a simple time series plot of running sums (or cumulative) of 5 - day (Pentade) rainfall for a given year for the period for which data were available. The plotted graphs have running sums of pentade rainfall as ordinates and pentades (days) as abscissa. This is shown in Fig. 16 .

a. Definition of Onset and Cessation of Monsoon Rainfall

Onset of the summer monsoon rainfall using this method is defined as the point A (day of the month) at which the pentade rainfall curve (see Fig. 1) just begins to rise monotonically. The point A does not, however, represent the first rainfall in the year at the station. The onset of monsoon rainfall, on the basis of the above definition, is therefore different from the "first rains" in the year for a given station. As a corollary, the point A automatically defines the end of the dry season in Nigeria for a given station.

Similarly, the cessation of the monsoon rains is also defined as the point B (day of the month) at which the pentade curve just becomes parallel to the abscissa. As a corollary also, the point B defines the onset of the dry season for the given station.

Mean values of A and B were obtained for each station and for the duration of the period for which data were available. For each rainfall station, these values were plotted on a map of Nigeria. A rainfall station as used in this paper refers to either synoptic station or climatological station. This is because for a sufficient coverage of the country rainfall or climatological stations. Furthermore, in Nigeria, every synoptic station is also a rainfall station, but there are typical rainfall or climatological stations which are not necessarily synoptic stations, like, for example, Umudike (08°13'N,10°35'E) and Samaru (Zaria)(11°33'N,10°10'E).

Isolines of onset dates and corresponding dates for the cessation of monsoon rainfall in Nigeria were drawn separately for the whole country. The resulting two distinct maps, obtained after smoothing of the resulting curves, are shown in Figs 17a and 17b Smoothing was necessary because of the heterogeneous data which were used especially in the Southern States to estimate the pentade dates.

A representative standard deviation for the whole country was necessary and was estimated to be 3 which is equivalent to 15 days, 68% of the observations will lie between plus or minus 1 of the standard deviation. The significance of this will be discussed in the next section.

b. Interpretation of the maps

Isolines on each of the two maps represent a climatological mean onset or cessation dates for the rainy season (i.e. summer monsoon). There is a 70 percent probability that the rainy season in Nigeria will commence or cease when the standard deviation value of 15 days are added to or subtracted from the mean dates shown on the isolines onset or cessation of the rainy season as the case may be. Take for example, the case for Ibadan (07°26'N,03°54'E) which the onset and cessation dates are respectively 21 March and November 15. Considering the former first, on adding to and subtracting 15 days from the mean onset date, we have two dates (6th March and 5th April) which constitute a range for the onset of the rainy season at Ibadan. It may therefore be concluded that in 7 out of 10 years, the rainy season will commence at Ibadan between 6th March and 5th April.

Similarly, for the cessation date (November 15), by adding to and subtracting 15 days from this date, we shall get that the rainy season at Ibadan may cease between 31 October and 30 November.

4.4.3 Application

Although the project was originally mean to give a backing for the Operation Feed the Nation (OFN) programme - a programme initiated and supported by the Federal Government of Nigeria, to encourage agricultural productivity in the country, it is presently being used by weather forecasters in Nigeria to refine their forecasts for the meridional displacement of the active weather zones of West Africa (See Section 4.2.3) which are directly associated with the ITD. This is because of the observation in the area that the first monsoon rains of the year are directly produced by squally thunderstorms. Thus the isolines for the onset of the rainy season give valuable information on the location of the rain-producing synoptic systems affecting the subregion in summer and as well as the onset of the Harmattan dust season which follows immediately the rainy season.

Further, the two maps are of great use by climatologists as well as agriculturalists and all others whose operation are weather-dependent. The range of onset and cessation periods shown as insets on the two diagrams are of high climatological significance especially for an effective planning for the farmer's calender year in terms of planting and harvesting of farm crops.

Since the method was based on the rainfall for each synoptic station, its use necessitated the drawing of space-time curves for the synoptic and rainfall stations in Nigeria used in the analysis. Thus, isolines for the onset of rainfall and the corresponding dates for the cessation were drawn for the whole country. The analysis and subsequent smoothing of the resulting curves produced the two maps depicted in Figs.17a and 17b.

The use of time series analysis for climatological variables, like rainfall, which has been used in the present analysis in Nigeria is considered a reliable method for forecasting such climatological features as the onset of the rainy season and its cessation. The method is sufficiently accurate for climatological forecasts which do not need a very high precis ion level. For the present time, on the agricultural needs of the farmer — information on the onset and cessation of the rainy season, the above simple method will suffice until topical Meteorological research reaches such a level that a more precise prediction may be necessary.

The method which has been applied in Nigeria with fairly good results may be extended to other parts of West Africa with identical climatic pattern as Nigeria. This recommendation is based purely on the realization that in most parts of West Africa, more than about 90 percent of the annual rainfall is produced by squall-line activities in West Africa (Trewartha, 1966).

PART II

EAST AFRICAN MONSOON SYSTEM

1. INTRODUCTION

So far we have considered one part of the African Monsoons - the West African Monsoon circulation system. In the following chapter, we shall treat an important monsoon feature - the East African Monsoon System (EAMS) which is in fact a part of the Asian Monsoon System. In this treatment we shall discuss the various pressure systems that control the Monsoon Circulation of the East African sub-region and at the same time highlighting the peculiarities of this very important Monsoon system in Africa.

2. PHYSICAL FEATURES CONTROLLING THE MONSOON SYSTEM

a. The Geographical Setting

In our earlier discussion in Chapter 1 (See section 4, page 6), we had considered various factors controlling the establishment and maintenance of Monsoon Circulation Systems in Africa. In that section the influence of topography was mentioned. In the present chapter, we shall treat this aspect of the monsoon climate in some detail as it specifically exerts a strong control in the weather and climate of East Africa.

Considering the relief features of Africa, it will be observed that the East African sub-region is located within the topographical area designated as High Africa (Udo, 1978; Adefolalu, 1979). This, like the influence of the high Andean Cordillera of the Pacific coast of South America, controls the climate of the region in its entirety.

The East African highland lies parallel to the coast such that the mainland of the subregion, extending from Lake Victoria lowlands to the African peak of Kilimanjaro in Tanzania, forms only a narrow strip of land with mostly off-shore winds most of the year in many parts of the region. This, in fact, makes the climatic peculiarity we observe in Eastern Africa. The East African highlands narrows the coastal lowlands so that it finally pinches out just north of Lake Victoria in Southern Uganda. This is evident in Fig. 44.

As a result, a most impressive climatic anomaly is observed in East Africa, particularly controlled by topographic features of the subregion. This climatic anomaly is in the form of a widespread deficiency of rainfall in tropical East Africa (Trewartha, 1966; Ogallo, 1981, Okoola, 1983). To an unusual degree, the restricted area with genuinely humid climates in East Africa following Thornthwaite's (1948) classification system, coincides with the higher elevations. Along the whole of East Africa bordering the Indian Ocean - from Cape Guardafai at about 12°N to 30°S, considerably less than half of the coastline, has as much as 102mm of annual rainfall, while only three relatively short stretches of the coast may be classified as humid, following Thornthwaite's classification of moisture regions in Africa.

b. The Climatic Pattern

East Africa may be described as a region with even more striking climatic features than are found in West Africa. Instead, what is observed is climatic characteristics which are greatly determined by topography of the region as discussed in Section (a) above. The climate is very unique and distinct in a manner that is lacking in other parts of the continent.

Rainfall in East Africa, especially in the western interior parts, occurs in association with irregular incursions of unstable air from the Congo Basin - the so-called Congo air mass (See Fig. 18).

There is a corridor of wet climate along the coastal areas and this reflects the topographical features of the area.

Distribution of rainfall is very difficult to describe. This is because a clearly discernible synoptic pattern for rain prevailing systems is also complicated. For example, north of the equator, areas of higher elevation constitute the sites of heaviest rainfall. Humid climates are found in parts of the coastal lowlands while dry Savanna climate prevails over the Kenya-Uganda highlands. Genuinely arid climate are lacking south of the equator, except a few areas in Eastern Kenya. In contrast, dry sub-humid and semi-arid climates are widespread both along the west and in the interior plateau of Kenya. The highlands provide necessary trigger action for precipitation systems which are orographically induced in most cases.

The moisture transport into Kenya is controlled by the Mascarene High pressure and it has been observed that an intensification of the anticyclone generally causes a freshening of the South Easterly Monsoon in East Africa (Okoola, 1982). An important evidence in this connection is that there is a relationship between the intensity of ITCZ in East Africa, though highly diffuse (Trewartha, 1966) and the extent and intensity of the semi permanent anticyclone in the South-West Indian Ocean. Sansom (1955) has, for example, reported that the S. E. monsoon which brings most of the moisture into Kenya, was to a large extent controlled by the Mascarene High. He further studied the relationship between seasonal rainfall over Central Kenya and the sea-level pressure changes (the 24-hours pressure tendency values) for the preceeding three months at stations located to the north and south of Kenya. His results indicate that seasonal rainfall was above average of the normalized pressure departures during the three months preceeding the rainy season.

Also evidence has been established for a mid-latitude influence on the climate of Eastern Africa. For example, Lamb (1966) in his study of the disturbances causing rainy season along the East African region during May, has associated rainy periods with the remnants of cold fronts that intrude into the southern tropics. The effect of cold air surges into the Mozambique Channel is to sharpen the coastal ridge located to east of the Malagasy republic.

Findlater (1974) has observed that during periods of the East African low-level Jet, rainfall occurs to the East African coast (near the Port of Mombosa) close to the position where the jet approaches the coast. Also Findlater (1972) and Okoola (1982) have reported that the low-level jet core found near the 850 hpa level during northern summer is associated with horizontal velocity convergence and not related directly to the ITCZ.

Abnormally wet conditions over most parts of East Africa are associated with westerly winds from the South Atlantic. The dry zone of the semi-arid area of Kenya and Tanzania which is always under the influence of low-level diffluent monsoon current (N.E. Monsoon during southern summer and S.E/S.W monsoon during northern summer). See Fig. 11. This zone receives most of its precipitation during occasions of intense ITCZ activity. The month of January is generally dry in most parts of East Africa except perhaps southern Tanzania, whereas April is a peak rainy month for a greater part of the subregion. There are two major rainy periods in East Africa. These are: (a) the Long Rains: March - May and (b) the Short Rains: October through December.

Seasonal rainfall variations over Equatorial Africa as well as other Equatorial regions the world over, are controlled for the larger part by the behaviour of the ITCZ. This is in terms of its intensity, location and width. Adequate rainfall (or lack of it) over an area which is affected by the meridional movement of the ITCZ in general can be ascribed to an expansion (compression) of the area covered by the ITCZ or an enhancement (dimination) of the moisture convergence (Obasi, 1964) in such an area. The non-randomness of rainfall in Africa in general (and in East Africa in particular) calls for a closer look at the large circulation patterns that will uniquely characterize rainfall anomalies of a particular area. But the absence of a well defined Easterly wave system in East Africa due largely to orographic forcing distorts the rainfall distribution and hence the climate of the region.

3. Explanation for Observed Climatic Pattern

Now that we have surveyed the climatic pattern of Eastern Africa, it is necessary for us to examine briefly the atmospheric features associated with the observed climatic pattern. Firstly, the presence of a large body of water - the Indian Ocean - lying approximately parllel to the East African subregion meridionally, as would be expected, should bring moisture into the highland region of Eastern Africa. However, observational evidence simply indicates that the reverse is the case - in which the two principal monsoon circulation systems - the N. E. and the S. E. monsoons fail to bring sizeable amount of moisture into the area.

What then is the cause of this apparently dry area in Equatorial region of Africa? According to Trewartha (1966), the origin of the general rainfall deficiency over East Africa may be attributable to several causal factors. Topography and the low-level circulation features of the tropical atmosphere are to the greatest extent responsible for the observed low rainfall in this region of Africa. There is a general concensus that both monsoon systems in the region are divergent and subsident over extensive areas. The low-level flow is such that the wind fail to deposit the moisture in the area. This implies that the dynamical mechanisms associated with rain-producing systems in East Africa are rather too weak to precipitate the available moisture. In this WAY THE INSTABILITY is not usually released, although the atmosphere may be cloudy. This is very much similar to the situation in West Africa during the meso-climatic phenomena of the Little Dry Season (Kalu, 1972) which we had discussed in part I of this book (See section 4.3). A common characteristic synoptic situation observable in East Africa, for example over Nairobi, is the prevalence of persistent Stratus, stratus-cumulus cloud genera with occasional overcast conditions over Nairobi during the dry season. This is the period when the monsoons are at their maximum development.

A possible realistic explanation for this striking climatic feature of Eastern Africa may be sought from the divergence field and less so from the trade wind confluence in East Africa. Observations in the area confirm that low-level circulation features over East Africa is largely divergent. Thompson (1965) points out that the S. E. monsoon which is fairly moist but shallow as it approaches the Kenyan Coast and Tanzanian Island becomes abruptly diffluent as it moves inland with one branch continuing westward across the Island and spreading north and south over the interior, while the other branch turns abruptly northwards to parallel the Somali coast. This is illustrated in Fig. 19a.

Another argument which has sometimes been used to account for the paucity of rainfall in East Africa is the capping inversion phenomena which has been discussed by various authors in African Meteorology, especially Riehl and Malkus (1958). These shallow monsoon currents are capped by another air of different thermodynamic characteristics originating from a different direction. See Fig. 12. The moisture content of the capping air mass is low and variable such that lapse rates are weak and sometimes subsident and stable, subsident with inversion. The lapse rate may in fact be favourable for precipitation as in excess of the wet adiabat and the moisture also sufficient, but rain does not occur. This is principally due to the general atmospheric environment being divergent for most part of the lower troposphere.

Furthermore, the observed charactristic strong meridional flow over East Africa during each of the two monsoon components is favourable for moderate rainfall. The more humid S. E. monsoon has had a long trajectory across the Indian Ocean before reaching the African low-level Jet which has been discussed by Findlater (1969, 1971, 1977) as follow this trajectory. However, the drier northerly N. E. monsoon has a more meridional trajectory both over the ocean and over land areas of East Africa. The flow at times is such that the wind is parallel to the coast. This is highly unfavourable to moisture release over the African high. The result is therefore, as would be expected, a much smaller transport of moisture from the ocean to land than would be true if the air flow were nearly normal to the coast, while at the same time the lifting effect of the eastward-facing plateau escarpment is greatly minimized. Ironically, however, it is significant to note that it is during the transition period between the two monsoon systems, when air movement is more zonal and from the east, that rainfall reaches its maximum in East Africa.

It is also observed that in the vicinity of the equator, the S.E. monsoon during northern winter may extend up to 8000 — 12000 feet above mean sea-level, but this still means a relatively shallow maritime current over the East African Plateau where sea-level pressure is almost at the 850 hpa level (5000' level). As a result the depth for convective overturning is very shallow and hence does not favour the release of moisture for rainfall processes (Palmen and Newton, 1969). Additionally, as has been pointed out earlier, these air masses at a higher level with different thermodynamic characteristics originating from a different direction.

It is necessary to stress the point that the depth of moisture plays a very significant part in the actual process of producing rainfall in tropical lands. For example, in the coastal region of East Africa/Southern Africa, the southerly flow is only 1 - 2km deep and hence too shallow to surmount the escarpment and reach the Kenyan plateau. This explains why Nairobi, for example, has significantly temperate climate and vegetation pattern. This, in fact, reminds me of the usual emphasis of my one-time lecturer, Mr. John Findlater-famous for the East African Low-Level Jet (Findlater, 1969, 1972, 1974, etc). This was while I was doing my professional Class 1 Meteorologist training course at the University of Nairobi, Kenya in the 1971/72 session. We used to be told of the importance of the depth of moisture which will produce rainfall. There IS USUALLY A CRITICAL DEPTH OF MOISTURE AS MAY BE INFERRED FROM T-ϕ diagrams obtained from radiosonde ascents. It is therefore not enough to forecast rainfall simply because of the flow field, but a most important requirement is how deep is the moisture available and synoptic mechanisms (e.g. the collision process) to precipitate the available moisture?

Furthermore, Koteswaram (1958) has proposed a meridional circulation pattern between equator and the heat source of the Tibestan plateau. It is to be noted that the East African monsoon system is a part of the Asian South-West monsoon system.

According to the model proposed by Koteswaram (1958), the Tibestan plateau, an extensive land mass of an average height of about 4km. receives cupious amount of solar radiation during the summer thereby raising its mean temperature to about 2 to 3°C above its surroundings. It therefore, so to say, becomes an elevated heat source generating an area of rising motion owing to the heating of the air surrounding it. The air ascending here spreads southwards and gradually sinks over the Equatorial region in the vicinity of the Indian ocean thereby generating a reverse flow from south to north and creating a South-west monsoon at lower levels of the atmosphere. This mechanism has sometimes been tagged Reverse Hadley Cell and assumes the origin of S. westerly monsoon winds near the Equator. This is not observed. There is some doubt regarding the role of the Tibestan Plateau itself as the initiator of the monsoons (Singh, 1986).

The above consideration, as well as the sea-breeze effect used sometimes to account for the West African monsoon circulation system do not give adequate explanation which is in full agreement with observation (Kalu, 1983). In the author's view, these theories are observational consequences of the monsoonal circulation systems in the tropics and not necessarily the cause, for the system itself.

Meteorologists in many cases have tended to emphasize the observed influences of a particular meteorological phenomenon. For example, in West Africa, earlier meteorologists had tried to explain the causes for the Little Dry Season (LDS) of West Africa in terms of its outstanding effect - the strong stability of the tropical atmosphere. Investigations by Kalu (1972) in collaboration with Obasi (1972) demonstrate that this is not true. The stable atmospheric environment usually associated with the LDS is not a cause, but its direct effect (See section 4.3d)

4. THE CIRCULATION SYSTEMS

A major difference between the circulation systems of West African monsoon and that of the East African monsoon is the nature of the Inter-Tropical convergence Zone (ITCZ). In East Africa, the latter appears diffuse and not clearly defined as in West Africa, thereby making its use as a predictor variable rather difficult. Unlike in West Africa, where its application forms major forecasting model in the region. In fact, there are multiple convergence zones East Africa implying the existence of more than two wind systems. The Trade winds are weakly defined in association with the Easterly waves which are of little synoptic consequence over the Eastern African Plateau, except perhaps further East over the Indian Ocean area.

[illegible]

In addition to the northerly and southerly surface/low-level winds, there are also occasional invasion over East Africa, especially west of Lake Victoria area, by moist westerlies - the Equatorial westerlies which have been properly documented by Kiangi (1984) over Kenya. They are considerably unstable and give rise to most of the rainfall in the Central part of East and Central Africa. This is associated with the so-called Congo Air Mass (CAM).

5. FORECASTING MODELS IN EAST AFRICA

5.1 Introduction

In view of the established relationships between surface pressure systems to the north and south of East Africa (e.g. over Kenya) and the weather-producing systems, East African Meteorologists have routinely used surface pressure field changes over (i) Arabia, (ii) the Mascarene Islands, (iii) the South-East Atlantic ocean (to the east of St. Helena Island) to give both short-range and medium range forecasts of rainfall in East Africa. Since these pressure systems methods have been variously described in the literature, they will only be summarized here. These are :-

(i) The pressure tendency method.
(ii) The Johnson and Morth (1964) pressure configuration model, the (a) the DUCT, (b) the BRIDGE and (c) EQUATORIAL MODELS.

They have received an increased applicability both in Eastern Africa as well as in other areas of the tropics especially in regions which lie astride the geographical equator. For example, both the DUCT and the BRIDGE models are useful forecasting tools for rainfall areas of the Easterly waves especially in the near-Equator zone where isohypses and prognosis become less useful forecasting tools owing to the collapse of the Coriolis principle. Also the crossequatorial flow technique especially in connection with across-equatorial moisture transport (Obasi, 1864) is very popular in both East and Western Africa.

(iii) The Easterly wave model

This method does not receive a wide applicability in East Africa. This is especially because of the fact that the Easterly waves are weakly developed in Eastern Africa, unlike in West Africa and the Caribbean Islands (Riehl, 1954). East African Meteorologist only use the Easterly wave model when the other models are not appropriate to forecast a particular weather situation especially in the South-West Indian Ocean area.

(iv) The Trade Confluence Technique.

Where the ITCZ is well developed, this technique may prove very useful. The major problem with it is that the ITCZ is weakly defined over East Africa. Unlike in West Africa where there is a clearly defined confluence zone or a surface of discontinuity in moisture content, wind field and cloud cover, the situation in East Africa is different - there are multiple ITCZs. This makes weather forecasting based on this technique rather weak especially as strong rain-producing systems, like squall-lines, are concerned.

(v) The Climatological technique

This method has been found very reliable not only in East Africa, but in all parts of the African tropics. The method has to be used with caution because climatological fields themselves have been found in a number of cases to exhibit some significant variability.

(vi) Long-Range Weather Forecasting. Technique

This type of weather forecast is still in its infancy in many parts of the tropics and East Africa is not an exception in this respect. However, the Commission for Atmospheric Sciences (CAS) Working Group on Tropical Meteorology has strongly recommended an increased interest in the practice and application of long-range Weather Forecasting research. It is interesting to note that a number of national Services in Africa attended the last CAS Long-Range training course in Sofia, Bulgaria preceeding the 9the Session of CAS in October, 1986.

6. Further Studies on the East African Monsoon System

As the East African Monsoon System has not been fully studied on a large-scale like the other monsoons of the world, e.g. the Indian Monsoon and the West African Monsoon circulation systems, serious effort is at present being made by the WMO Regional Association I (Africa) Working Group on Research in Tropical Meteorology (WMO No. 671). This regional Monsoon Experiment is being organized by the WMO through the Commission for Atmospheric Sciences (CAS) Working Group on Tropical Meteorology for

a more detailed study and documentation of the EAMS (WMO, 1986). This regional observational study of the African Monsoon is being proposed with the view that some of the details of the EAMS will become clearer than is the case at the present moment.

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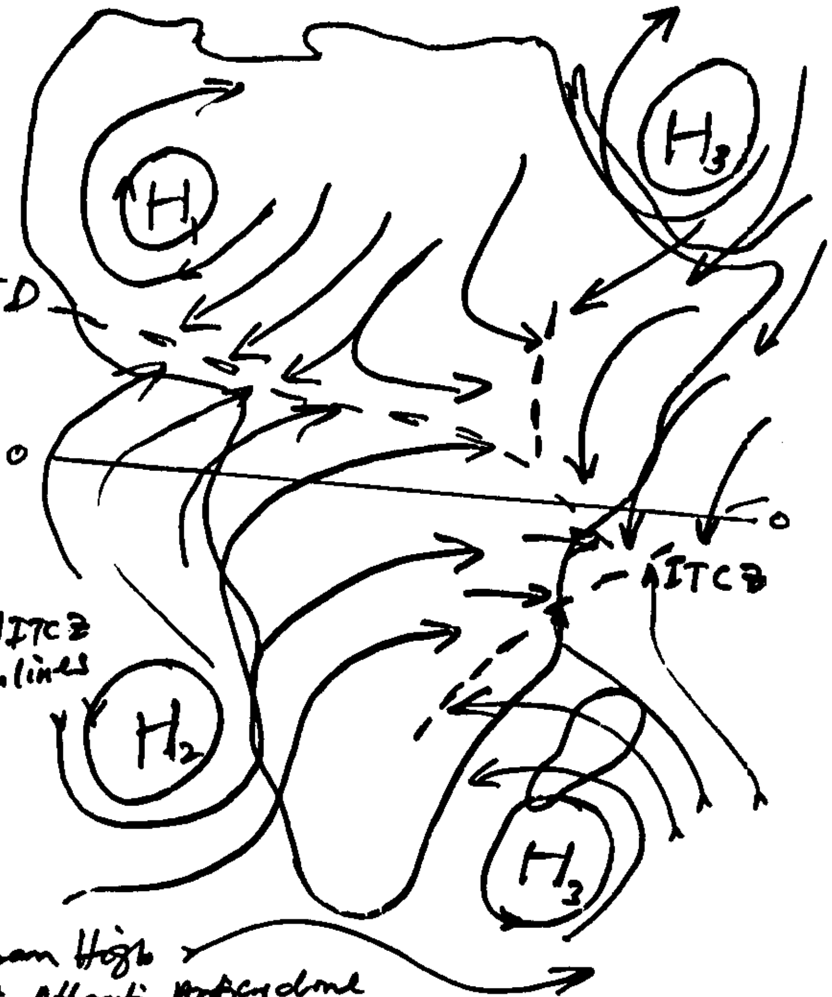
FIG 1(b) Primary Pressure Systems Controlling Monsoon circulation over Africa for Northern winter (Mean surf. circulation features).

JAN. N.B (schematic).



--- ITD/ITCZ
→ streamlines

H1 = Saharan High
H2 = South Atlantic Anticyclone
H3 = Mascarene "
H4 = Arabian High

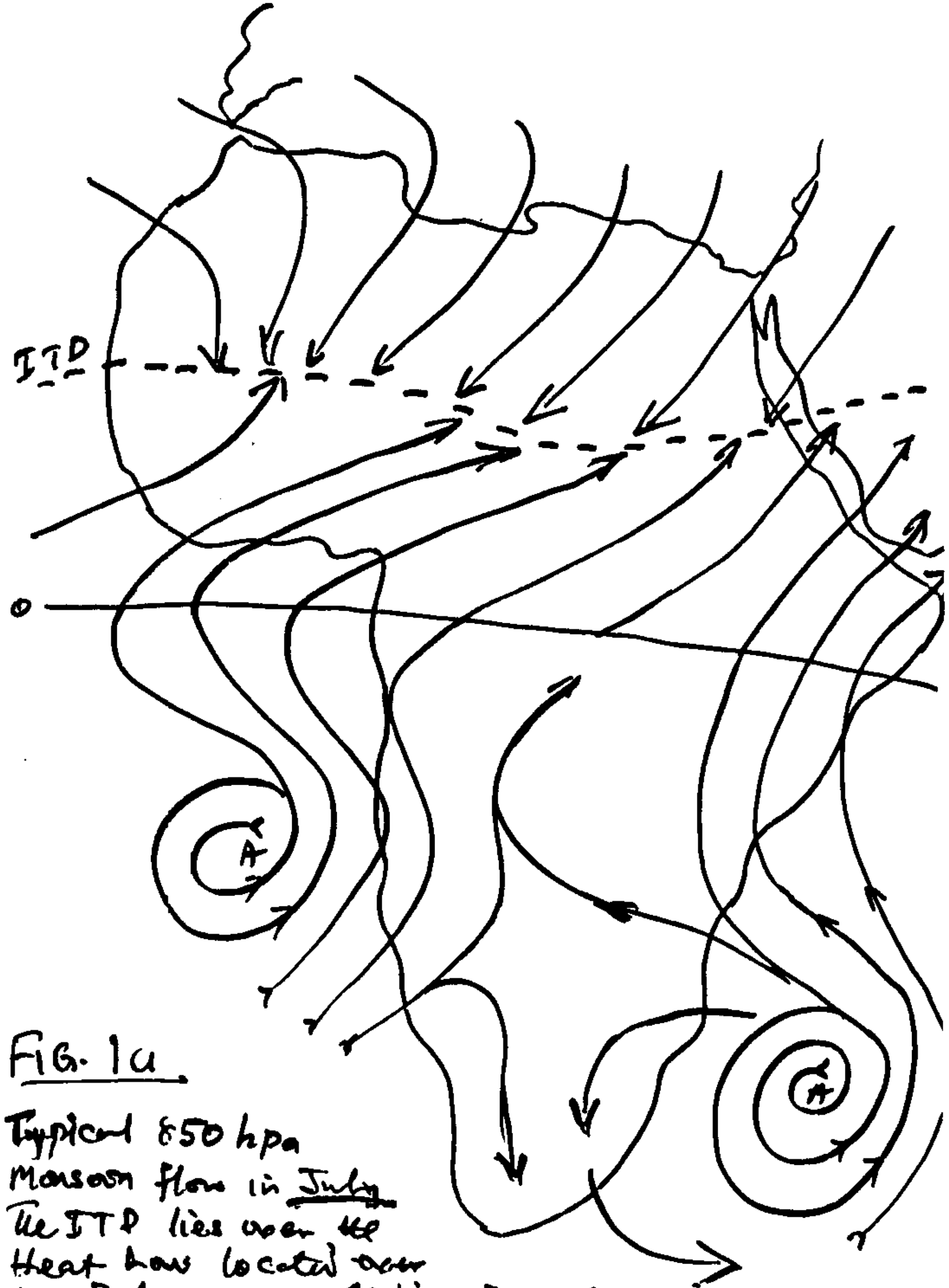


FIG. 1a

Typical 850 hpa Monsoon flow in July. The ITD lies over the Heat Lows located over the Sahara and Arabian Deserts.

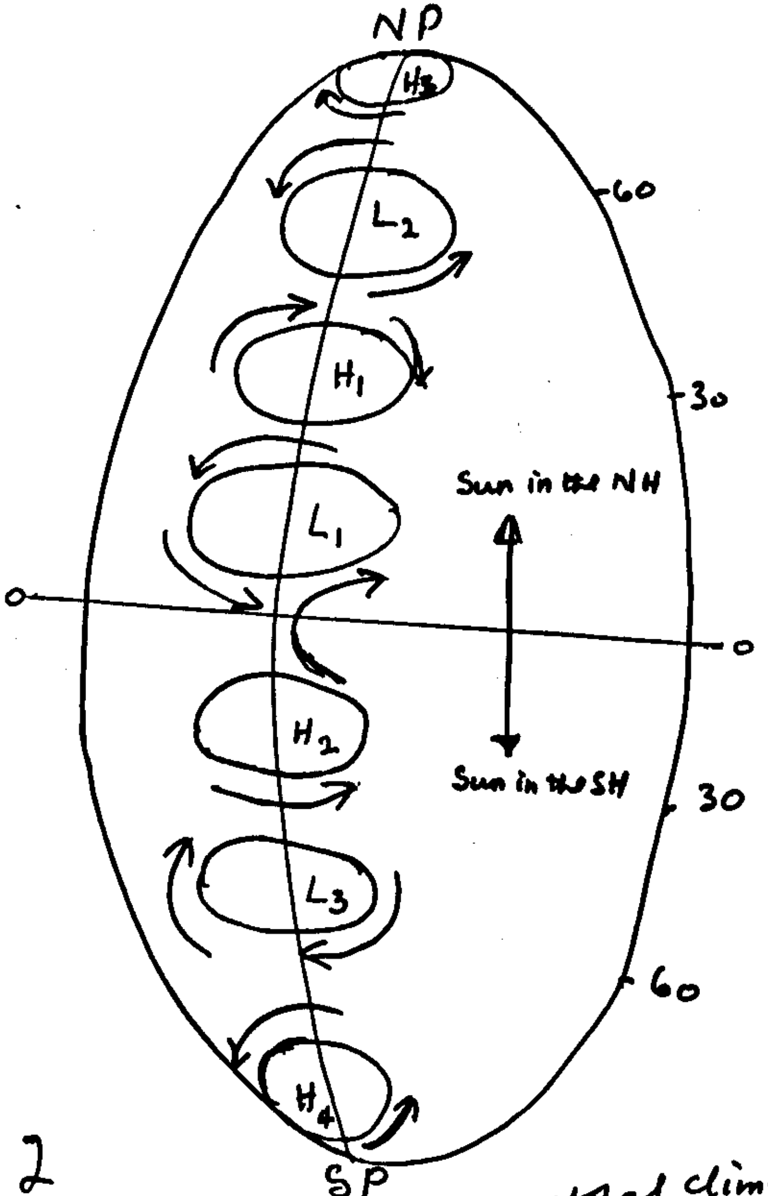
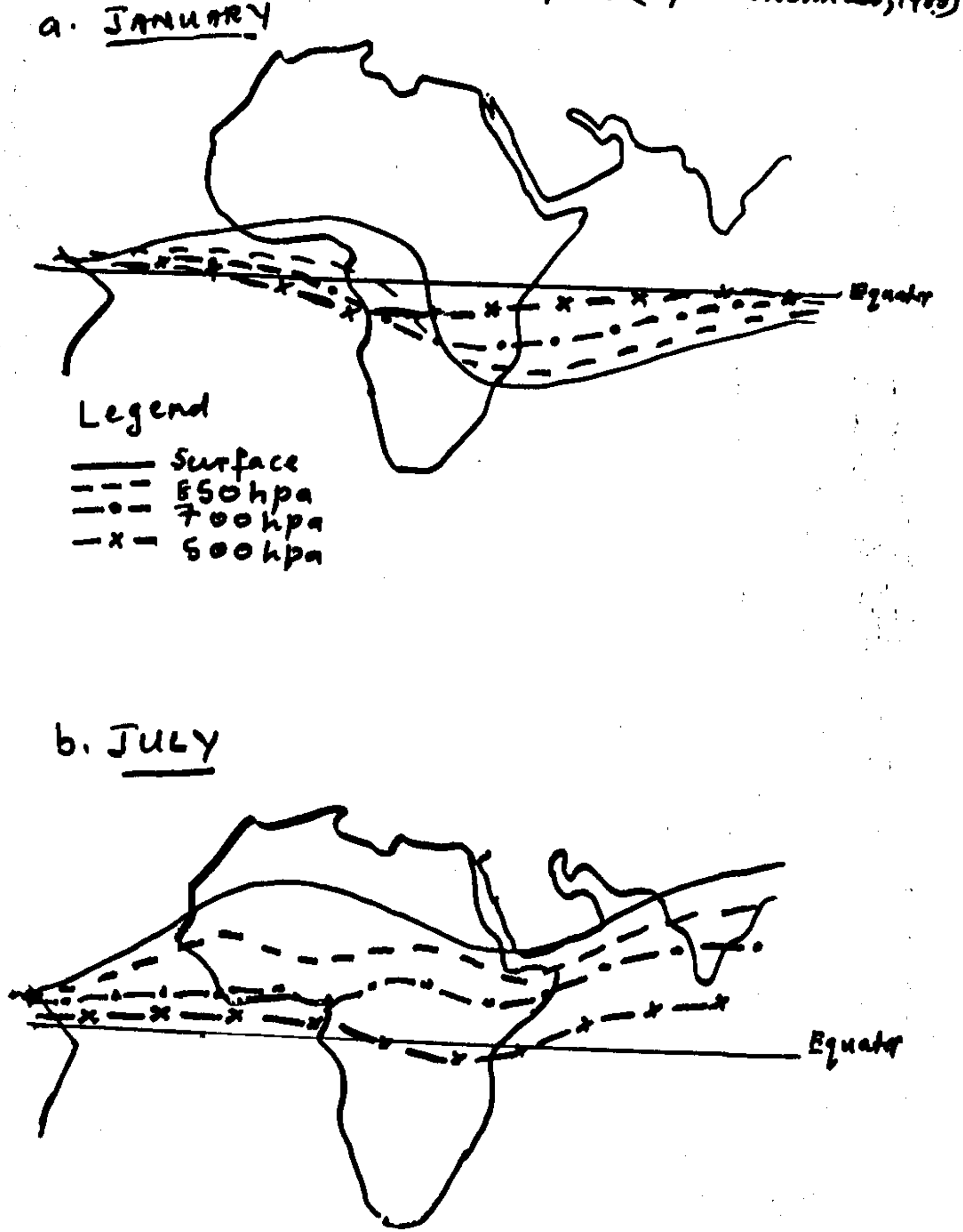


FIG. 2

Schematic illustration of the global climatological pressure systems along the longitude of Accra (Ghana) indicating a "spongy" connection between them in a meridional direction. The arrows indicate direction of air circulation around each pressure cell (After Kalu, 1985). 3

FIG. 3 Seasonal Variation of the Position of the Equatorial Trough (ET) at Various Levels in the Lower Atmosphere (After Dhonneur, 1985)



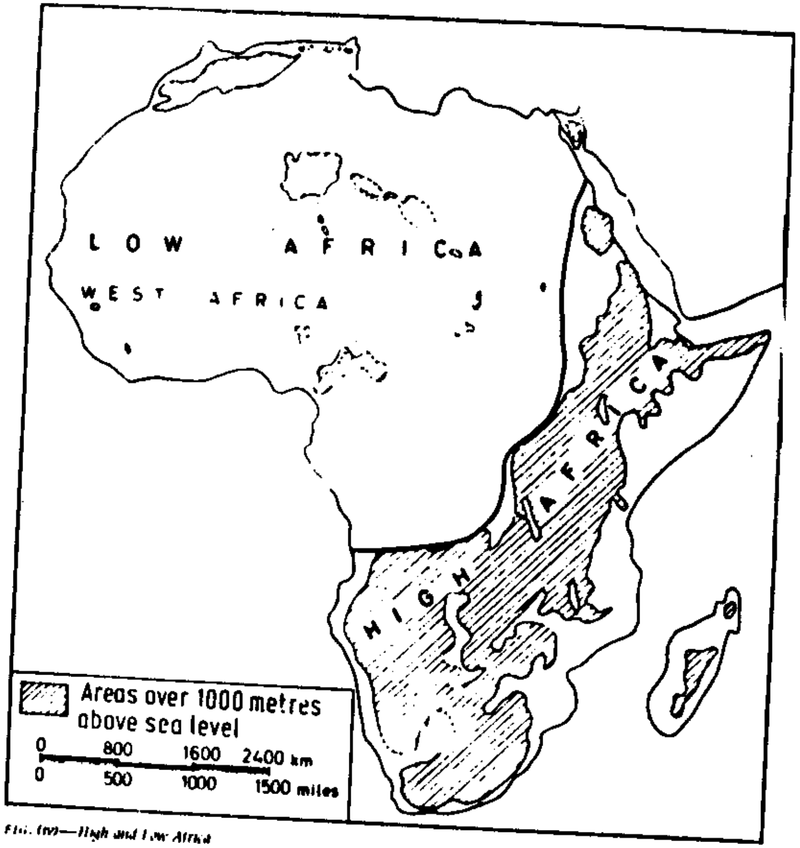


Fig. (iv)—High and Low Africa

FIG. 4 Topographical map of Africa showing Low Africa and High Africa (After Udo, 1978).

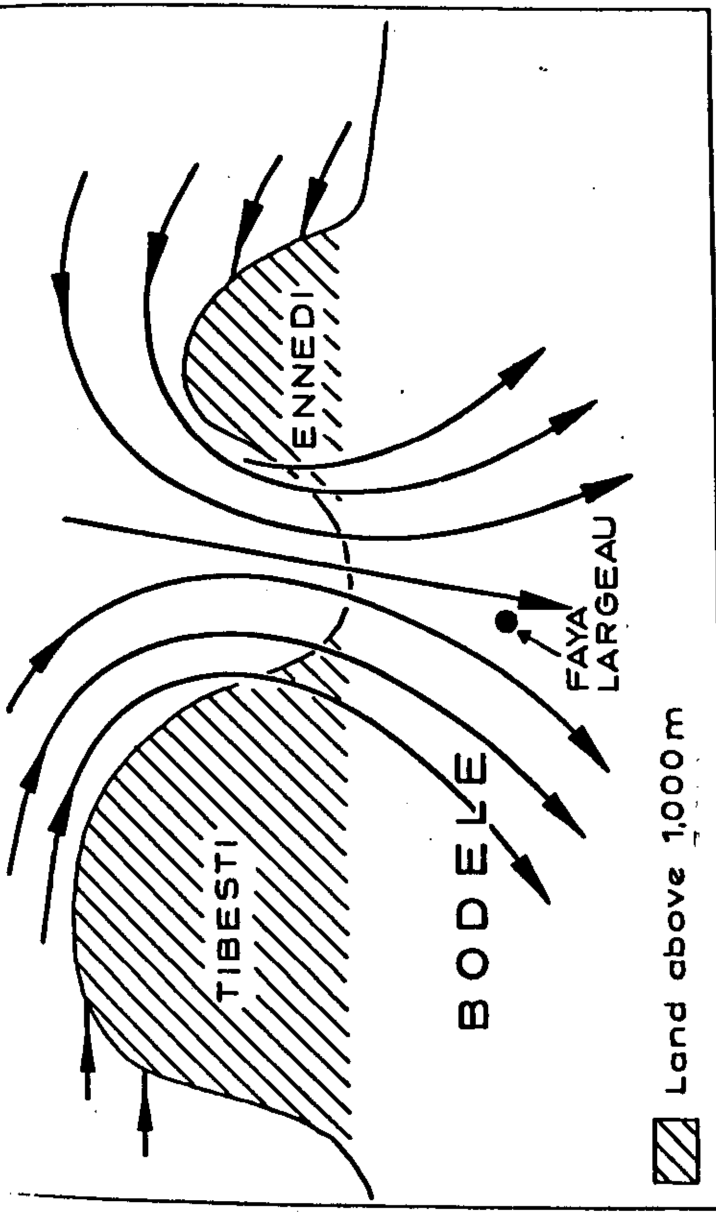


Fig. 5 Funnelling of air through a mountain valley into Faya Largeau (Chad)
(A plan view looking NE-SW)

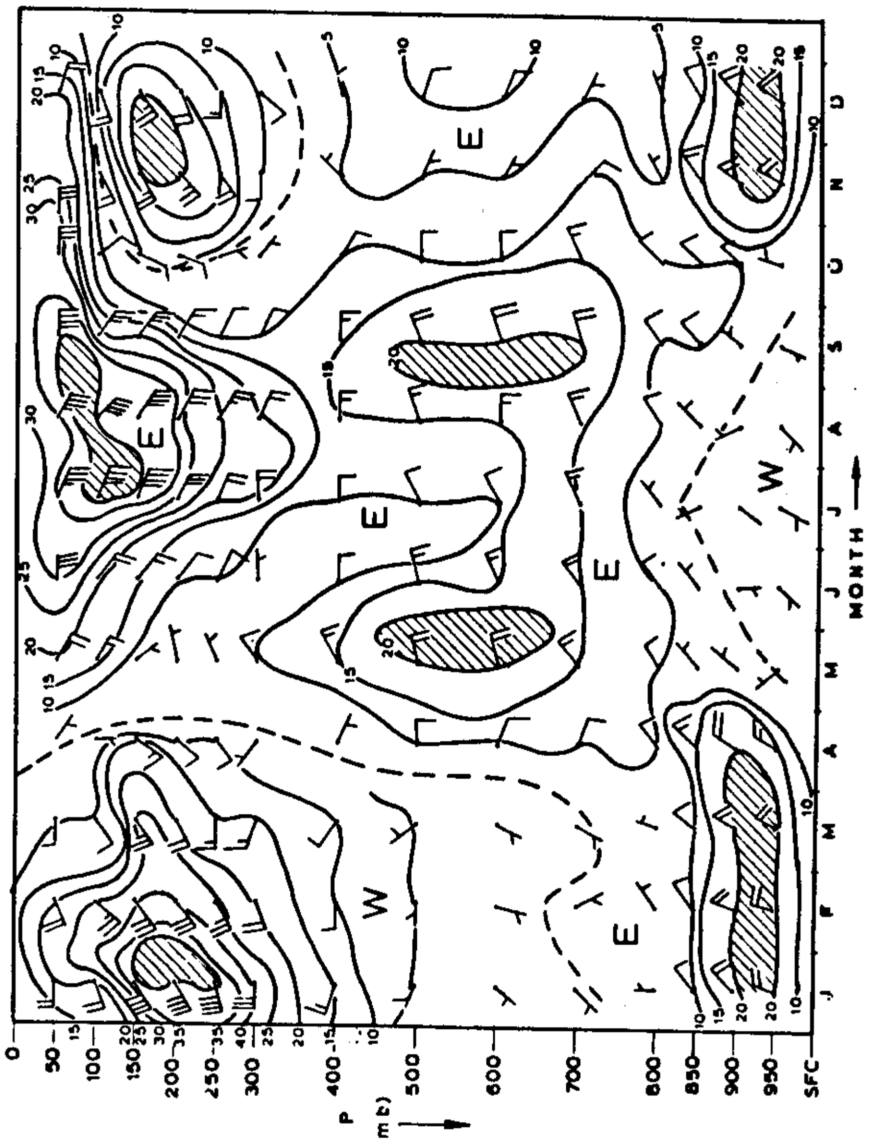


Fig 6a. Height-section of mean monthly vector winds over N'djamena (Chad), 1970, 0700 GMT. Hatched areas are jetstreams and dashed lines bounding Easterly (E) and Westerly (W) winds (After Kahn, 1983).

7

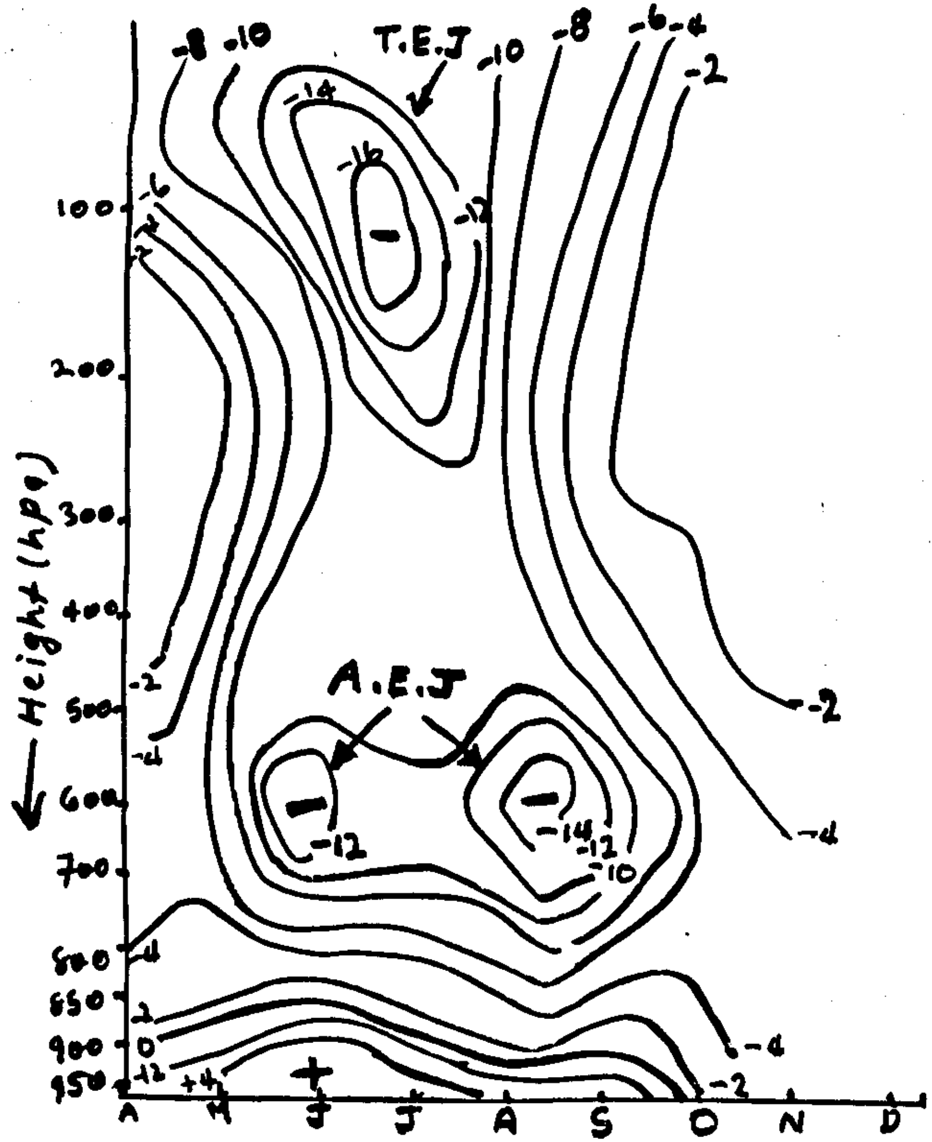


Fig. 6b. Zonal Wind Component (m/s) for Niamey (After Dhonneur, 1985). 8

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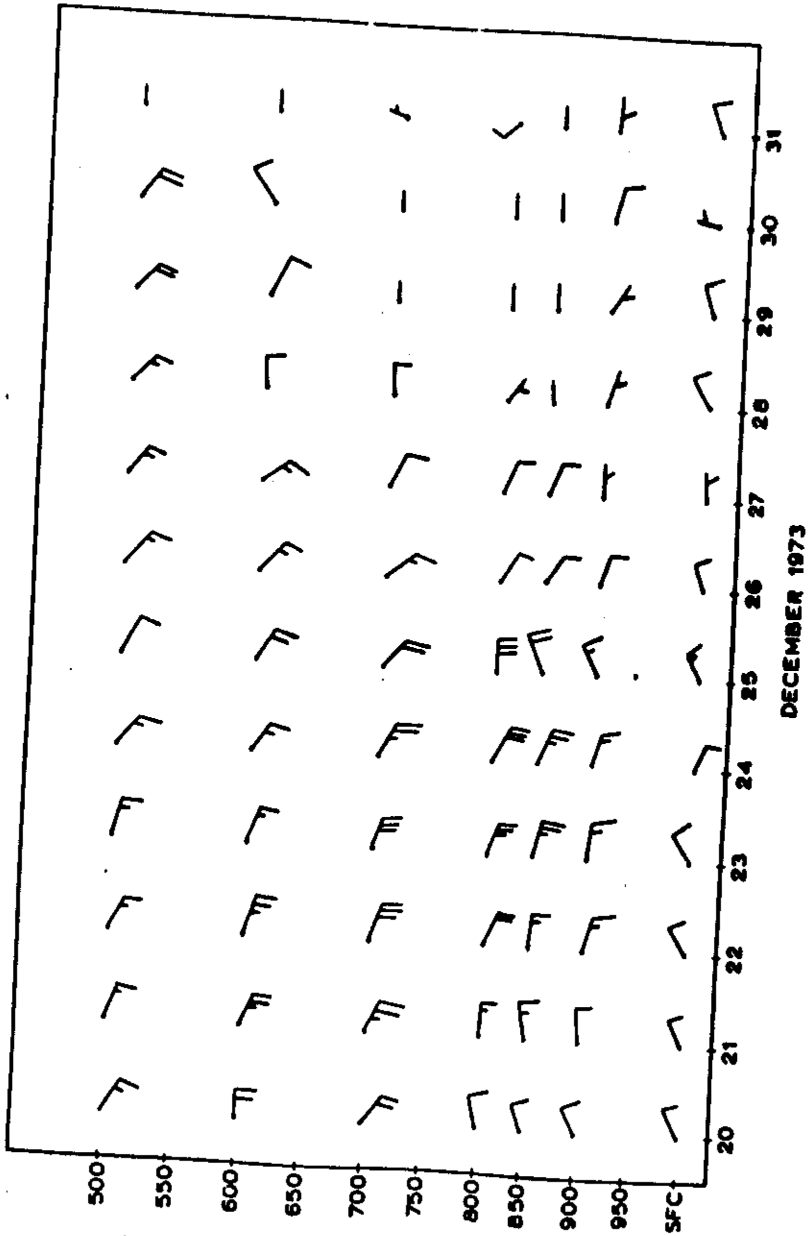

Fig. 7. Vertical Cross-Section of vector winds (kt) at Kano, Dec. 1973, 1200 GMT.

FIG. 8

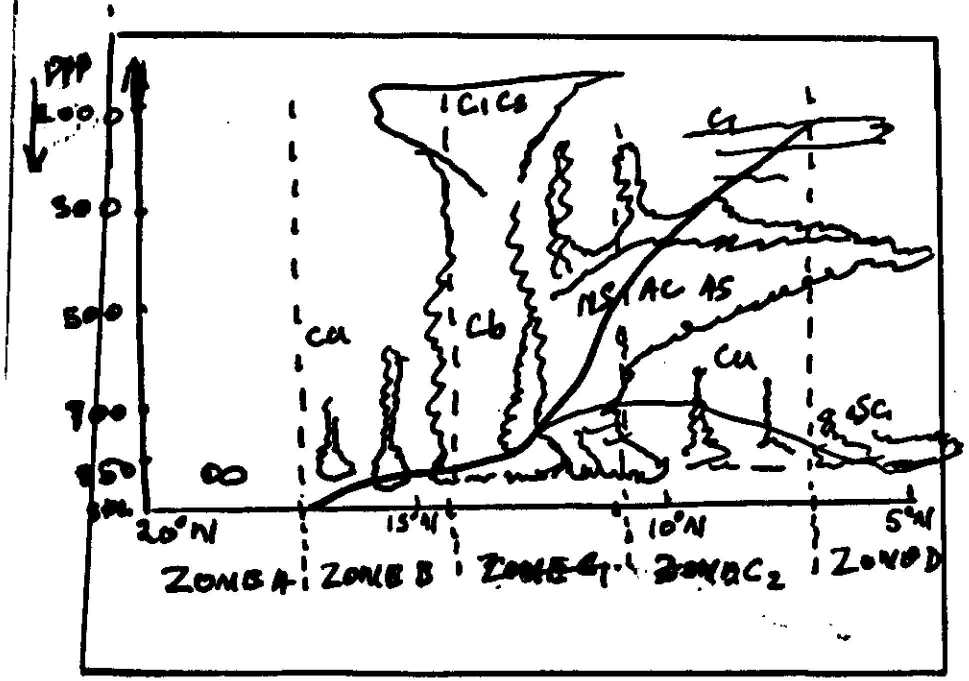

FIG. 8 Vertical structure of the Inter-Tropical Discontinuity (ITD). Schematic. (After Dhonneur, 1985).

FIG. 9 Relief Features of the African bulge and its influence in the perturbation of the Easterly waves.

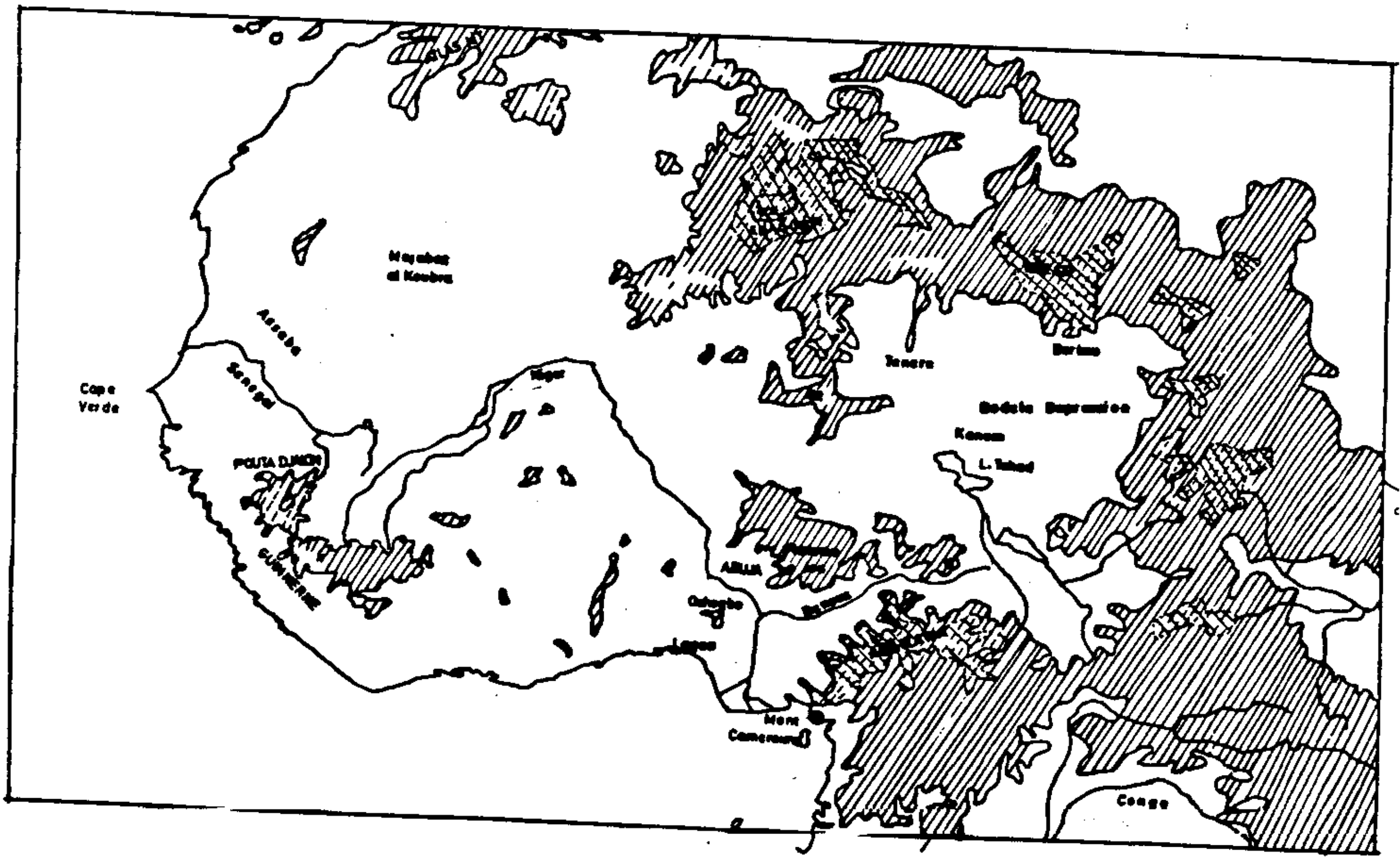

FIG. 10 An illustration of the Saharan Dust Plume Transport across West Africa.

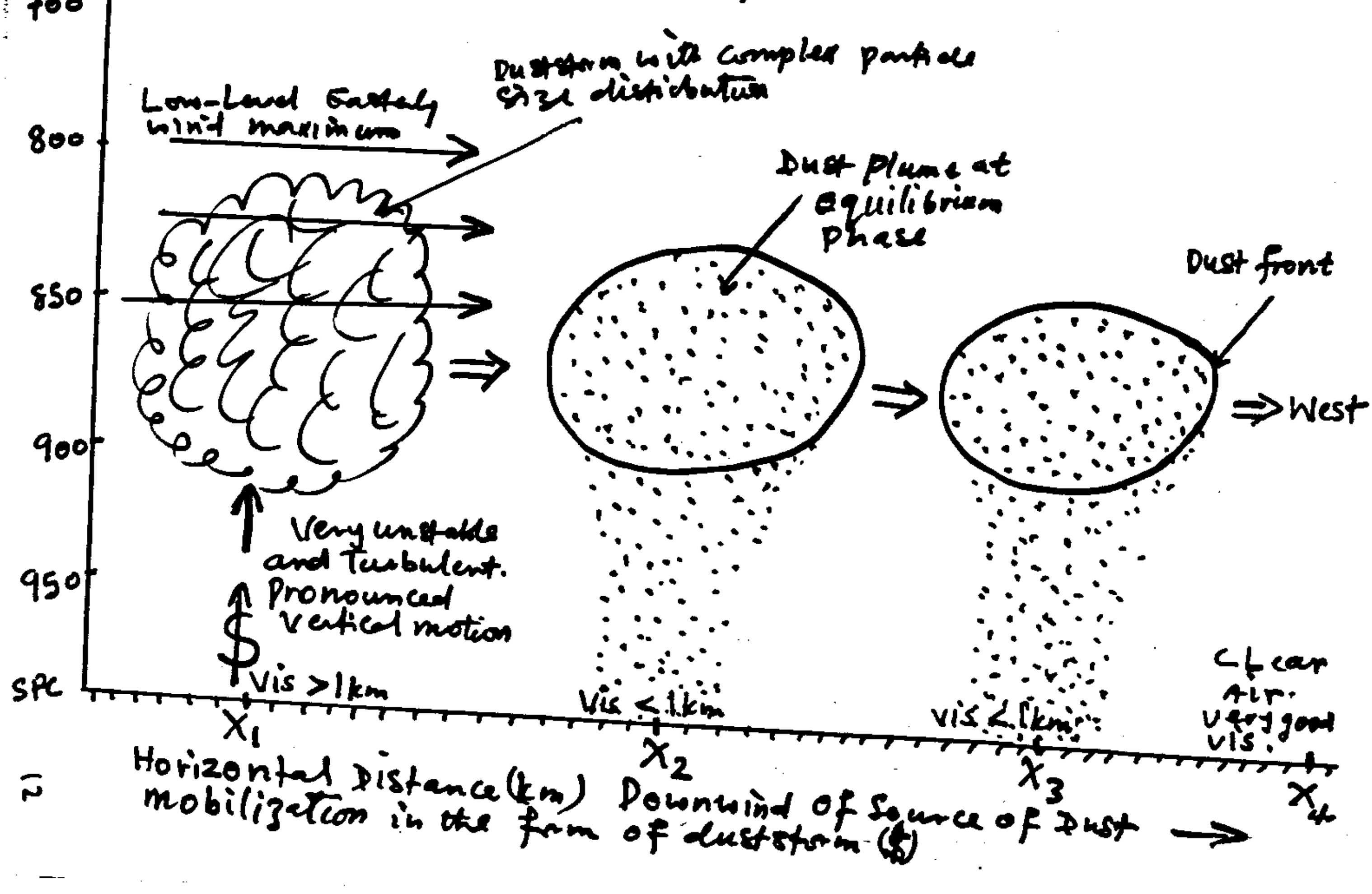

FIG. 11(a) Temperature profiles in a dusty atmosphere for March, 1977, Kano. 1200 GMT. showing dust induced Low-Level capping inversion (After Kalu, (1987a).

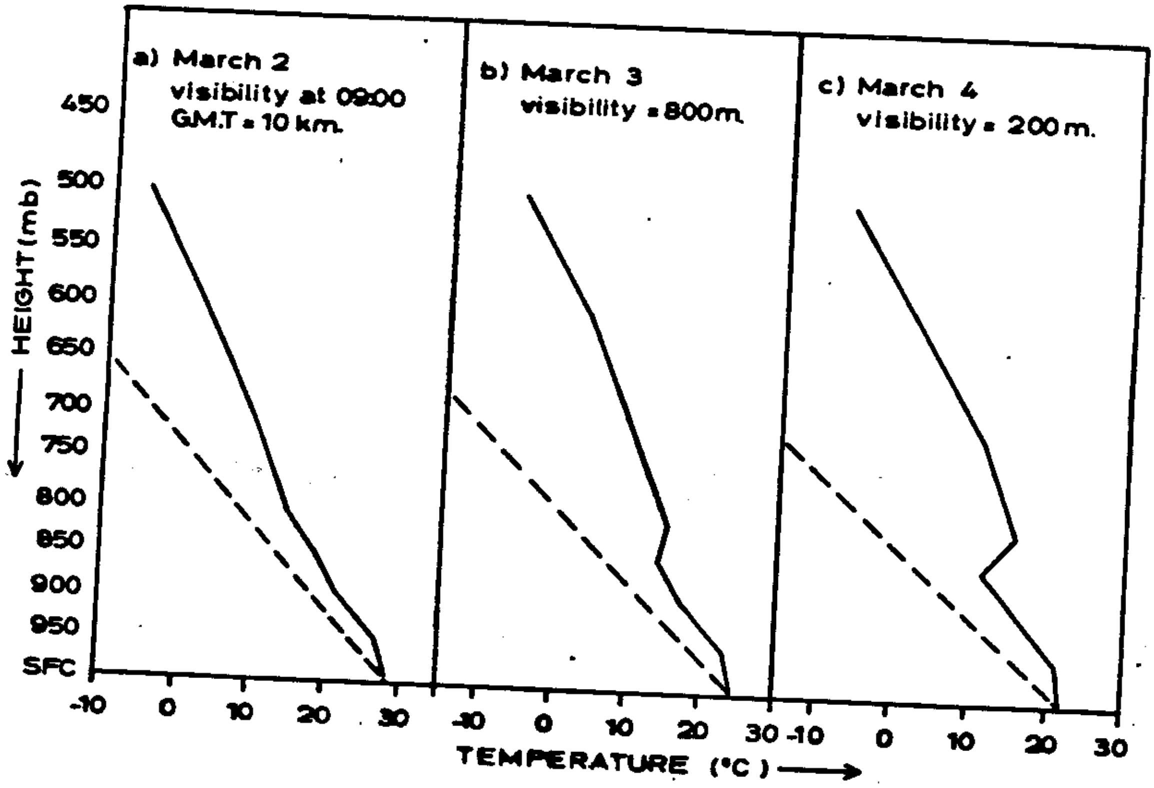

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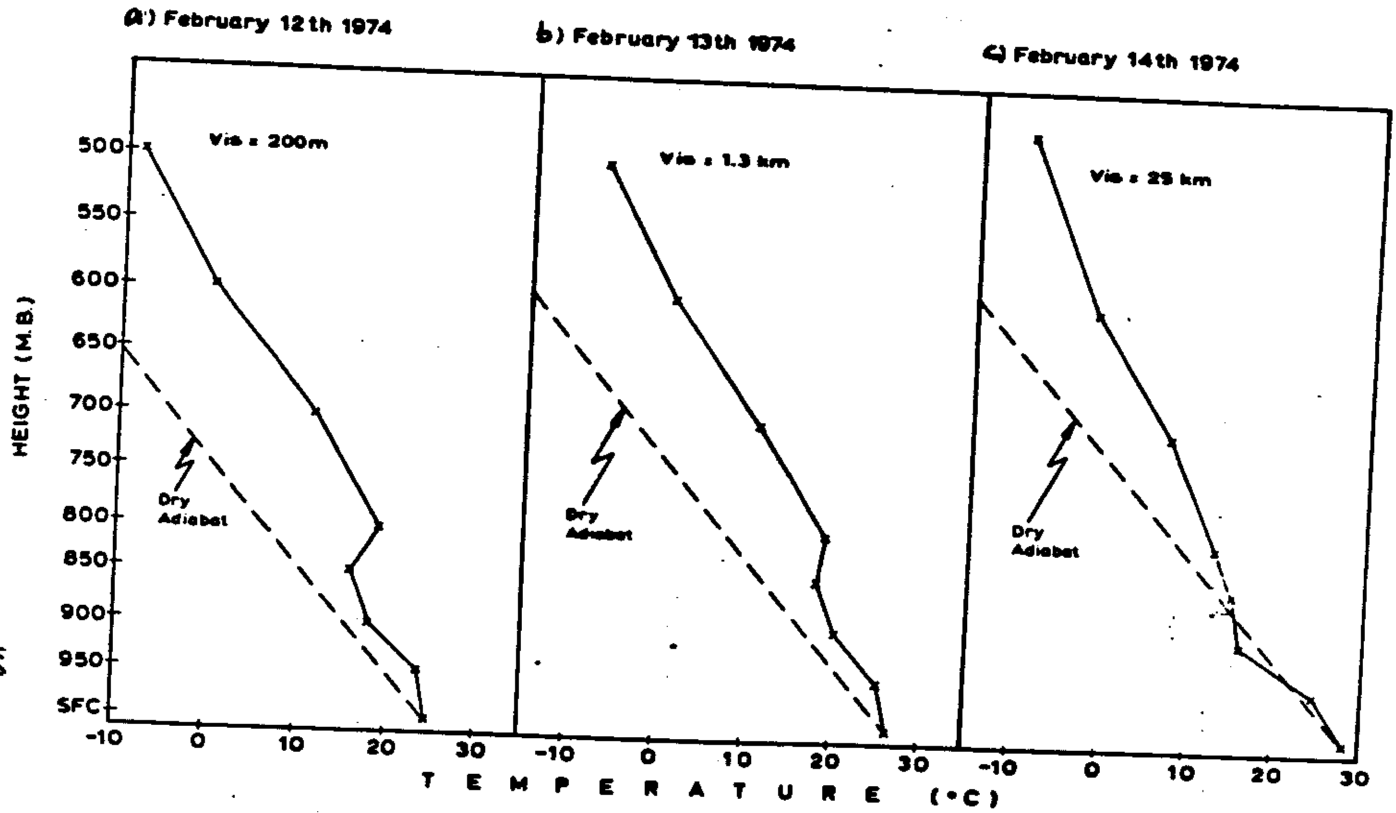
FIG. 11(b). As in Fig. 11(a), except for february, 1974, 1200GMT, Kano.



14

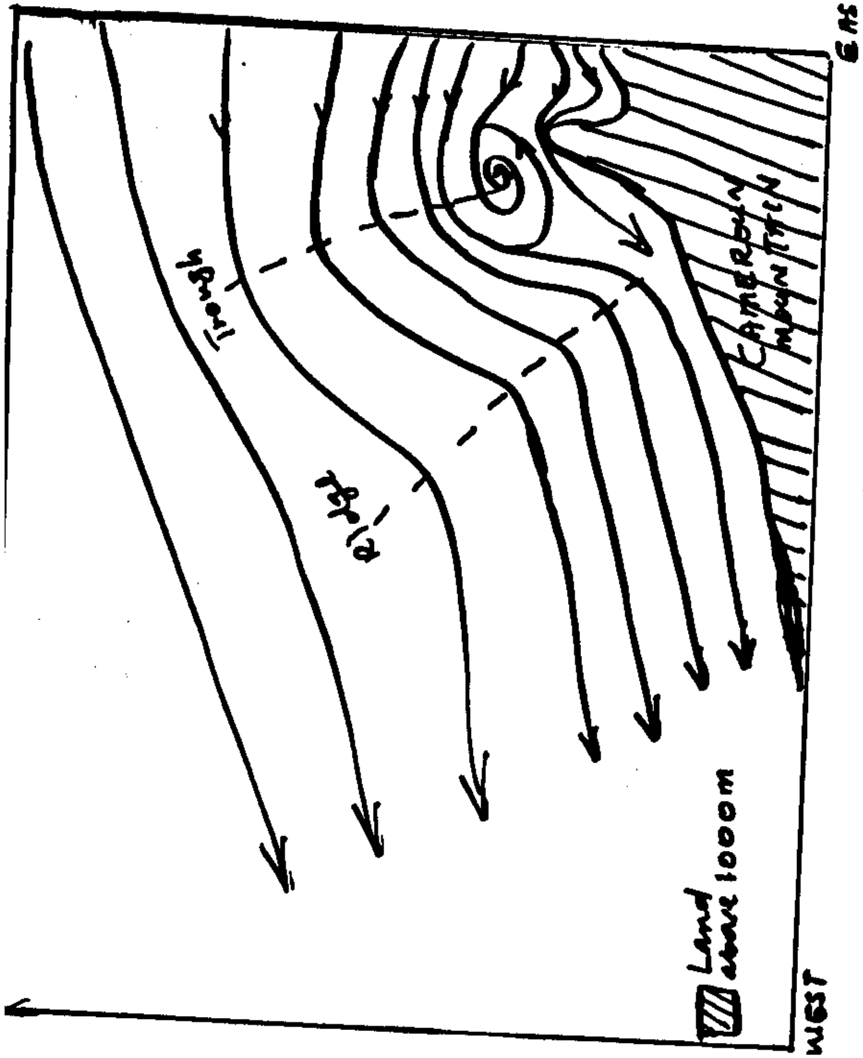


FIG. 12 An illustration of perturbed Easterly Waves into closed vortex on crossing the Cameroon and Adamawa Highlands (Not drawn to scale).

PLATE A

METEOSAT 1983 MONTH 1 DAY 30 TIME 1155 GMT (NORTH) CH. VIS 2
NOMINAL SCAN/RAW DATA SLOT 24 COPYRIGHT - ESA -

METEOSAT IMAGE CATALOGUE SUMMARY FOR YEAR 1983 DAY 30 - 30/01/83

SLOT	TIME	VIS	IR	WV	AAN
1	0000-0030		Y	Y	
2	0030-0100		Y	Y	
3	0100-0130		Y	Y	
4	0130-0200		Y	Y	
5	0200-0230		Y	Y	
6	0230-0300		Y	Y	
7	0300-0330		Y	Y	
8	0330-0400	Y	Y	Y	
9	0400-0430	Y	Y	Y	
10	0430-0500	Y	Y	Y	
11	0500-0530	Y	Y	Y	
12	0530-0600	Y	Y	Y	
13	0600-0630	Y	Y		
14	0630-0700	Y	Y	Y	
15	0700-0730	Y	Y		
16	0730-0800	Y	Y	Y	

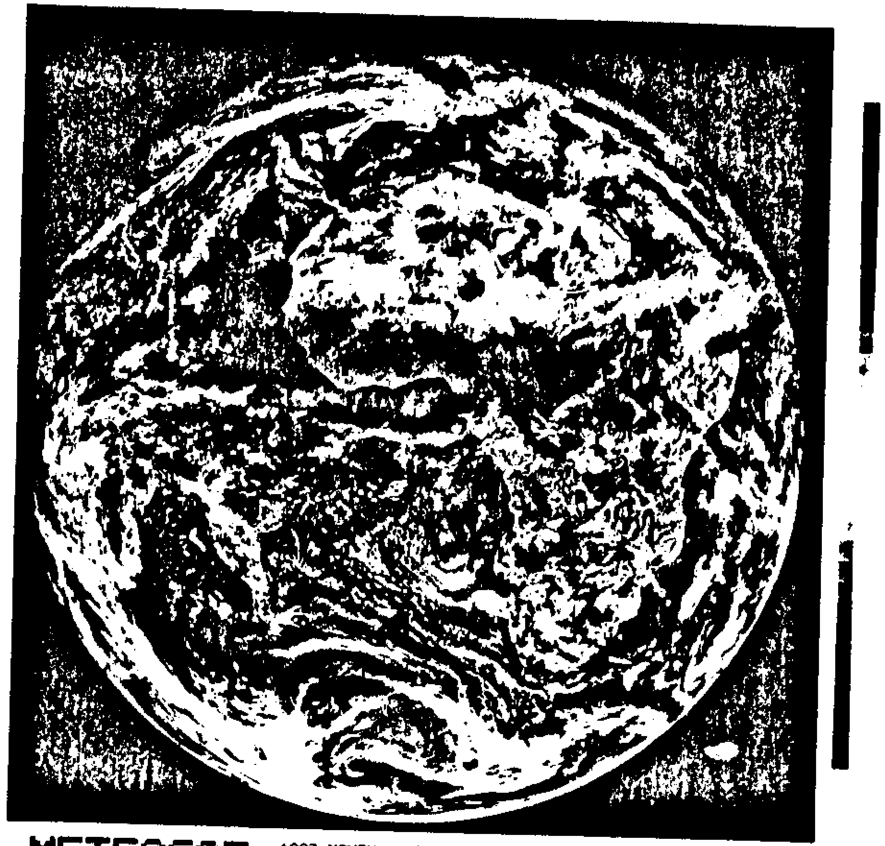
SLOT	TIME	VIS	IR	WV	AAN
17	0800-0830	Y	Y		
18	0830-0900	Y	Y	Y	
19	0900-0930	Y	Y		
20	0930-1000	Y	Y	Y	
21	1000-1030	Y	Y		
22	1030-1100	Y	Y	Y	
23	1100-1130	Y	Y		
24	1130-1200	Y N	Y N	Y N	
25	1200-1230	Y	Y		
26	1230-1300	Y	Y	Y	
27	1300-1330	Y	Y		
28	1330-1400	Y	Y	Y	
29	1400-1430	Y	Y		
30	1430-1500	Y N	Y N	Y N	
31	1500-1530	Y	Y		
32	1530-1600	Y	Y	Y	

SLOT	TIME	VIS	IR	WV	AAN
33	1600-1630				
34	1630-1700				
35	1700-1730				
36	1730-1800	Y	Y	Y	
37	1800-1830	Y	Y	Y	
38	1830-1900	Y	Y	Y	
39	1900-1930	Y	Y	Y	
40	1930-2000	Y	Y	Y	
41	2000-2030		Y	Y	
42	2030-2100		Y	Y	
43	2100-2130		Y	Y	
44	2130-2200		Y	Y	
45	2200-2230		Y	Y	
46	2230-2300		Y	Y	
47	2300-2330		Y	Y	
48	2330-2400		Y N	Y N	

DIGITAL DATA : X = CONDITIONED , Y = ONLY DEMULTIPLEXED - N = PHOTOGRAPHIC NEGATIVE,FULL DISK,20X20CM

METEOSAT 1983 MONTH 1 DAY 29 TIME 1155 GMT (NORTH) CH. IR 1
NOMINAL SCAN/RAW DATA SLOT 24 COPYRIGHT - ESA -

METEOSAT 1983 MONTH 1 DAY 29 TIME 1155 GMT (NORTH) CH. WV
NOMINAL SCAN/RAW DATA SLOT 24 COPYRIGHT - ESA -



METEOSAT 1983 MONTH 1 DAY 31 TIME 1155 GMT (NORTH) CH. VIS 2
NOMINAL SCAN/RAW DATA SLOT 24 COPYRIGHT - ESA -

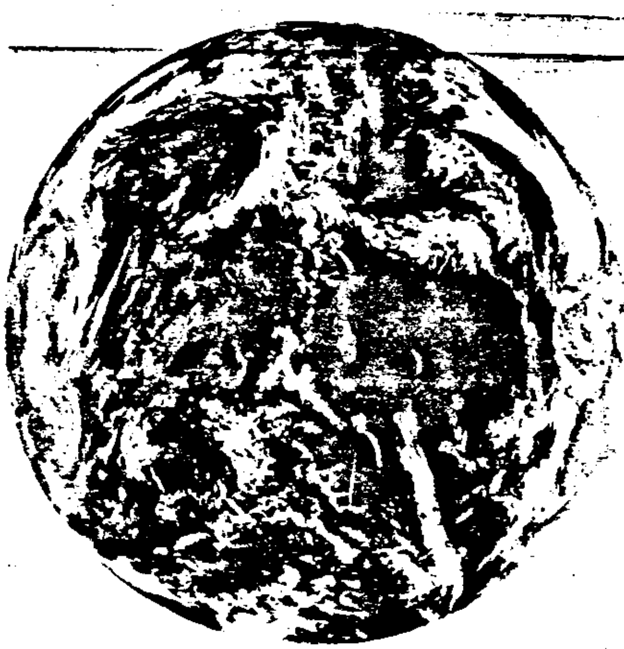
METEOSAT IMAGE CATALOGUE SUMMARY FOR YEAR 1983 DAY 31 - 31/01/83

SLOT	TIME	VIS	IR	WV	RAW
1	0000-0030		Y	Y	
2	0030-0100		Y	Y	
3	0100-0130		Y	Y	
4	0130-0200		Y	Y	
5	0200-0230		Y	Y	
6	0230-0300		Y	Y	
7	0300-0330		Y	Y	
8	0330-0400	Y	Y	Y	
9	0400-0430	Y	Y	Y	
10	0430-0500	Y	Y	Y	
11	0500-0530	Y	Y	Y	
12	0530-0600	Y	Y	Y	
13	0600-0630	Y	Y		
14	0630-0700	Y	Y	Y	
15	0700-0730	Y	Y		
16	0730-0800	Y	Y	Y	
17	0800-0830	Y	Y		
18	0830-0900	Y	Y	Y	
19	0900-0930	Y	Y		
20	0930-1000	Y	Y	Y	
21	1000-1030	Y	Y		
22	1030-1100	Y	Y	Y	
23	1100-1130	Y	Y		
24	1130-1200	Y N	Y N	Y N	
25	1200-1230	Y	Y		
26	1230-1300	Y N	Y N	Y N	
27	1300-1330	Y	Y		
28	1330-1400	Y	Y	Y	
29	1400-1430	Y	Y		
30	1430-1500	Y N	Y N	Y N	
31	1500-1530	Y N	Y N		
32	1530-1600	Y	Y	Y	
33	1600-1630	Y	Y		
34	1630-1700	Y	Y	Y	
35	1700-1730	Y	Y		
36	1730-1800	Y	Y	Y	
37	1800-1830	Y	Y	Y	
38	1830-1900	Y	Y	Y	
39	1900-1930	Y	Y	Y	
40	1930-2000	Y	Y	Y	
41	2030-2030		Y	Y	
42	2030-2100		Y	Y	
43	2100-2130		Y	Y	
44	2130-2200		Y	Y	
45	2200-2230		Y	Y	
46	2230-2300		Y	Y	
47	2300-2330		Y	Y	
48	2330-2400		Y N	Y N	

DIGITAL DATA : X = CONDITIONED , Y = ONLY DEMULTIPLEXED - N = PHOTOGRAPHIC NEGATIVE,FULL DISK,20X20CM

PLATE B

METEOSAT 1983 MONTH 1 DAY 30 TIME 1155 GMT (NORTH) CH. WV
NOMINAL SCAN/RAW DATA SLOT 24 COPYRIGHT - ESA -



METEOSAT 1983 MONTH 1 DAY 30 TIME 1155 GMT (NORTH) CH. IR 1
NOMINAL SCAN/RAW DATA ... SLOT 24 COPYRIGHT - ESA -

FIG 14 Trajectory of Squall-Line across Nigeria in May (Schematic)

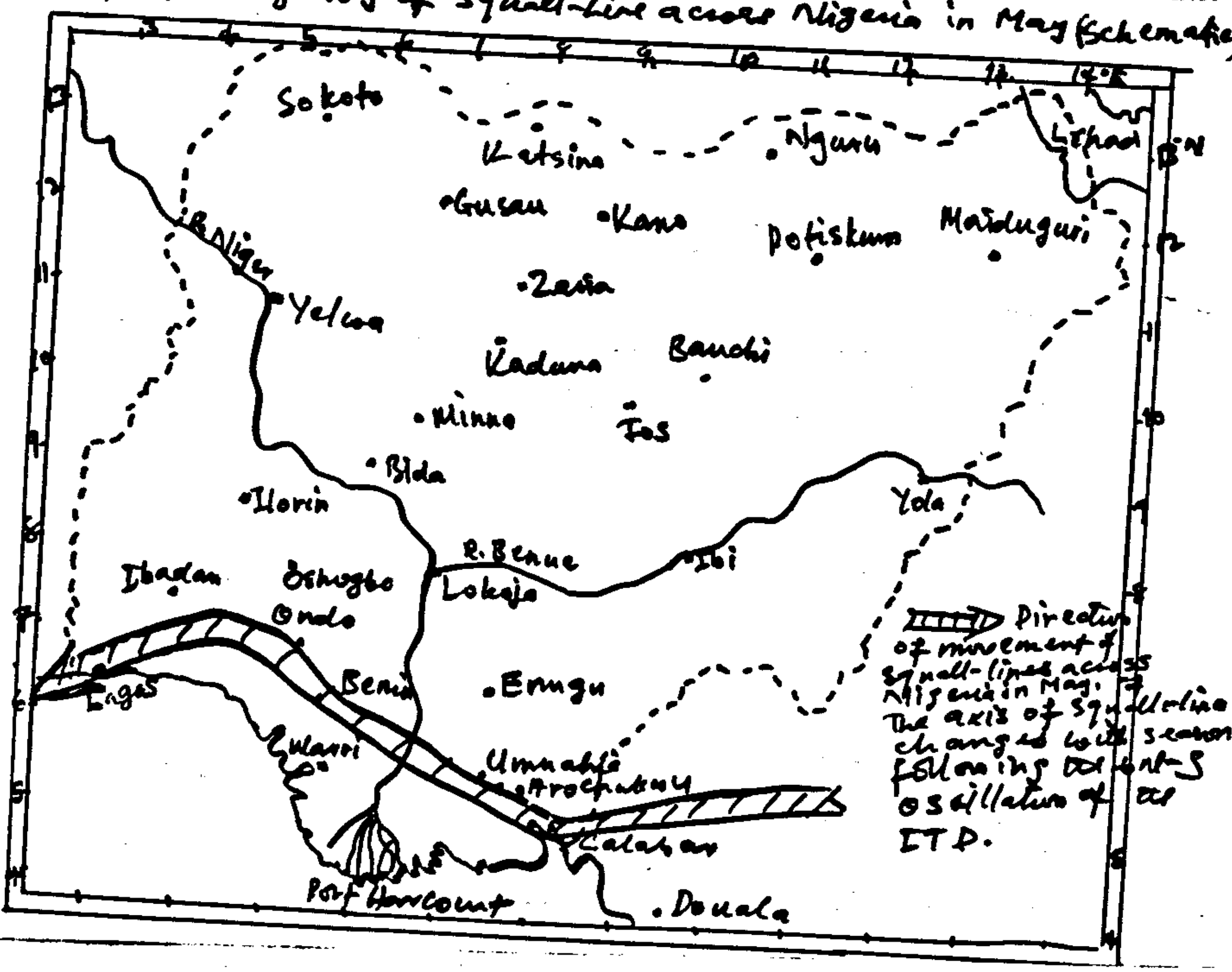
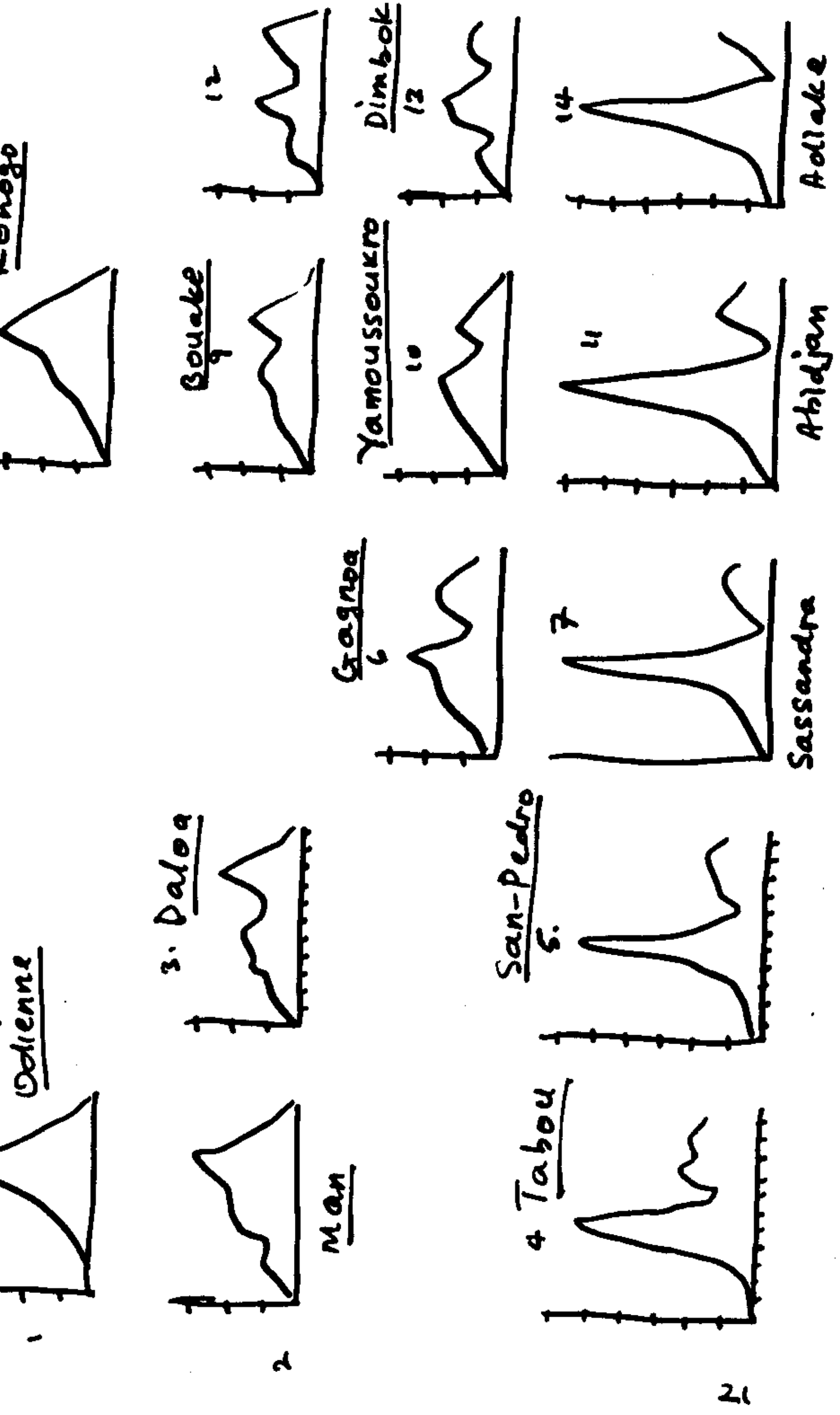


Fig 15a) Annual Rainfall Distribution Curves for Selected Stations in West Africa (Mainly from Ivory Coast).



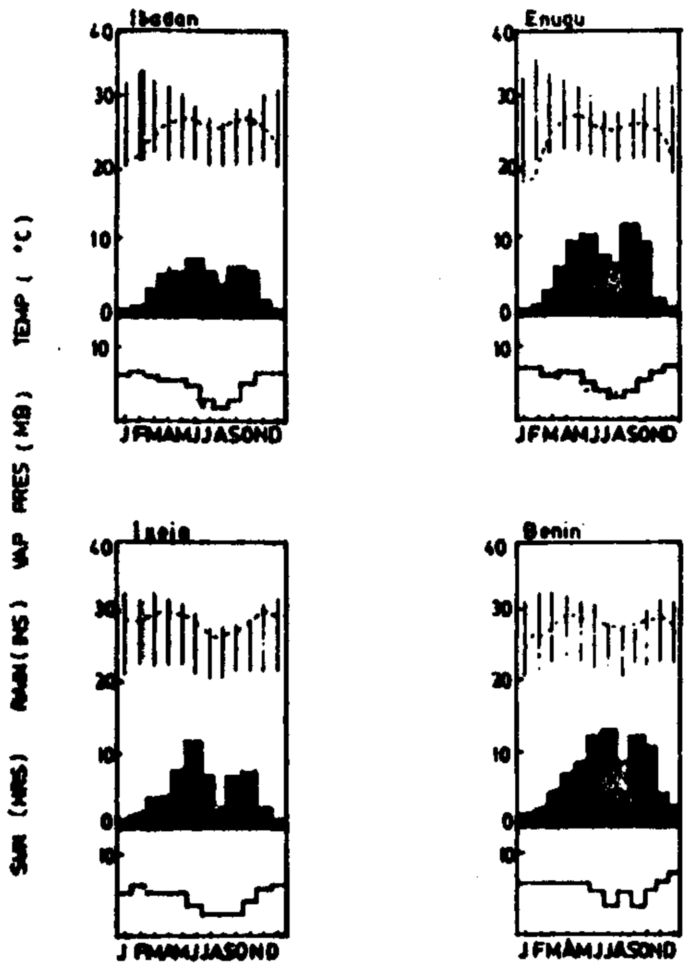


FIG. 15b As in fig. 16a, except for selected stations (middle diagram on rainfall only) in Nigeria (after Ngoka, 1987)

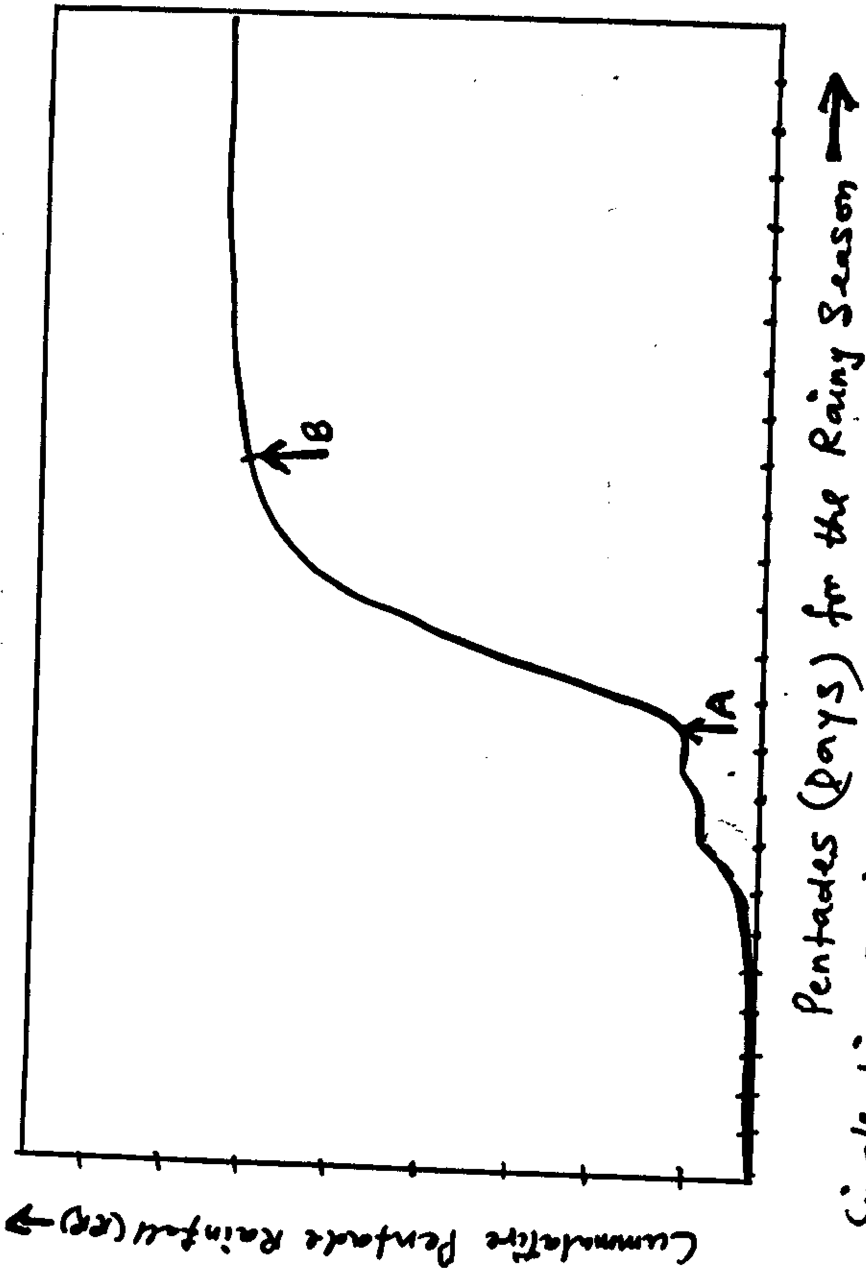


Fig. 16. Simple time series of cummulative rainfall (pentades) illustrating a statistical method for estimating onset and cessation of the Raing Season in Nigeria (after Obasi et al., 1977).

To be supplied.

Fig. 17a,b: Mean Onset and Cessation Dates for the Rainy Season in Nigeria.

Fig.18 Major Air Masses affecting East Africa during northern winter.

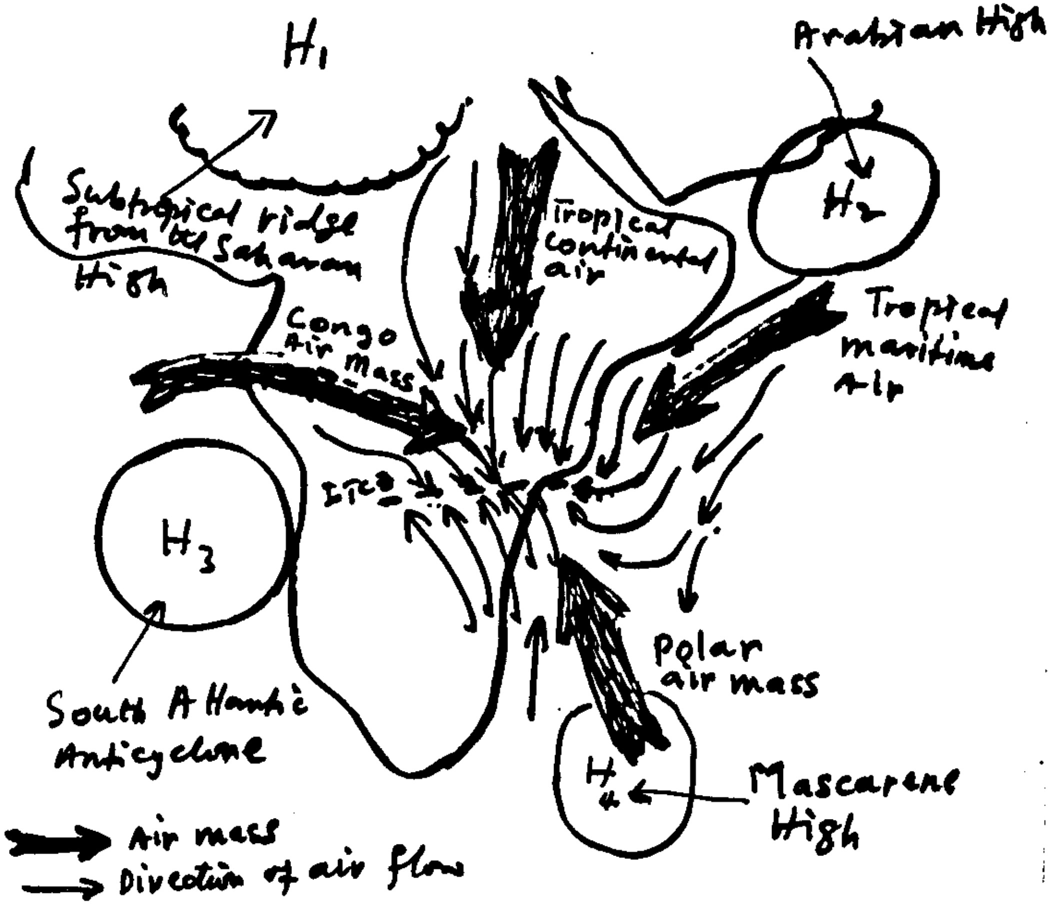


Fig. (19 b)

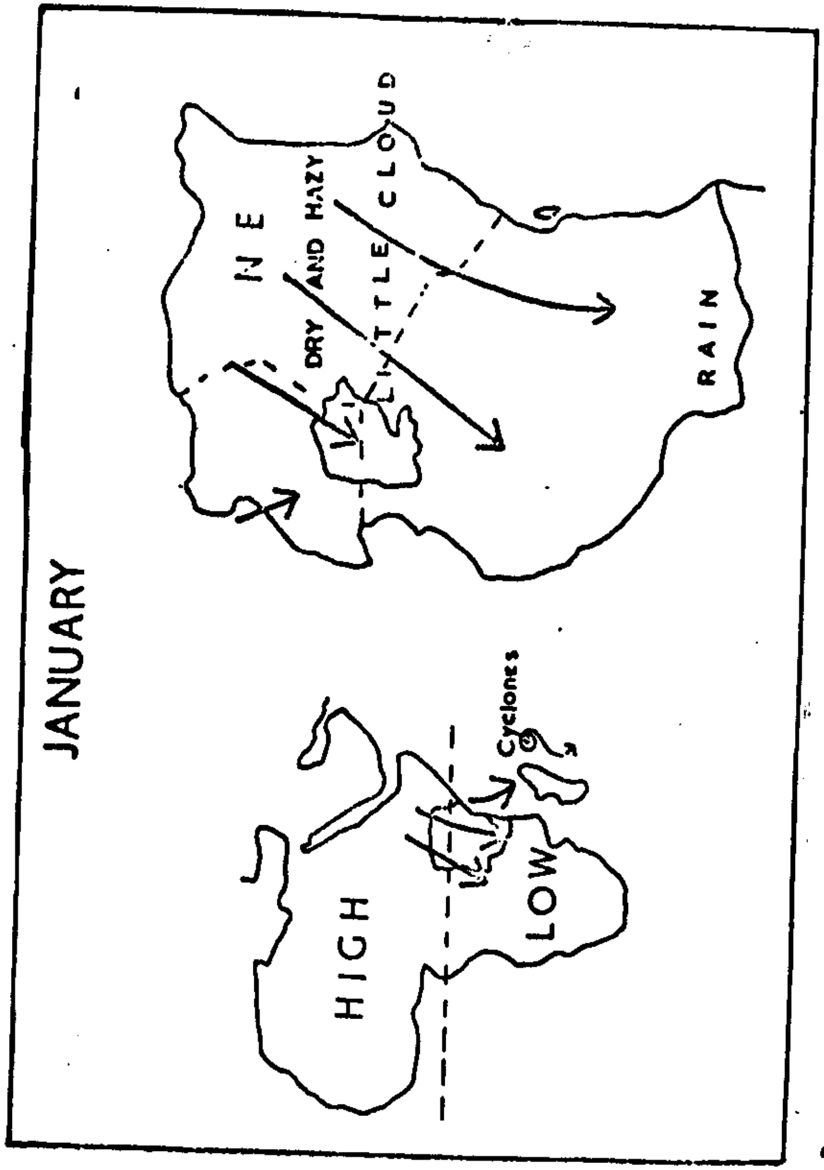


FIG. Prevailing winds (at or surf.) and associated weather during the two monsoon components in East Africa for January.

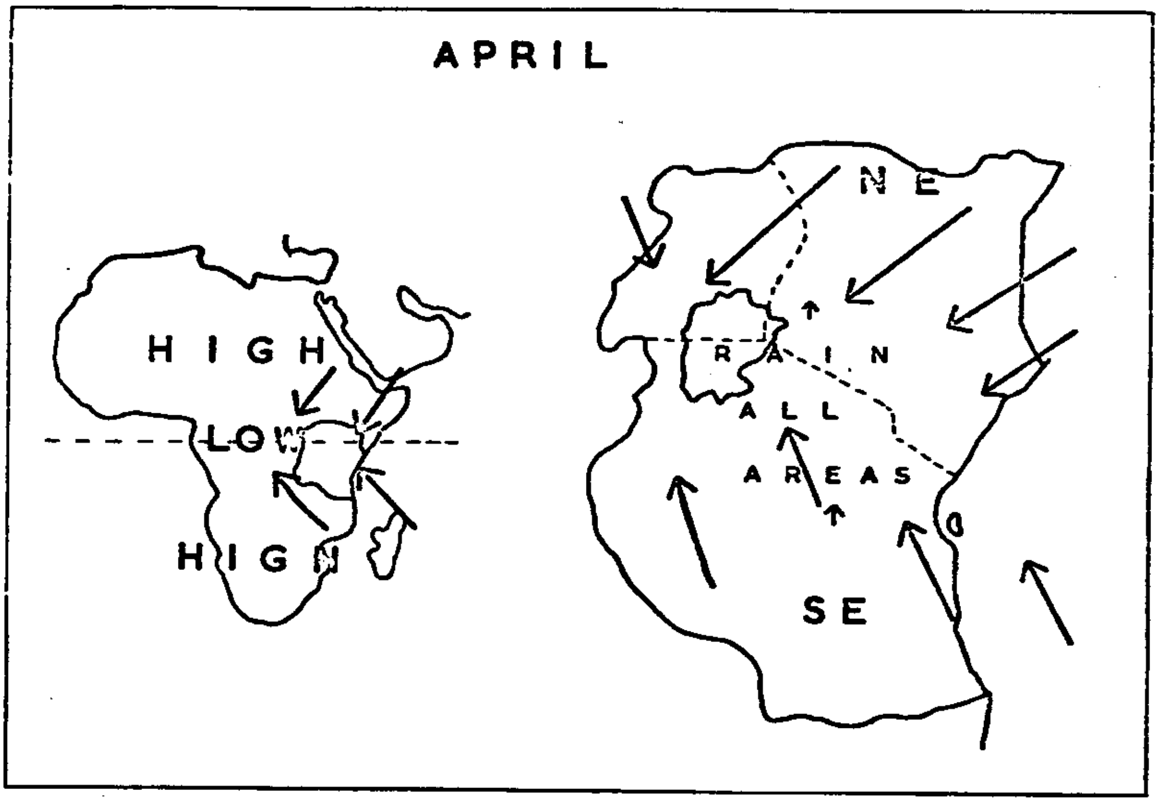


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Fig. 19(b) As in Fig. 19(a), except for April.

Fig. 19c. As in Fig. 19a, except for July

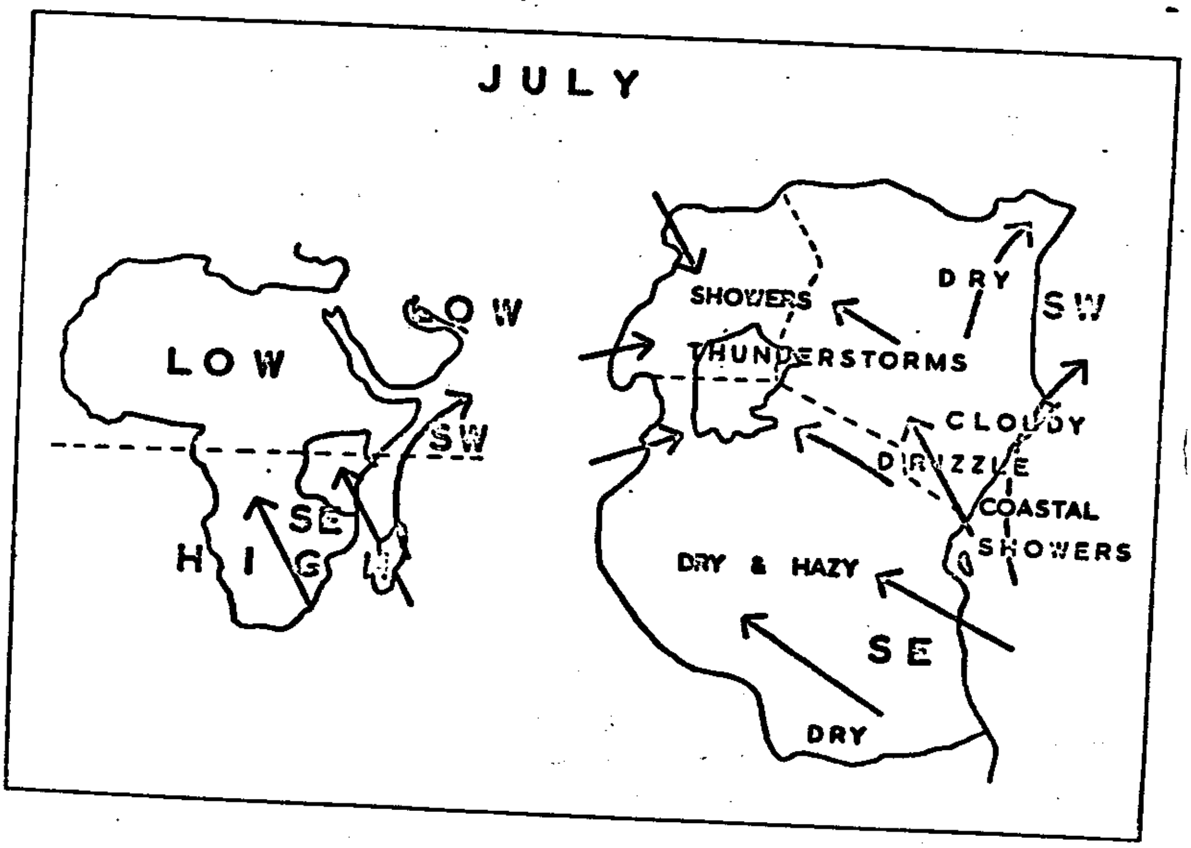

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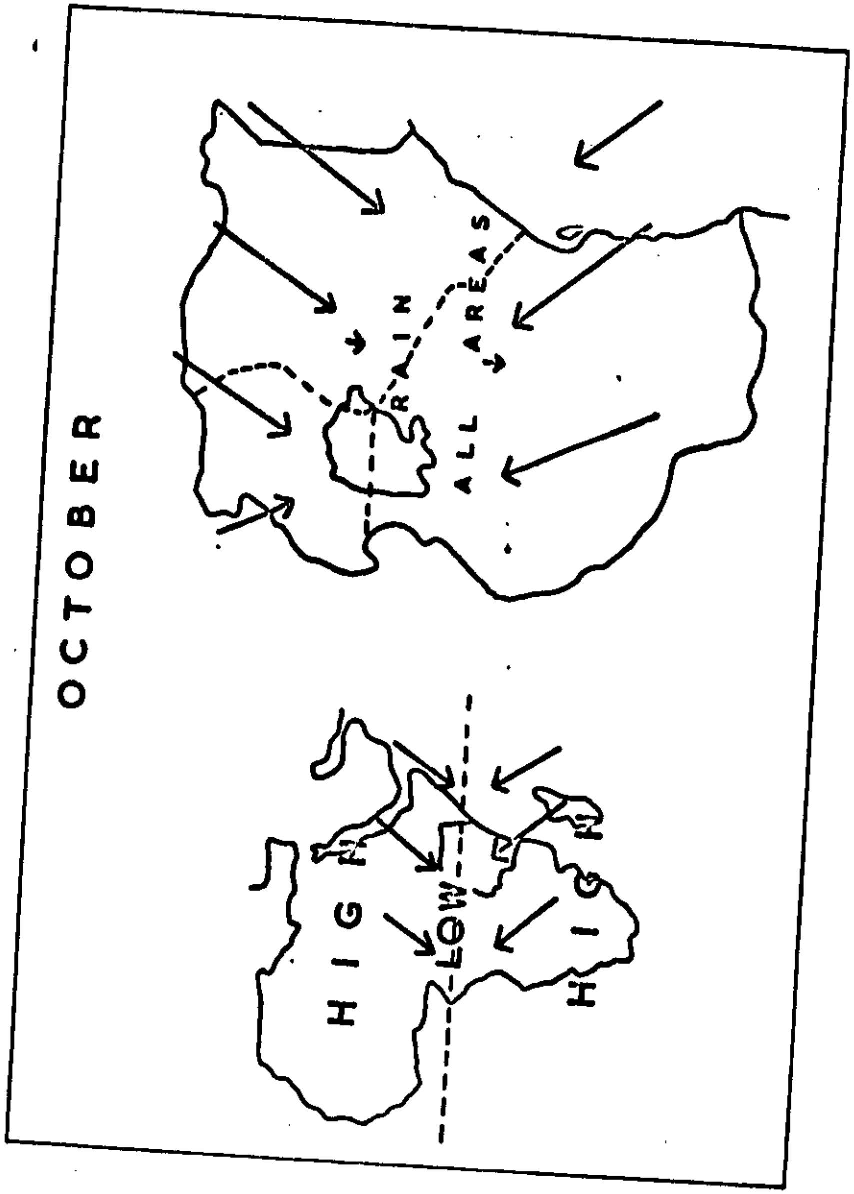
FIG. 19d. As in FIG. 19a, except for October.



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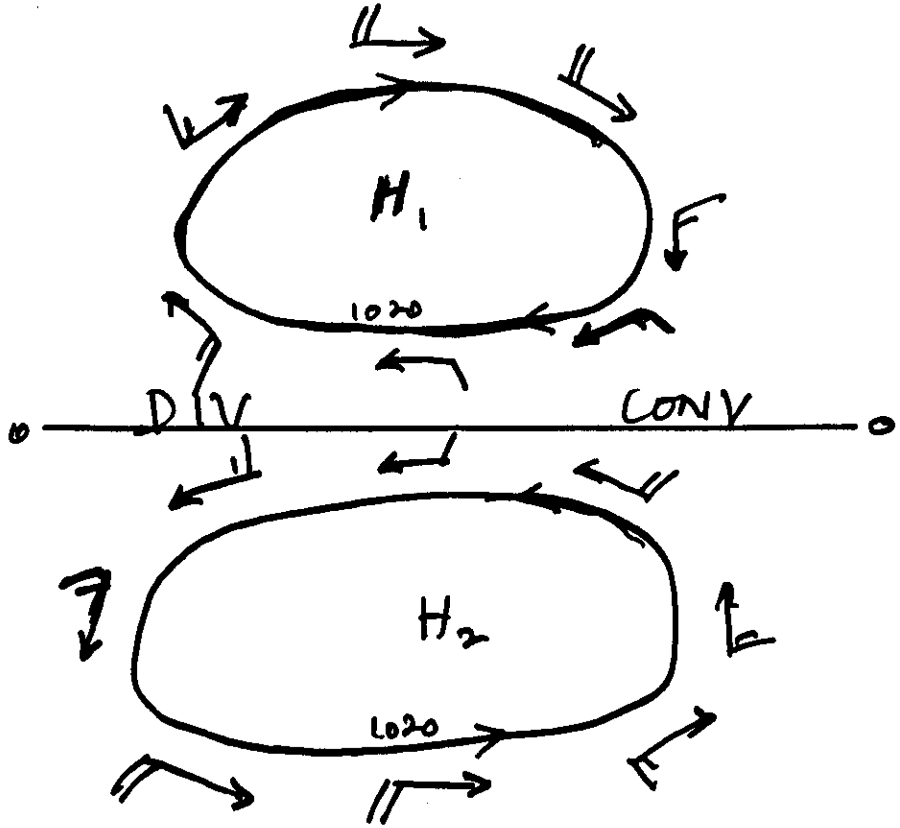

FIG 20a THE DUCT MODEL

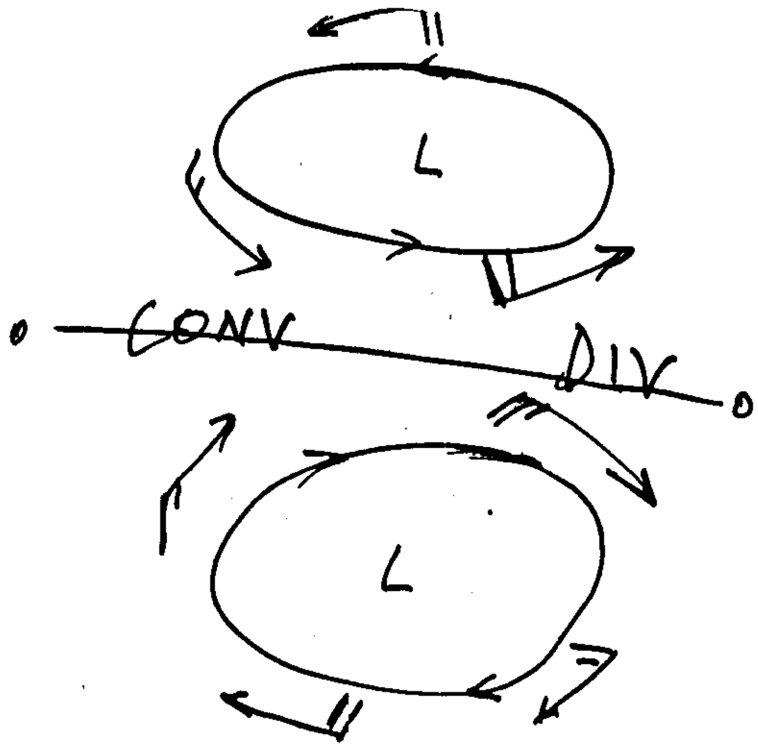

Fig 20b THE BRIDGE MODEL