1976

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Recommended Citation
Oppong, Jacob Emmanuel., "A suggested rainfall model of West Africa." (1976). *Electronic Theses and Dissertations*. 837.
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A SUGGESTED RAINFALL MODEL OF WEST AFRICA

by

Jacob Emmanuel Oppong

A Thesis
submitted to the Faculty of Graduate Studies
through the Department of
Geography in Partial Fulfillment of the
requirements for the Degree
of Master of Arts at
The University of Windsor

Windsor, Ontario, Canada
1976

ABSTRACT

A SUGGESTED RAINFALL MODEL OF WEST AFRICA

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The thesis proposes a three dimensional model based upon the horizontal and vertical components of the atmospheric circulation for the description and explanation of both the general patterns and the finer details of weather and climate of West Africa. The writer argues and demonstrates that the existence of upper level subsidence, particularly within the moist monsoon airmass, and its seasonal and spatial variations explain all the apparently "anomalous" features of weather in West Africa. The incorporation of this large-scale subsidence within the ITCZ model thus stands as the central theme of the thesis.

The second part attempts to validate the model by using it to account for recent developments in the climate of West Africa viz. the southward shift in the general circulation showing that such an event should generate drought in the Sahelian Zone and increased rainfall at the equatorward portions of West Africa. The method of measuring proportional change by the use of <u>index numbers</u> is employed to compare the relative change during the time of the shift in the general circulation with the normal (1931-60) climatic conditions, using Ghana's weather (rainfall) records for the case study. The average percentage change is then used to prepare maps by drawing isolines through stations with the same proportional changes.

Results obtained confirm all the theoretical postulations that are derivable from the model and which have actually been observed in West Africa, and suggest that the recent trends in weather and circulation of West Africa are related to the weakening of the mid-latitude upper-level easterlies and the subsequent southward shift in the general circulation.

DEDICATED TO:

My mother, Madame Abena Ampomaah.

ACKNOWLEDGEMENT

I am deeply grateful to the members of my Thesis committee for giving me the desired criticisms, comments and directions by which the final draft of this thesis has been prepared. In this connection, I specifically wish to mention Dr. John D. Jacobs, who as the Chairman of the Committee, was immediately and directly responsible for the supervision.

In making my maps and diagrams, I had to consult Mr. Ron Welsh, Head of the Cartographic section of the department, for "technical advice". I am very grateful to him. He showed incredible enthusiasm with his assistance and was regularly visiting my desk to make sure I was on the right path.

Ms. M. Patricia Morton, typed the manuscript, for which I am very grateful. Many friends of mine had to help with the corrections after the proof-reading, to all of them I am grateful.

I also wish to express, in all sincerity, my heartfelt thanks to Dr. Frank Innes, Chairman of the (Geography) Department for the moral support and encouragement he consistently gave me throughout the length of my studies, particularly during the preparation of this thesis. His concern over my social and academic welfare was evidently SINCERE, and I believe that without him the story might have been different.

My final thanks go to the officers of the Ghana Meteorological Services Department, Accra, Ghana, who with miraculous speed mailed my requests of the relevant climatological data on Ghana to me. Mr. Samuel Kweku Enchill, a second-year student of the Mensah Sarbah Hall, University of Ghana, who ensured that the data were mailed on time deserves a special praise. I am very grateful to him.

PREFACE

The present thesis is an attempt at organizing the essential features of the West African climate and to demonstrate the holistic unity that underlies the elements of the said climate. Far from being simple and conservative, the climate of West Africa has proved to be a climate of contradictions and seemingly irreconcilable complex tendencies, a realization that has served as the motive force for the preparation and execution of the present study. It is hoped that researchers and teachers will find the model a useful tool in the identification of areas for further studies and in the organization and presentation of climatological facts about West Africa.

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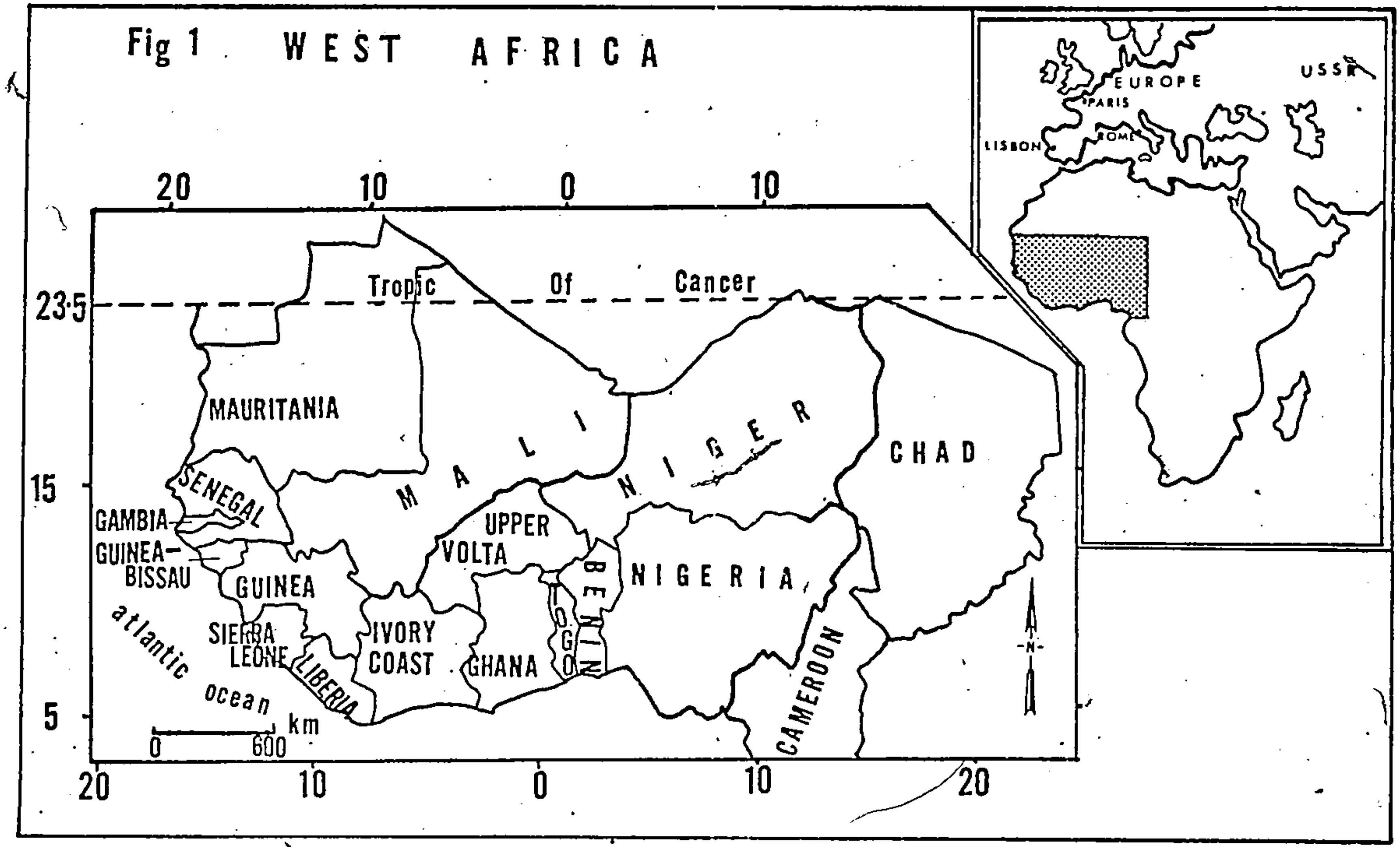
LIST OF ABBREVIATIONS

1.	ATEX	Atlantic Tropical Experiment (1969)
2.	BOMEX	Barbados Oceanographic and Meteorological Experiment (1969)
3.	DLS	Disturbance Lines
4.	GMSD	Ghana Meteorological Services Department
5.	ITCZ	Intertropical Convergence Zone
6.	ITD	Intertropical Discontinuity
7.	ITF	Intertropical Front
8.	MCZ	Maximum Cloud Zone
9.	WMO	World Meteorological Organization
10.	GARP	Global Atmospheric Research Project
11.	GATE	GARP Atlantic Tropical Experiment

FRONTISPIECE

Fig 1 WEST AFRICA



CHAPTER ONE

INTRODUCTION

The implication of climatic change on the socio-economic arrangements of the world both from historical evidence and present day experiences gives sufficient grounds for mankind to show concern over the ultimate state of world climate. Particularly in the developing countries, where there is generally greater intimacy between human activities and climate, persistent unfavorable trends have always been costly in terms of human plants and animal loss.

Even when unfavorable trends in climate have occured elsewhere, the chain effects on these areas have been most profound in view of the growing interrelationship amongst the countries of the world.[1] In these areas, therefore, the concept of climatic change, regardless of the areas directly affected, has always involved anxious questions for their governments and peoples. From the mid-1960's to the early 1970's, West Africa experienced drastic change in climate by way of drought along its northern margin, the Sahelian

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[1] This point has been well illustrated by the recent rainfall failures and low wheat yields in the USSR and their subsequent effects on domestic wheat prices in the United States (Janick, et. al., 1974) and on wheat supply cuts to the famine striken areas of the Sahel in Africa and India (Mesarovic, et. al., 1973).

Zone. It may be observed that whilst the Sahel was dessicating many areas along the southern coastal margins were experiencing significant gains in rainfall. Thus, Ghana, for example, experienced serious floods in 1968 (Hookey, 1970). (Appendix 1, fig 21)

The oddity of the situation perhaps is seen in the light of the explanations that have been offered for the drought by Bryson (1973). To Bryson, the drought had resulted from a southward shift of the main position of the sub-tropical high pressure belt and the intertropical discontinuity (ITD). According to his illustrations, if the mean position of the sub-tropical high moved southward by half a degree rainfall in the Sahelian Zone could decrease by 10-14 inches. Viewed in the larger perspective particularly with respect to development at the equatorial or southern margins, it is not very apparent how this theory of Bryson's could accomodate all of the observed variations in West Africa at the time of the drought.

Why should a shift in the mean position of the ITD over a contiguous region such as West Africa result in Aridity in one part of the region and increased rainfall in the other parts? Whilst the simultaneous occurences of the floods and drought in West Africa may be confusing it however has revealed one significant fact namely that the climate of West Africa and its underlying mechanisms are still far from being completely understood. In other words, the weather and climate of West Africa may be related to the general circulation characteristics of the region as universally held, (Griffiths, ed., 1972 , Cochemé and Franquin 1967 , H. Church 1957), but it is clear from these complexities that the exact nature of the relationships may not be so simple. Clearly a re-examination of the observed relationships is called for.

Aims and Objectives: It is this need for a complete understanding of the patterns of weather and climate of West Africa that has motivated our present research effort. It is an exercise at climatic modelling. To begin with, therefore, we attempt to synthesise all of the known facts about the general circulation that are immediately relevant to the climatology of West Africa into a three dimensional rainfall model that describes and explains the seasonal and spatial distribution patterns in West Africa in the entirety.

That done, an initial verification of the implications of the model is made using Ghana's rainfall records. The model, it will be realised is definitely a useful tool in research and teaching, since it readily points to other areas where further research may be conducted to enhance our knowledge about the region's climate. (See Chapter 5)

With the publication of Riehl's (1951) Tropical Meteorology and Flohn's (1960) discussion of the ITD and the meteorological equator, there has been an increased interest in tropical meteorology in general. The resulting proliferation of ideas on tropical meteorology has only tended to make more difficult the teaching of the region's climate in High School geography. It is hoped that the suggested model has fulfiled the need for organising these ideas into a simple and internally consistent model that explains the processes and mechanisms that control the region's climate.

In other words, the new knowledge about the region's climate has made understanding and teaching more difficult. In spite of all the new information becoming available on the climate of West Africa there has not yet been a clear and concise (and correct) presentation of this information in a form useful to the geographer, researcher, teacher and student. We are doing just that with this thesis.

Operational Hypothesis of Research: Two operational hypotheses underly the present work, viz,(1) that all of the significant features of the weather and climate of West Africa are a direct consequence of the general circulation of the atmosphere, particularly the effects of the activity within the airmasses that circulate within the region; and (2) that the airmasses that prevail over West

Africa are structurally arranged such that any significant shift in the general circulation over West Africa has diametrically opposite effects on the rainfall at the northern margins as against the southern margins. Thus, the simplest procedure for testing the validity of the hypothesis is through the examination of the spatial variations from the "normal" weather conditions over the whole territory during known periods of persistent southward or northward shifts in the general circulation.

Following the works of Lamb (1966, 1973) and Winstanley (1973 b) the observation that there has been a <u>southward</u> shift in the general circulation is noted. Matching this with our suggested model, it can be shown that such a southward shift should generate drought in the Sahelian Zone, as conceived by Bryson (1973), but should induce increased rainfall in the southern margin (hypothesis no. 2). This is demonstrated by comparing the climatic period prior to the shift with that during and after the shift.

Following the World Meteorological Organization (W.M.O., 1960, 1967) the 1931-60 period is accepted in our analysis as "normal" and is taken to represent the period prior to the shift. It is also to be noted that as early as 1963 drought had already affected many parts of the Sahelian Zone (Bryson, 1973) lasting up until the early 1970's.

Since the drought is presumed to be a function of the southward shift of the circulation it has been necessary to take the whole 14 year period, 1961-74. to represent the sub-normal period during which the said event (the shift in circulation) occurred. The two time-periods selected for our analysis thus make the year 1960 to seem to mark the critical point in time when the net southward shift in the circulation, began to have observable and specific climatological significance.

The verification of our model has therefore involved the comparison of the 1931-60 mean weather conditions with the 1961-74 mean conditions as explained above.

In the West African situation rainfall is the only climatic parameter which shows conspicuous and readily demonstrable seasonal and spatial variations (Griffiths, 1972) so that climatic variation is virtually synonymous with or, better still, is more expressible in terms of rainfall variation. Our climatic model has therefore been based primarily on rainfall - hence the title, "rainfall model".

Method of Analysis: The method of measuring and depicting proportional change by the use of index numbers has been found to be the most appropriate method of analysis for the defined objective. These index numbers express each figure as a percentage of the base year so that comparisons of growth and decline, or increases and deficits, can easily be made, (Hammond and McCullagh, 1974). The great advantage of this method is that the index numbers are independent of the initial magnitude of the data and of the units in which they are measured.

Using the 1931-60 average rainfall values as our base values, the mean monthly and annual rainfall totals for the 1961-74 period (inclusive) were individually expressed as percentages of their corresponding 1931-60 average values. The relative change in rainfall in the 1961-74 period with respect to the normal conditions is thus given by the value of the average index number of each station for the month or year in question.

We are basically interested in the spatial aspects of these changes, consequently the idea of using <u>isolines</u> to depict the spatial dimensions of the change was also introduced into our analysis. Our average indeces were thus used to prepare percentage change maps (Fig. 22 - 24). Isolines on these maps show areas of equal or proportional rates of change from their "normal" mean rainfall values. Areas crossed by isolines with index of less than 100 may thus be interpreted as having received less rainfall than normal. Isolines with values exceeding 100 define areas which received more rainfall than normal, whereas isolines with index of 100 connect areas which experienced no change in rainfall.

By this extension in our analysis, therefore, the spatial dimensions of the rainfall variation thus become apparent. This later method of analysis is similar to that used by Sabbagh and Bryson (1962, figures 2 and 3) in their study of the precipitation climatology of Canada. The first aspect of analysis too is similar to that used by Bunting (1976) in his study of the trends in the Sahelian mean annual rainfall. However, since he (Bunting) was primarily interested in tracing trends and in detecting periodicties from the succession of rainfall, he worked from the reverse direction to ours and instead computed zonal averages of the mean annual rainfall for each of the number of years of the period he studied. These yearly zonal averages of the mean annual rainfall were then plotted and analysed with a regression model for their trends. He did not find significant long-term negative trends, which led him to doubt the hypothesis that the weather and circulation systems in the lower latitudes are related to that of the middle and high latitudes.

It may however be noted that the shift of the circulation stemming from the weakening of the mid-latitude upper level easterlies had disproportional spatial repercussions on the climate of West Africa (see chapter 5 for instance). Hence areas of slight magnitude of change would reduce the magnitude of the overall zonal average and thereby diminish the level of significance in the negative trends of the mean annual rainfall as represented by the zonal averages. Besides, rainfall during the dry period is not directly related to the ITD (Illesanmi, 1972), therefore any existing relationship between the weather systems of the tropics and the mid-latitude regions should be reflected more in the average rainfall during the rainy season. This is particularly significant as a southward shift would increase the significance of the "dry season". Finally, the possibility of a time lag existing between the shift (of the circulation) and its repercussion in the lower latitudes does not seem to favor a search for negative trends in a direct cause-effect manner, so that the search of significant trends should have been studied with respect to the period during which the effects of the shift had "materialised". A far too long a period would only reduce the level of significance in the negative trends, viewed in this context.

Be that as it may, it is seen that the rationale behind his approach up till the point where averages are computed is definitely the same as ours. (His modification was introduced to accomodate his different point of emphasis). Indeed it is that as recommended by the W.M.O. (1966 a).

CHAPTER TWO

THE BACKGROUND (LITERATURE REVIEW)

The climate of West Africa has generally been portrayed as simple in its spatial and seasonal distribution patterns. Temperature which is high throughout the year is a rather conservative element[1] here whilst wind speed is generally low compared with the temperate regions. Like the rest of Africa, the climatic feature of most significance is rainfall (Griffiths, 1972). In this area, therefore, the availability of an effective rainfall model is a necessary tool in the analysis and study of the region's climatology.

The ITCZ Model(s):

The Intertropical convergence Zone (ITCZ) model, like its counterpart the " ITD rainfall model" (Illesanmi, 1972) agree with this point of view. These models see in a very broad manner the existence of only two climatic seasons[2], the 'dry' and 'wet' seasons.

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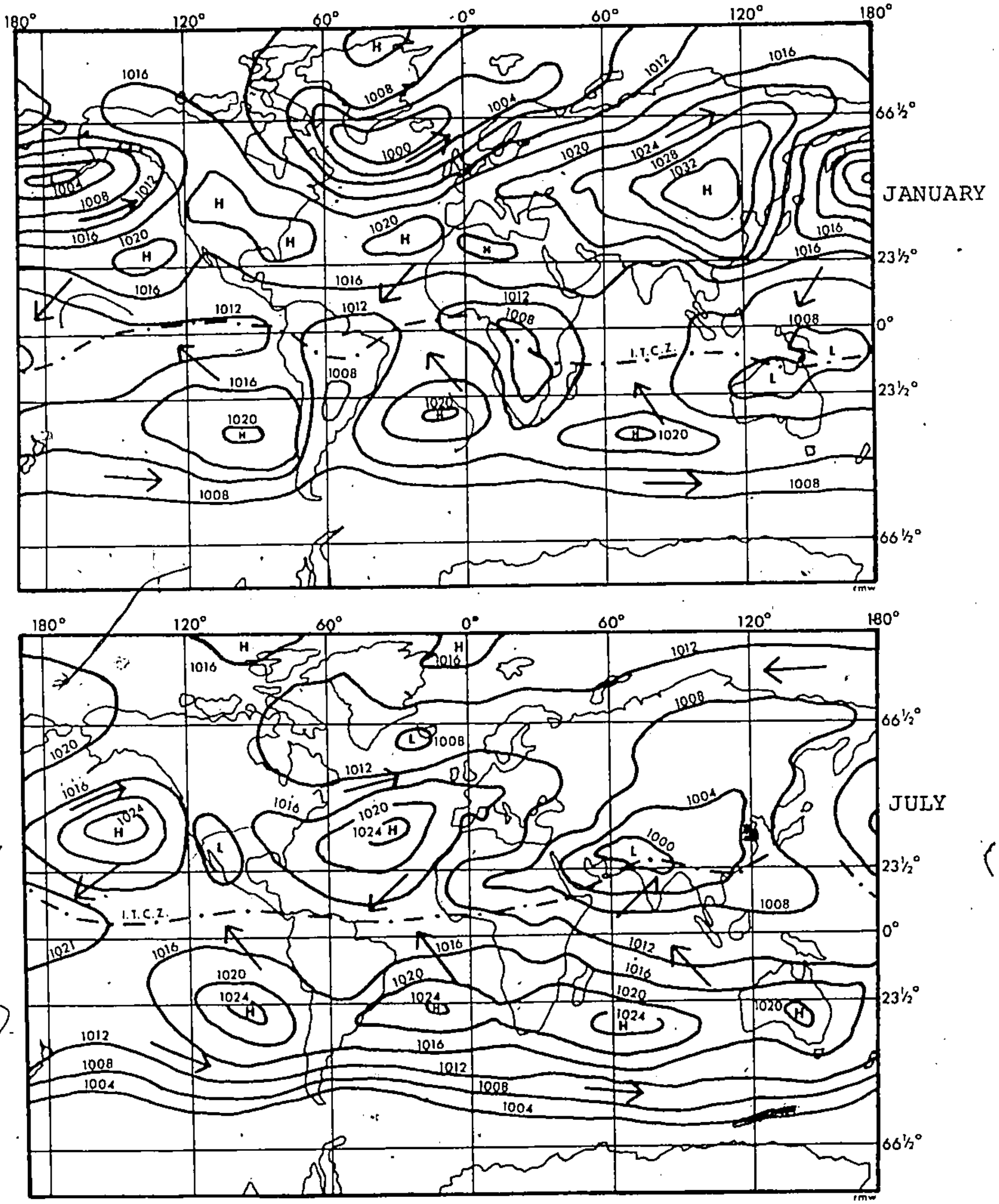
[1] The designation "winter" as opposed to "summer is therefore not strictly applicable here. Where these terms are used in the text they should be considered as collective terms referring to the months of December-February and June-August respectively.

[2] On the basis of the relative humidity and temperature the dry season could be further subdivided into the "Hot season" (March-April) and the "Harmattan season" (November-February), Ayoade (1975).

Fig. 2 PRESSURE AND WINDS



After McIntosh and Thom (1973)

which they associate with the seasonal alternation of dry and moist airmasses over the region. (Fig. 2)

The dry airmass is a continental tropical (CT) airmass which originates in the heart of the Saharan desert. Being an extension of the northern hemisphere trade winds, its prevailing direction is northeasterly. (Fig. 2). Since its route is wholly over land which is desert or semidesert it tends to be dry and dusty. Locally, it is referred to as the "Harmattan".

From the south comes the moist maritime tropical (MT) airmass across the south Atlantic Ocean. Being tropical, it is also hot though its long route over water results in some cooling (one to two degrees) as well as a gain in water vapour content. Beginning as a southeast trade wind it tends to be deflected to the right on crossing the equator reaching West Africa as the southwest monsoon.

Walker (1957) identifies a third airmass which he designates as the easterly "Equatorial Airmass". Apparently, he was making allusion to the Disturbance Lines of West Africa which traverses the area in a generally easterly direction. Discussion of the Disturbance lines by Eldridge (1957) shows that the disturbance lines of West Africa can no where be equated with an airmass, which means that easterly equatorial airmass may not exist in reality. According to Ayoade (1975) the disturbance lines are formed by convection due to local heating (op cit, p. 17). For all intents and purposes, however, it does not appear the DLs have any effect on the general rainfall distribution pattern. According to Cocheme and Franquin (1967) it serves as a 'trigger mechanism' which merely disturbs the rain-bearing airmass to result in heavy rain storms. In effect the DLs merely influence the intensity of rainfall as a result of its passage through the monsoon airmass and has no effect on the total amount of rain an area receives. Besides, since they move parallel to the equator with decreasing frequency of occurence towards the north (Eldridge. 1957), their presence does not distort the general north-south gradation in the distribution patterns of the mean annual rainfall. Consequently the various ITCZ models have not explicitly incorporated the DLs within their frame of reference.

It will be observed that the ITCZ model has two significant merits. To begin with it is able to explain the general spatial distribution patterns of the rainfall in West Africa, attributing the south-north gradation in the mean annual rainfall to the decrease in the amount of precipitable water as the southerly airflow advances northwards. It is also able to explain the seasonality of the rains by reference to the alternations in the monsoon and harmattan winds across the region.

Failures of the ITCZ model:

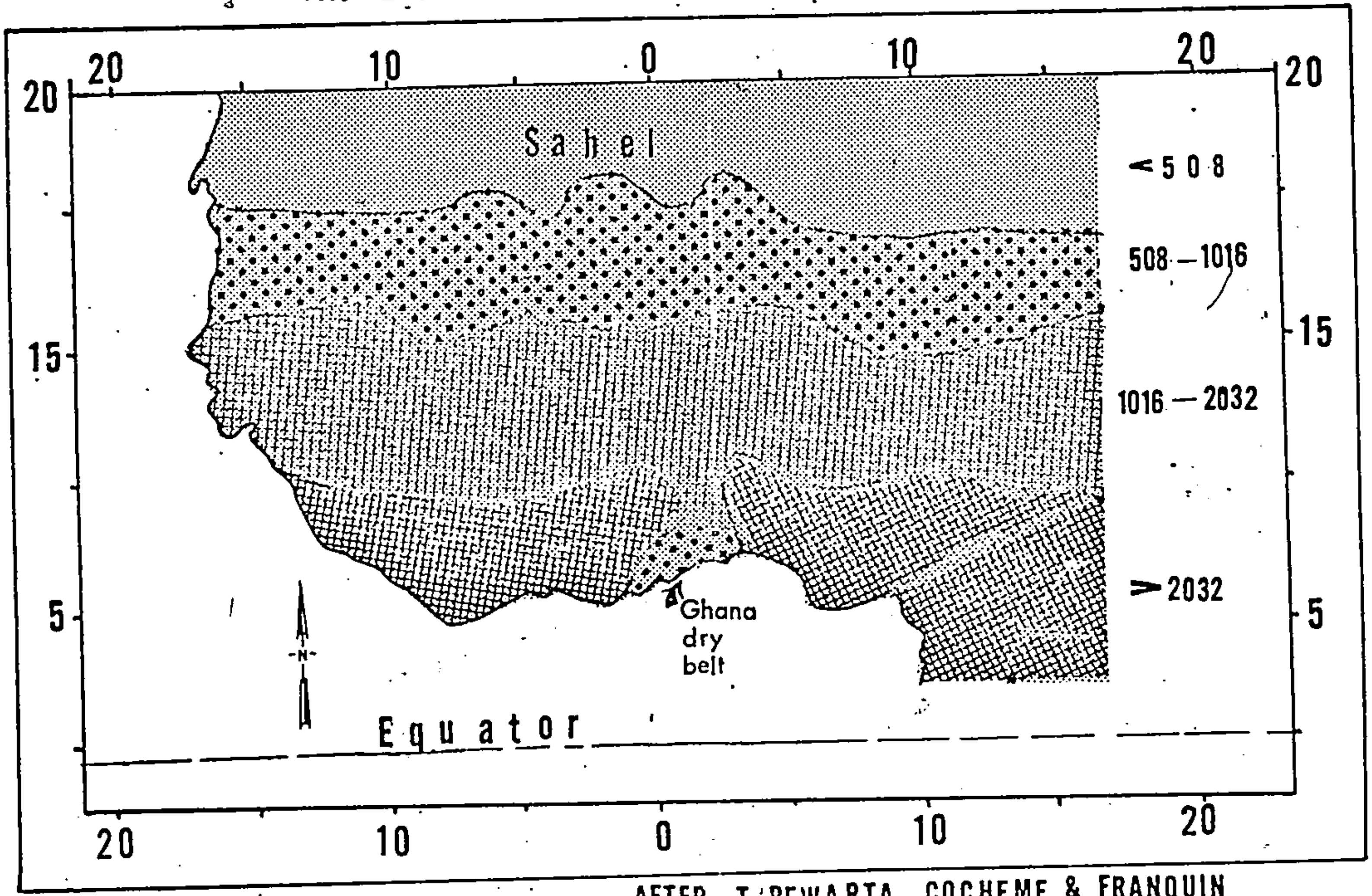
Despite these successes in accounting for the seasonality as well as the general distribution patterns of rainfall in West Africa the ITCZ model presents some serious difficulties. The monsoon and the harmattan, as we have seen, approach the tropics from opposite sides of the equator flowing towards each other. As a result of the maxim from the equation of continuity, namely, "horizontal convergence should imply vertical stretching" it had been thought that the meeting of the two airmasses would result in vertical ascending motion of the air which would cool adiabatically with height to produce rain. Consequently, the belt into which the two airmasses flow has been referred to as a convergence zone, hence the name (ITCZ). The ITCZ was thus conceived as a region of ascending air and maximum precipitation (Walker, 1957).

Contrary to expectation, however, it is realized that the region of maximum convergence (Barry and Chorlev, 1969), maximum cloud zone (MCZ) (Sadler, 1975) and maximum precipitation (Illesanmi, 1971) do not even occur within the convergence zone but, rather, many miles to the south of it. Illesanmi, for example, put his region of maximum precipitation at 9° south of the surface position of the meeting place of the two airmasses. In effect, the ITCZ model is unable to explain why the region of maximum rainfall should occur so many miles outside the ITCZ, which is supposed to be a region of maximum convergence and, hence, precipitation.

Another difficulty it encounters is how to explain the presence of a dry equatorial climate at the south east coast of Ghana through southern Togo to the Republic of Benin, formerly, Dahomey, (see Fig. 3). Considerable difficulty has been encountered in the search for a valid explanation to the existence of this climatic region (Walker, 1957 : Trewartha, 1968) without success. However in the absence of any vying or alternative explanatory model it was merely branded as "anomalous" situation and allowed to stay as if it were above rational explanation.

However, the most difficult problem was how it was to explain why there should be a "check" or break in rainfall in July and August at a time when there is maximum solar energy for convective activity and an abundant supply of moisture in the presence of the monsoon airmass.

Fig 3 GENERALISED RAINFALL DISTRIBUTION PATTERN OF WEST AFRICA (Mean Annual, in mm.)



AFTER TREWARTA, COCHEME & FRANQUIN

This was attributed to the displacement of a "rainfall belt" northward (Iliesanmi, 1971). Yet the more important factor of explaining why there should be a rainfall belt, if any, was surprisingly glossed over. Indeed, the ITCZ model does not explicitly nor even by implication suggest that a rainfall belt should exist within the rain bearing airmass, which in effect means that the mid-summer dry weather stands unexplained by the ITCZ model.

Despite these grave difficiencies, the ITCZ model has been allowed to stand unchallenged. We have already suggested that this was probably because there was no alternative model to replace it. Besides, the model was useful in, at least, providing some explanation for the broad seasonal and spatial distribution patterns and could thus be used even if as a temporary tool for explaining and describing the West African weather.

With the rising demands of scientific research and teaching of tropical climatology and in the face of abundant information about the weather and circulation features of the region, it is felt that the ITCZ model, as it stands, ought to be replaced (if not improved upon) since it is evidently outmoded.

The Period after 1960

The various aspects of the ITCZ model have been intensively studied since 1960 and the wealth of information now available should be sufficient for the construction of a new rainfall model for West Africa. We shall take these subject by subject and analyse the current state of knowledge as is now available in the literature.

The ITCZ as a Heterogeneous Climatological Entity

(J. C. Sadler, 1975)

That the term ITCZ is evidently one of the most profusely used terms in the literature need no further emphasis. As Sadler points out, the term has been used and misused to represent a variety of parameters so that it is now virtuallv ambiguous. Generally speakinq, the term is used either to represent some features of the wind field, or to represent a feature of cloudiness and weather. R. H. Simpson (1967). for example, defined the term as "the fluence asymptote associated with the equatorial trough without regard to cloudiness". It has also been defined by reference to wind observations only (Stechnovsky and Krouzkova, 1970).

Using the August mean position of the ITCZ as defined bv these and other definitions Sadler (1975) easily demonstrated that "none of these definitions are synonymous" (Fig. 4) bv which he implied that they do not refer to the same phenonenon. In the light of this

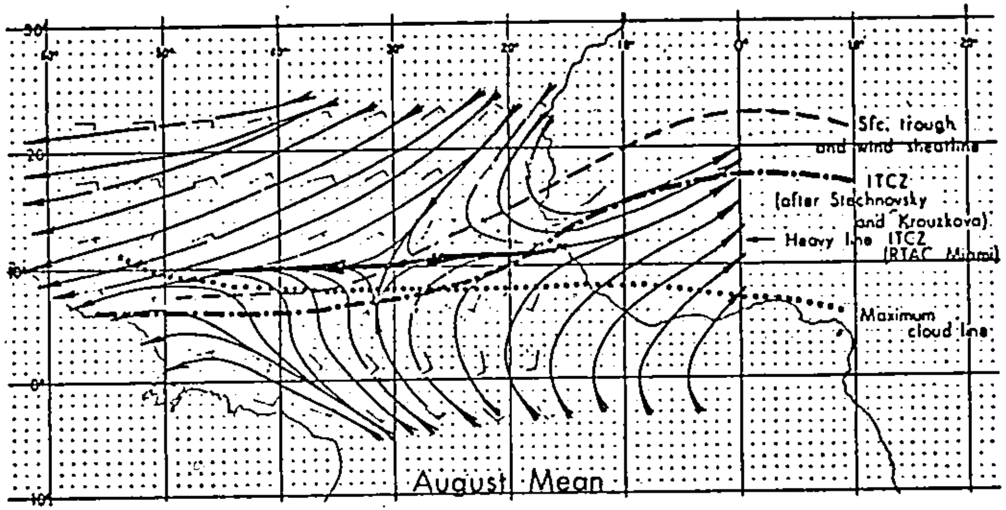


FIG 4 Illustrating four definitions of the ITCZ

Arrows indicate surface circulation in summer. Note the **EASTERLIES** west of 30W below the trough line

From J C Sadler (1975)

semantic confusion over the term (ITCZ) which has increased the uncertainty as to what it actually represents, he (Sadler) decided to avoid using it altogether. In its place he chose to use the term trough, defined as "the line or region of lowest atmospheric pressure". This region also coincides with the line of maximum cyclonic curvature of the wind field", he explained. Based upon wind circulation he suggested that the trough may be further stratified into (a) a region of generally westerly circulation to be referred to as Monsoon Trough, and (b) an area of predominantly easterly circulation known for the lack of a better term at this time as the Zonal Trough in the easterlies.

The monsoon trough then refers to both the pressure field and the wind field since it is a region of lowest pressure as well as an area of maximum cyclonic curvature of the wind field. In August (summer) the mean position of the monsoon trough extends south westwards from Africa to a wind col point just west of 30°W; westwards of this point the trough is within an easterly flow, hence the term "Zonal flow in the easterlies". (Fig. 4). It is therefore evident from the work of Sadler that the use of the term ITCZ is not strictly correct since the implication of the existence of a climatologically homogeneous zone within which a westerly wind component predominates <u>throughout</u> the tropics, (inter-tropical), is unjustifiable. This point is quite significant. What it means is that the southeast trade winds on crossing the equator are "deflected to the right" only in the areas east of the 30°W meridian. To the west of this meridian, towards the Americas, no such deflection appears to take place and the winds maintain their easterly component. This is contrary to classical models of the general circulation. (We shall not attempt to explain this finding for our present purposes since it is outside our defined objective).

The trough terminology is thus delineated into the region of westerly component flow east of 30°W and a region of predominantly easterly component west of 30°W. As Sadler (1975) explains these two segments of the trough possess significant physical difference in the relationship between the positions of the trough and the cloudiness (and hence, rainfall). Using evidence from satellite pictures he showed that the maximum cloud zone is, within the westerly flow, <u>south</u> of the monsoon trough line. No such relationship has yet been determined for the zonal trough in the easterlies.

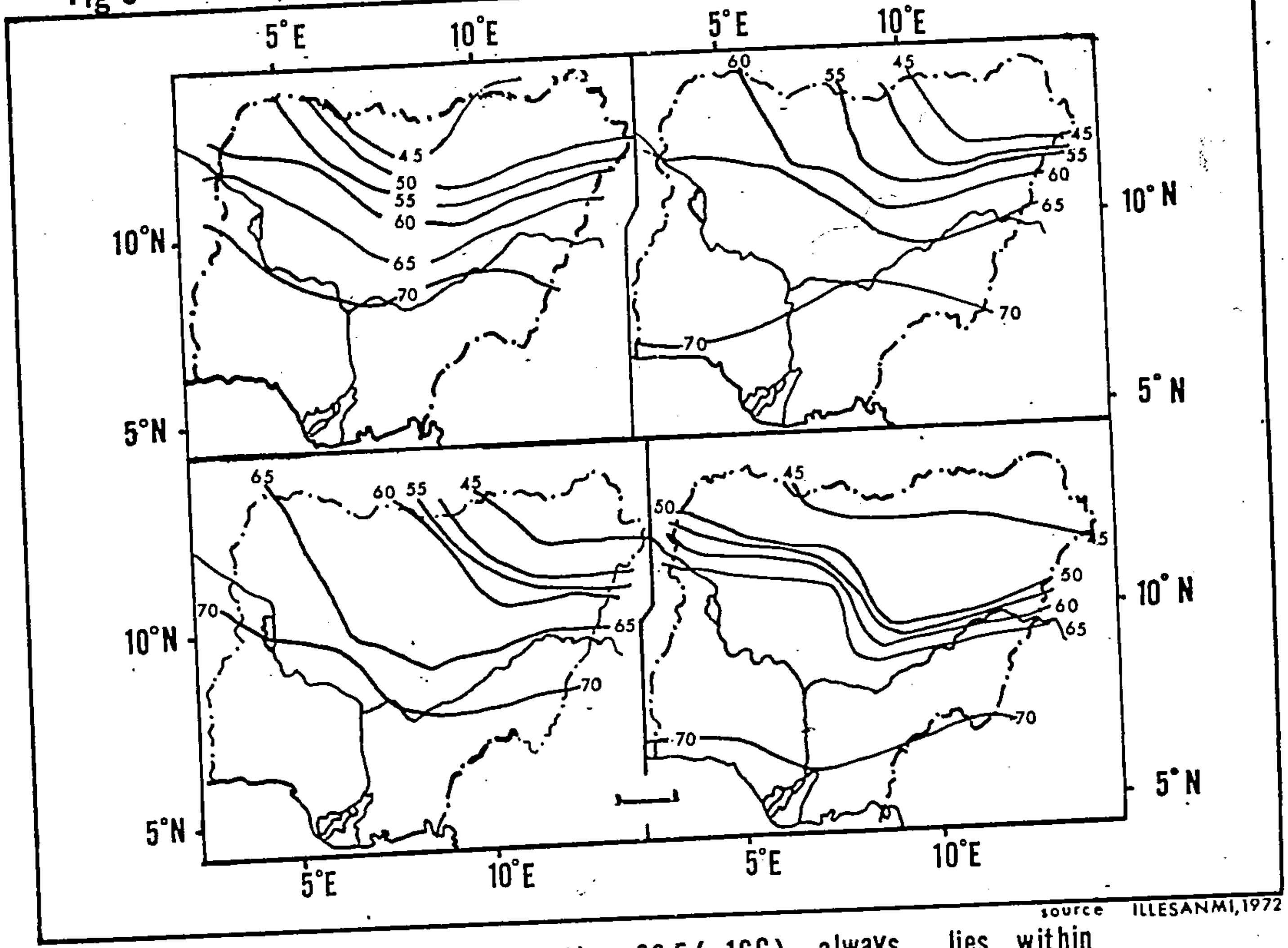
Our present dissertation thus refers to the monsoon trough (MT) region and does not necessarily apply to the whole of the tropics since the region is obviously not homogeneous climatologically. In view of this realization we shall follow Sadler and avoid the use of the term ITCZ in the rest of our present work. Instead we have adopted his term, monsoon trough.

The monsoon trough then refers to a region of lowest pressure and maximum cyclonic curvature of the wind field in West Africa within which the monsoons and the harmattan winds meet. This trough oscillates widely across West Africa and reaches its most southern position in January and its most northern position in August in consonance with the apparent movement of the sun.

The ITF as a Moisture Boundary(ITD):

As we have already indicated above, the airmasses of the monsoons and of the harmattan may be differentiated from one another mainly by reference to their humidity characteristics. Their temperature characteristics are nearly identical as both are tropical in origin. Influenced by the airmass climatologists of the Norwegian School, the very early tropical climatologists assumed that the region where the two airmasses meet is frontal and therefore referred to this region as the intertropical front (ITF). This view was disputed by Forsdyke (1949)

Fig 5 DEWPOINT TEMPERATURES OVER NIGERIA AT 0600 GMT 20–23 MARCH, 1955. (F°)

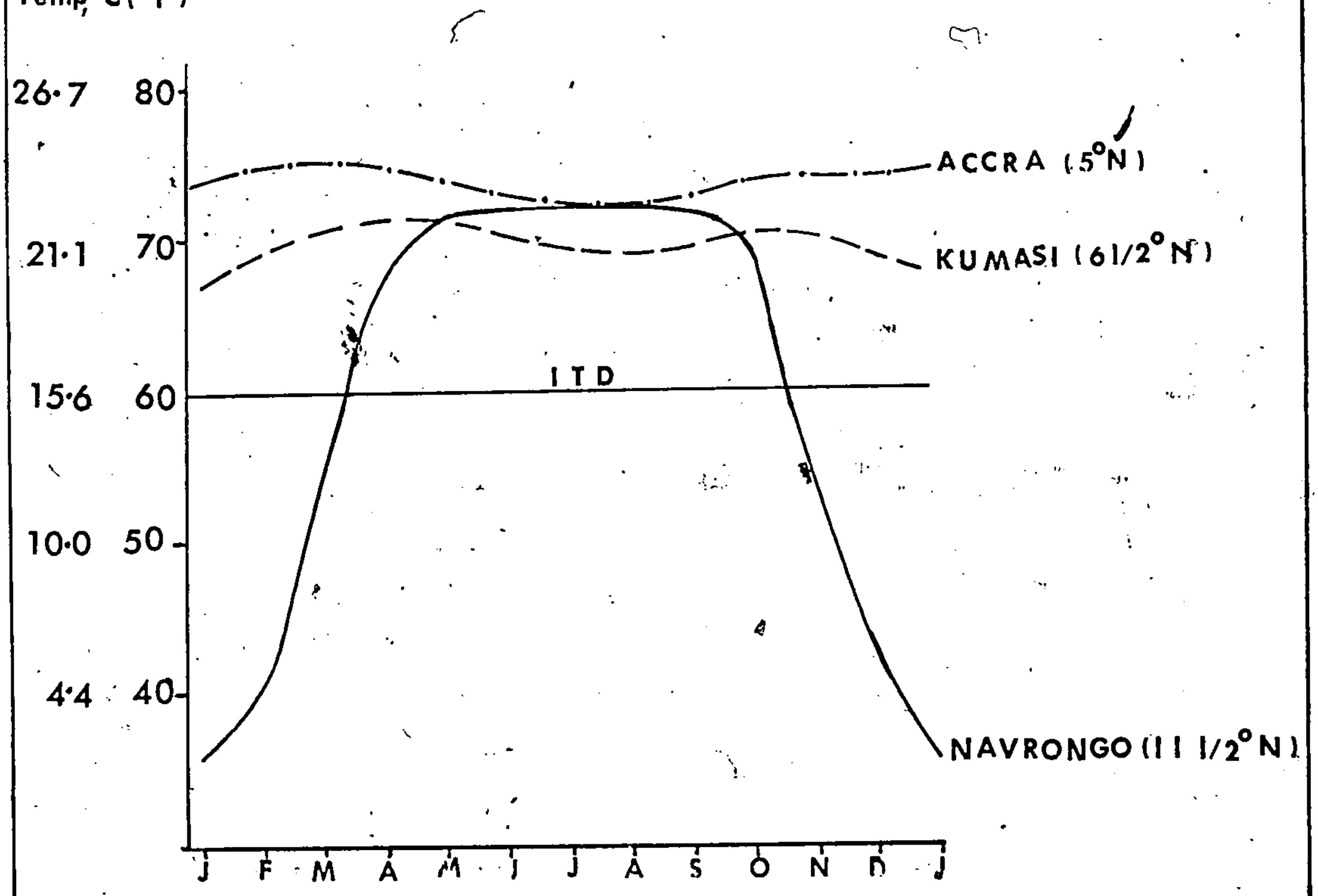


source ILLESANMI,1972

Note that the 60 F (~16C) always lies within the region of steepest gradient of the Td isolines.

who pointed out that the region where the hot and dry northern air is separated from the moist southern air is neither frontal nor convergent, (but is primarily) a region of maximum moisture gradient. As paraphrased by Illesanmi (1969), the boundary ought be seen as a line marking out "the region of greatest moisture gradient." (Fig. 5). As illustrated by this same figure, (5), the hot and dry northern air, the harmattan, is characterised by very low, and sometimes even by negative dewpoint temperatures. To further illustrate this point it will be noted that at Navrongo (11° 34'N, 0°) in Ghana the mean January dewpoint temperature is as low as 1.7°C (35°F), February 4.2° C (39.5°F) and that of December 5.6°C (42°F.(see Fig. 6), yet their corresponding mean air temperatures (1952-70) are as high as 27.3°C (81.1°F), 29.4°C (85.0°F) and 27.1°C (80.7°F) (Table 2). The corresponding mean monthly (1946-70) relative humidity of the said station and months range between 14% at 1500 hrs. G.M.T. and 32% at 0600 hrs G.M.T. (in January), 15% and 34% (for February) and 17% and 42% (in December) (Table 1). The characteristically dry nature of the harmattan airmass should therefore be obvious. For the harmattan airmass, therefore, considerable cooling is necessary before dew may be realized.

Fig 6 AVERAGE DEWPOINT TEMPERATURES, GHANA



source: GMSD, Accra

The monsoon airmass on the other hand is characterised by high relative humidities. hence very slight cooling may be required for dew to be realised (Fig. 6, Table 1). Thus in August when the whole of Ghana is covered by the monsoons the mean (1946-1970) relative humidity at Navrongo for example is at a maximum of 94% at 0600 hrs and a minimum of 70% (Table 1).

TABLE 1: MEAN MONTHLY RELATIVE HUMIDITIES(%)
NAVRONGO (1947-1970)

HR GMT	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
00	29	29	38	57	70	82	88	91	92	84	58	36	63
03	29	31	43	64	73	86	91	93	94	89	65	39	66
06	32	34	48	70	81	89	93	94	95	92	69	42	70
09	21	26	39	57	66	75	81	85	83	73	48	27	57
12	15	18	27	41	51	63	69	74	71	57	33	19	45
15	14	15	20	32	43	56	64	70	66	50	26	17	39
18	21	20	24	37	49	61	70	77	76	65	39	26	47
21	26	26	32	49	63	72	83	88	88	77	50	32	57

Source: Ghana Meteorlogical Services Department
Accra, Ghana

Note: the very low value in December, January, February as against the high values in July to September

From Fig. 6 too it is observed that dewpoint temperatures during the rainy season and time of the monsoons, at Navrongo are as high as 72°F (22.2°C) throughout the rainy (monsoon) season (May - September), with the mean monthly temperature fluctuating between 78.5°F (25.8°C) in August and 86.2°F (30.1°C). (Table 2)

It will be seen from Fig. 6 that dewpoint temperatures during the time of the monsoon are greater than 16°C (60°F) all throughout Ghana, and indeed all throughout West Africa. Based upon analyses similar to this, the term intertropical discontinuity (ITD) has been proposed by the *WMO Provisional Guide to Meteorological Practice*, to refer to the region of maximum humidity gradient (WMO. 1960) separating the two airmasses. On the ground the ITD is therefore marked by the 16°C (60°F) dewpoint isotherm with the regions within the harmattan, and lying to the north of the (ITD) having dewpoint temperatures persistently below the 16°C. Regions within the monsoons or to the south of the ITD are on the other hand marked by persistently high dewpoint temperatures exceeding 16°C. Conditions in Navrongo amply clarify this state of affairs. (Fig. 6)

TABLE 2: MEAN MONTHLY TEMPERATURE (°C), NAVRONGO, GHANA (1951-1970)

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
°C	27.3	29.4	31.5	31.6	30.1	27.8	26.6	25.8	26.6	27.8	28.2	27.1	28.3

Source: Ghana Meteorological Services Department
Accra, Ghana

The ITD, thus defined, provides a more objective means for the identification of the zone that separates the monsoons from the harmattan.

It will also be noted that the occurence of rainfall is closely associated with persistentlv high dewpoint temperatures. As Sellick (1960) found out in his research at Salisbury, the chances of rain occuring are greatly enhanced to about 75% as the dewpoint temperatures exceed 60°F whereas at lower dewpoint temperatures the probability of rain occuring is reduced to 31%. The use of dewpoint temperatures to identify the ITD is therefore justified in view of the observed close relationship between the two parameters.

It has also been suggested that of all the measures of the contrast between the two airmasses, the humidity content of the air in terms of its dewpoint is the most representative (Illesanmi, 1972). Besides the dewpoint temperatures have the added advantage of being readily available.

The relationship between the ITD and the monsoon trough may now be stated thus: the monsoon trough represents the zone of lowest atmospheric pressure into which the two principal airmasses flow, whereas the ITD marks the boundary of the zone of moisture discontinuity that separates the two airmasses from each other. Hence, the ITD is always located within the monsoon trough. In other words the position of the ITD is a function of, and is determined by that of the trough. Consequently, the movement of the ITD like that of the trough follows the apparent movement of the sun with a time lag of four to six weeks (Coche me and Franquin. 1967). This lag is explained by the fact that the monsoon trough is primarily thermal in origin so that the trough would coincide more with the thermal equator rather than the sheer position of the high sun..

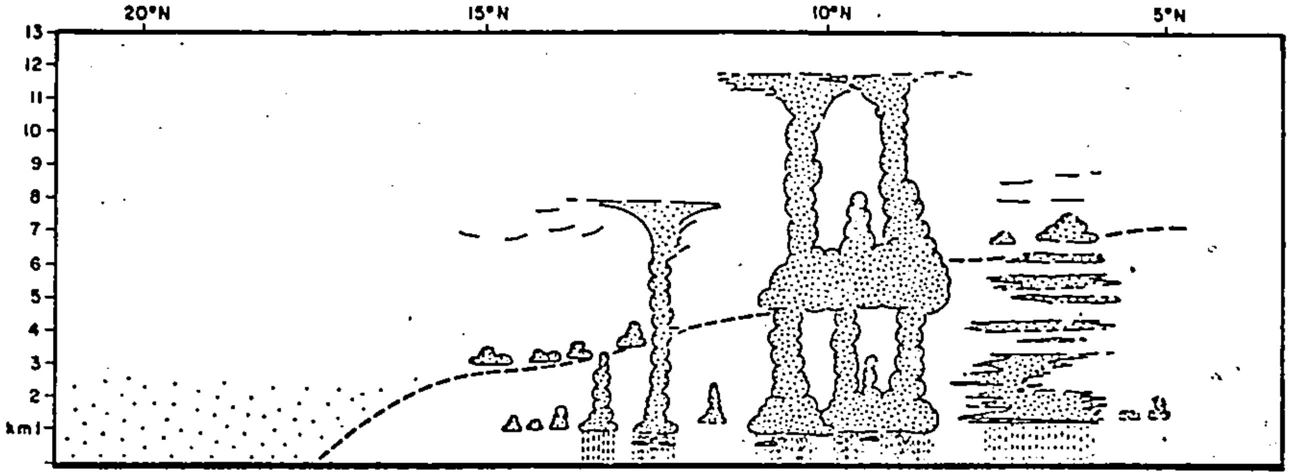
The rate of movement of the ITD may thus be estimated roughlv as follows. The southernmost limit of the ITD reaches as far south as 6°N whilst the northernmost limit is generallv believed to reach as far north as 20°N (Trewartha, 1961; Ayoade, 1975; Walker, 1957, 1960). This means that the northernmost and southernmost positions of the ITD are separated by an interval of 14°. Since an interval of one degree latitude is equivalent to 111 km. it follows that the ITD covers a distance of 1550 km (roughly 1000 miles) each way north and south. This distance is covered in a total time period of 5 months (September to January, inclusive) during its southward journey, ie. at a mean southerly speed of 10.3 km day^{-1} (6.4 mi day^{-1} or 193 mi month^{-1}). On the return north, the same distance (of 1550 km) is covered in seven months (February to August, inclusive), which gives a rough northerly average speed of 7.4 km day^{-1} (4.6 mi day^{-1}, 140 mi month^{-1});[3] the southward movement is thus about 1.4 times faster than the northward movement.

As noted above, it is . the position of the highest temperatures more than the position of the high sun that directly controls the relative direction of the movement of the ITD. Thus the relative northerly or southerly positions of the thermal equator dictates the northerly or southerly movements of the ITD respectively. As a result of the variation in the rates of movement of the ITD and in view of the close relationship of the latter and the incidence of rainfall, the southward "retreat" of the rainy season is about one and a half times faster than the northward "advance". This should explain Ayoade's (1975) observation about the Nigerian rain, viz, that the onset of the rains is more gradual than the retreat.

The Vertical Slope of the ITD

On meeting the northerly harmattan airmass the monsoon airmass undercuts the harmattan while the latter airmass flows freely on to the top of the monsoons. Vertically therefore the ITD slopes upwards to the south as indicated in Fig. 7.

[3] The northward average speed of 7.4 km. day^{-1} as calculated above agrees with Illesanmi (1972) figure of 4.5 mi day^{-1} (7.2 km day^{-1}) but underestimates Walker's (1957) figure of "100 miles per month". The southerly speed of 10.3km day^{-1} on the other hand agrees with Walker's estimate of "200 miles per month" but conflicts with Illesanmi's figure of 8 mi day^{-1}



Dhonneur et al.

Figure 7 -- Diagrammatic vertical cross-section through Area from north to south in early summer. From left to right: dry, hazy harmattan; surface boundary between harmattan and monsoon, or ITF which, shown as a dotted line, slopes upwards and southwards; small cumulus; scattered showers; disturbance line shown head-on; more continuous cloud layers with lighter rain.

Source WMO TECH NOTE NO 86

Observations of the vertical variation in the humidity content of the atmosphere with height within the monsoon may thus provide us with direct evidence for this arrangement of the 'dry' and 'moist' airmasses in West Africa. Thus Walker (1957) observed that along the coast, (in Ghana) in August, when the ITD is at its northernmost position, relative humidity in the moist airmass remains constantly high up to a level of 3.7 km (12,000 feet) along latitude 5°N but "falls off sharply" above this. From Fig. 7 it is seen that the height at which the relative humidity falls off reduces gradually northwards till one has reached the surface position of the ITD (at about 20°N in August).

The location of the region of maximum cloud cover may also be used as evidence of the validity of the described vertical and horizontal arrangement of the airmasses, and hence of the slope of the ITD. This is because the amount of cloud cover in the atmosphere, other things being equal, is a function of the humidity content in the atmosphere (which, for the West African situation, is directly related to the ITD and the depth of the monsoon airmass under the ITD). It is easily seen that the maximum cloud zone (MCZ) would have to occur south of the trough line (ie. south of the surface position of the ITD) as has in fact been observed by Sadler (1975).

In the same vein, it is clear that the areas of maximum convection or areas of maximum rainfall should similarly occur "many miles south of the monsoon trough" (Barry and Chorley, 1969).

The ITD is of great climatological significance in West Africa. As Clackson (1957) has observed, it serves as a reference line for the normal weather systems and structures associated with the two-dimensional boundary between the harmattan and the monsoon. Besides, the annual march of rainfall amount and the onset, advance and retreat of the rainy season depend primarily on the position and seasonal displacement of the discontinuity (Illesanmi, 1971). This then should explain our preoccupation with the ITD so far. We shall further explore the observed climatological significance of the ITD in chapter four.

CHAPTER THREE

RECENT DEVELOPMENTS LEADING TO AN IMPROVED RAINFALL MODEL FOR WEST AFRICA

Our objective of building a three dimensional rainfall model implies the need for a firmer understanding of the horizontal and vertical components of circulation. Indeed, as we have already indicated, the cornerstone of our present thesis rests on our dissatisfaction with the exclusion of the vertical motion of air in the various climatic models of West Africa. It is our conviction that the difficulties encountered by the various rainfall models stem from this particular state of affairs whereby the vertical component of circulation has been under emphasised.

The Vertical Component of Circulation in the Tropics- a re-appraisal:

The detailed derivation of the equation of motion has been exhaustively discussed elsewhere (Panofsky 1968, McIntosh and Thom 1973, Petterssen, 1969). The summary of the accelerations in the x, y, z axes are:

$$\frac{du}{dt} = -\alpha\frac{\partial P}{\partial x} + fv \qquad \ldots\ldots\ldots(1)$$

$$\frac{dv}{dt} = -\alpha\frac{\partial P}{\partial v} - fu \qquad \ldots\ldots\ldots(2)$$

$$\frac{dw}{dt} = -\alpha\frac{\partial P}{\partial z} - g \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where u, v, w are the velocities in x, y, z axis

α = specific volume

Ω = angular velocity of the earth

ϕ = latitude

g = acceleration due to gravity

dt = change in time

$\frac{\partial p}{\partial x}, \frac{\partial p}{\partial y}, \frac{\partial p}{\partial z}$ = pressure gradient in the x, y, z axes

f = $2\Omega \sin\phi$ is the Coriolis parameter, which is the function of the earth's latitude

The general consensus is that the net vertical movements come to about zero so that it is the accelerations in the u and v components that have attracted the attention of various climatic models explicitly. It is however to be noted that such results which apply to zonally averaged quantities are not necessarily representative of conditions over smaller regions. Commenting on similar problem with the vertical component of circulation over the North American continent, for example, Benton (1960) noted that "although mean (ie time averaged) vertical circulations in the zonally averaged flow ... may be extremely weak (and could be approximated to zero) there is reason to believe that substantial mean vertical circulation exist ... over limited areas..." This statement is even the most appropriate for the West African situation.

Since mean vertical circulations are not of sufficient magnitude at the surface level to be measured directly from observational data, indirect techniques have been used to obtain evidence for their existence Benton (ibid, p. 58) for example, suggested an investigation of the energy balance of the earth's atmosphere system within the region of interest as one of the most powerful of these techniques. In 1969 Brummer. (et al, 1974), also resolved the equation of mass continuity and then measured the various horizontal components of the equations of motion (as expressed by equations 1 to 3) and obtained a fairly good idea about the vertical motion of winds over the north Atlantic (tropical West Africa) in connection with the GARP Atlantic Tropical Experiment (GATE).

The equation of mass continuity is expressed as follows:
$$\frac{1}{\rho}\frac{dp}{dt} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) \quad \ldots\ldots\ldots\ldots\ldots(4)$$

where: ρ = density of air parcel

u, v, w = velocities of air in x. y, z directions

t = time

If the mass of the parcel of air is to be conserved ie. with a rate of change equivalent to 0 then equation 4 may be resolved into
$$-\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = \frac{\partial w}{\partial z} \quad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

in which case
$$\partial w = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\partial z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

For any given thickness layer of the atmosphere, say from the ground to the 500 m. level, equation (6) may be approximated to

$$\partial \tilde{\bar{w}} = - \frac{\bar{\rho}}{\bar{\rho}_{500}} \left[\frac{\partial \tilde{\bar{u}}}{\partial x} + \frac{\partial \tilde{\bar{v}}}{\partial y} \right] \partial z_{500} \quad \ldots\ldots\ldots\ldots (7)$$

where the tilde denotes the vertical average between the surface and the 500 m level. The horizontal gradients in equations1 and 2 may be given directly by the observed subcloud layer averages of the wind vectors at the surface. The vertical gradients of $\bar{u}$ and $\bar{v}$ at 500 m height may be derived from the respective profiles of the zonal and meridional wind variation between the given layer (Brummer, <u>et</u>. <u>al</u>., 1974).

Thus, with data about the various components of the equations of motion such as the pressure gradient force and the equivalent horizontal components of the geostrophic wind measured, a fairly good idea of the vertical motion of winds may be derived from the geostrophic wind equation. Using this method of analysis during the Atlantic Experiment (ATEX) of 1969 Brummer, Angstein and Riehl, for the first time, determined vertical component of circulation in the tropics (West Africa) and obtained net subsidence which confirmed Riehl's (1951) postulation of the existence of divergence and sinking vertical motion in the equator-ward moving trades. It would be noted that various partial verification of the existence of divergence in the trades have been made to support Riehl's point of view.[4] However, the first measurements had not been made until 1969 during ATEX as described above.[5]

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[4] Riehl (1951) postulated horizontal divergence and sinking vertical motion in the trades by integrating the vorticity equation about the vertical axis around a latitude circle for steady state conditions, and dropping all terms as small except those depending on the coriolis parameter (or the planetary vorticity itself).

The equation be used is

$$BV^* = f(W^*/H)$$

where B = variation of the coriolis parameter with latitude.

f = coriolis parameter

W*, V*, the asterisk denote the average W and V around a latitude circle

By this therefore Riehl successfully challenged the concept of the trade wind conversion as a material boundary.

[5] Observations made for a five-day period during the Barbados Oceanographic and Meteorological experiment (BOMEX) of 1969 (Holland and Rasmusson, 1973) also revealed divergence and sinking motion over the area of their ship array.

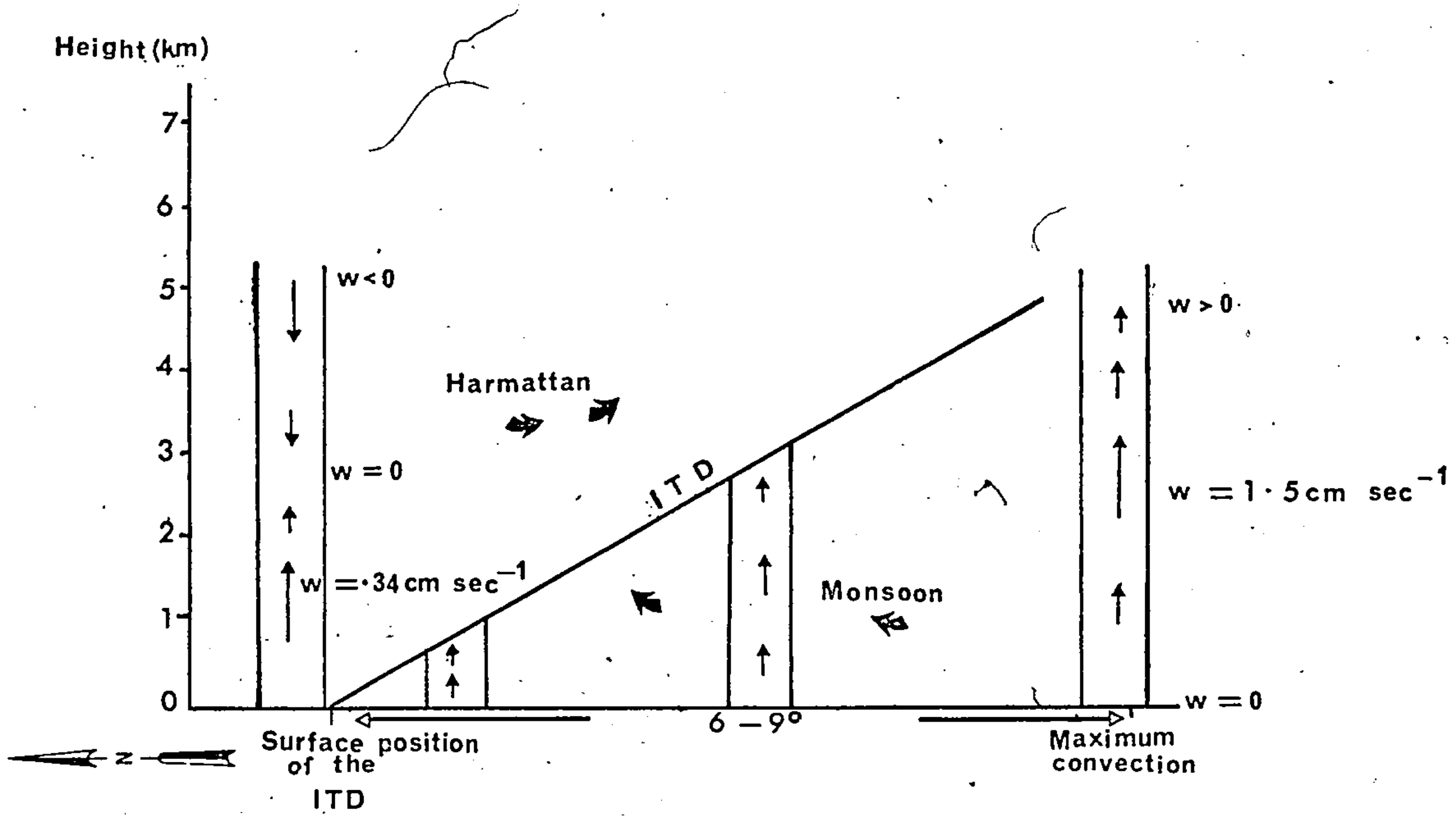
Yet the role of this component of circulation has not yet been explicitly incorporated in the various rainfall models in West Africa. (See the very recent discussions of the ITCZ model by Illesanmi 1972, and Ayoade 1975, for example).

Flohn (1960) has observed that within the northeasterly trade winds vertical motion is positive within the first 3 km of the surface and that above this level subsidence prevails. He also suggested that vertical wind speed increases from zero at the surface to a maximum upward motion of about 0.34 cm sec $^{-1}$(300 m day^{-1}) at the 1.5 km. level decreasing again to zero values at the 3 km level. Beyond this level vertical motion becomes negative. In effect, apart from being a ~~dry~~ airmass, the harmattan is also of shallow and relatively weak lift, so that it is this combined effects of both factors that accounts for the relative dryness that is associated with this airmass. In the southern trades however Flohn found upward and much stronger motions extending from the surface to 3-5 km. A typical maximum value of vertical ascent was about 1.5 cm - sec^{-1} (1300 m.- day^{-1}) at 500-600 km south of the monsoon trough, meaning that upward rising motion increases steadily southwards from a surface minimum at the surface position of the ITD. Even though Flohn did not apparently realize it the occurance of the region of maximum upward motion within the monsoon airmass (which he put at 500-600 km south of the monsoon trough) is evidently due to the vertical slope of the ITD as previously explained (Fig. 7, 9).

But the question that Flohn failed to answer was whether or not there could be subsidence associated with the moist monsoons also. Evidently. Flohn discounted or at best underemphasised the existence of subsidence within the monsoons. Thus works based on this work, while emphasising the relative difference between the strengths of the vertical up-moving currents within the two trades fail to make similar comparisons of the relative strengths of their subsidence. Yet all of them show their familiarity with the fact that within the harmattan subsidence prevails right down to the 3km level. (Fig. 8)

It need not be pointed out that upper-level divergence and subsidence are not confined to the northern trades alone but are associated with the southern trades as well. Indeed, Riehl's postulation of the phenomenon in 1951 was general enough to include

Fig 8 DISTRIBUTION OF DIVERGENCE IN THE TRADES



After Flohn, Illesanmi

both of the equatorward moving trades. From the works of Riehl and Flohn cited it could be said that while subsidence occurs within both the harmattan and the monsoon airmasses it tends to occur at lower altitudes in the harmattan than in the monsoon. The climatological significance of subsidence (p. 54) may thus tend to be more conspicious in the harmattan generally than in the monsoons. This should thus explain why much emphasis has not been laid on the subsidence within the monsoons, perhaps.

Measurements of the two dimensional divergence of the surface wind made during the 1969 ATEX experiment (Table 3) appear to indicate a relationship between subsidence intensity and the movement of the ITD, It is seen that subsidence in the monsoons shows seasonal variations which seem to depend upon the surface movements of the ITD. Indeed the ATEX researchers in discussing their results did observe that subsidence is largest "when the (S.E.) trade winds prevailed" but smallest when the trough touched the experiment site. In other words subsidence is largest when the ITD and the surface trough are farthest to the north from a given spot. and is generally small within and around the monsoon trough.

In the terminology of our suggested model, we may say that, as the ITD migrates southwards the axis of the subsidence shifts south and its climatological significance to those areas it is moving away from accordingly diminishes.

Larger subsidence values are observed, again, further to the north of the trough ie. as one gets farther to the centre of the northern hemisphere subtropical high pressure belt.

Axis of the Monsoon Subsidence:

Conceptually, therefore, the subsidence within the monsoon may be represented by an axis which slopes upwards and northwards (Fig. 9). In this figure (9) the length of arrows on top of the axis represent the proportional intensity of the subsidence and, hence, the general spatial variations of the monsoon subsidence. It is seen that at any given instant subsidence is largest in the south and decreases as one approaches the surface position of the ITD. The corollary of this statement is that the monsoon subsidence over any given area intensifies as the equatorial trough moves northwards away from the said location. As the trough migrates farther and farther to the north the regions to the south experience increasingly, the effects of the monsoon subsidence. Thus, by July-August when the trough had reached its northernmost position subsidence within the monsoon would have sufficiently intensified as to have perceivable climatological consequences (p. 52).

According to Griffiths (1972), in July an "850 mb contour extends from the South Atlantic ocean and

reaches the West African coast near Ghana".
This contour obviously is a high pressure cell, a ridge, hence, it would induce horizontal convergence and net downward motion, that is, net subsidence below whereas above this level the mean vertical motion would be positive (Griffiths, 1972).

This further confirms the notion of seasonal variations in the intensity of subsidence, and the relationship between subsidence intensity and the north-south migrations in the circulation across the region.

From the works of Barry and Perry (1973) and Lamb (1972) it is seen that we require, further, the examination of daily surface and upper-level weather charts of West Africa at each of the standard synoptic hours over a considerable length of time in order to obtain direct evidence for this hypothesis. In other words we need to have incorporated basic synoptic climatology in our methodology.[6] Unfortunately such <u>daily</u> synoptic maps (of West Africa) could not

[6] The operational hypothesis of synoptic climatology presupposes that each of the various circulation systems :zonal and mendional flows, cyclonic and anticyclonic systems and their associated trowal, etc., bring along with them clearly identifiable states of weather. So that, if for a given span of time the various circulation systems that cross a region could be identified then an insight may be had about the usual or 'average' state of weather for agiven region.

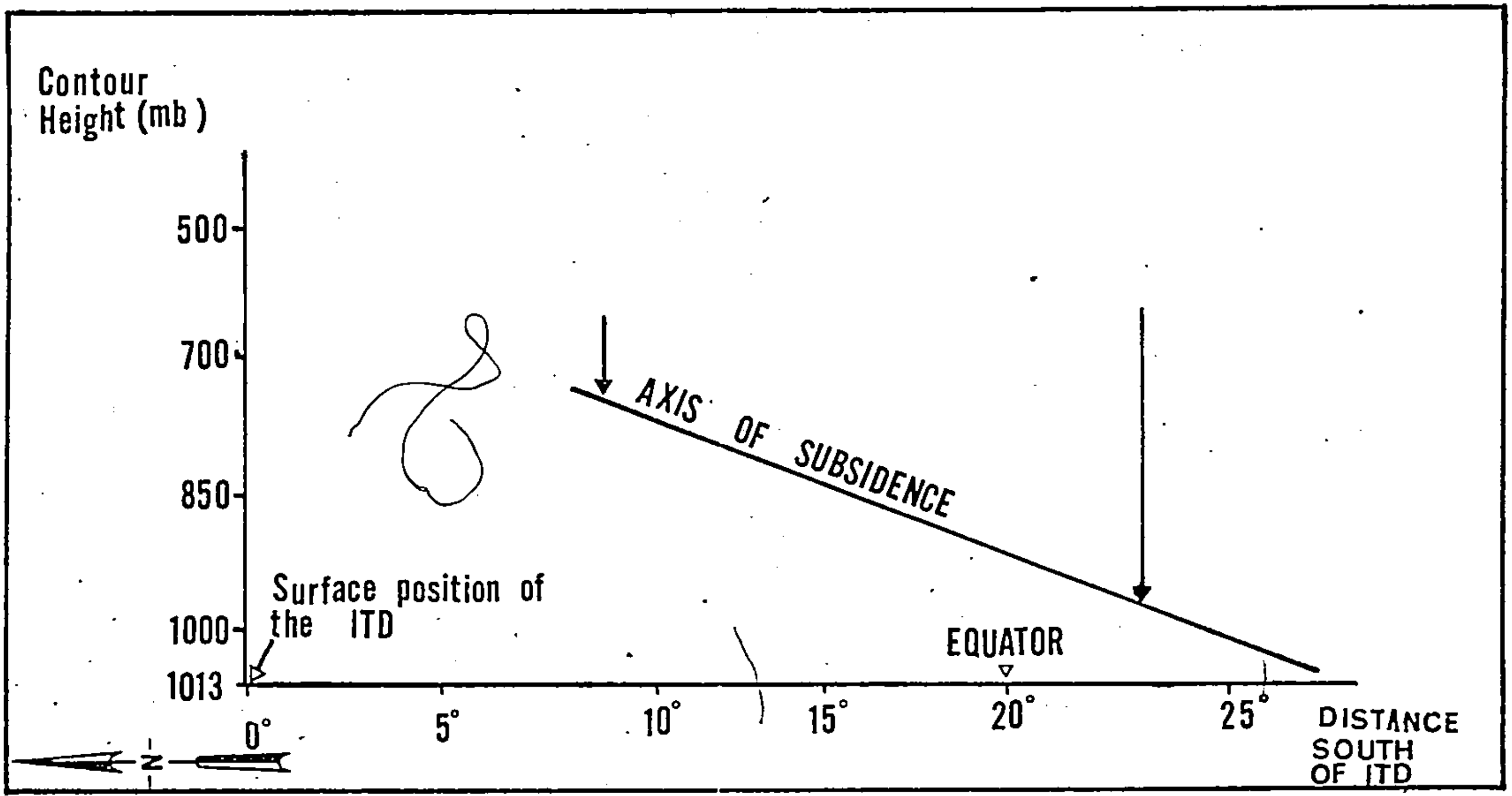


FIG 9 Ideal Representation of the subsidence within the monsoon in August

Note: Arrows indicate relative subsidence intensities be obtained by the writer. The few average surface maps which were examined together with Gregory's (1964, p. 4-7) daily surface weather maps did show that the area of the anomalous dry climate tended to be 2-3 mb. above the zonal average of the surface pressure distribution (Fig. 10). This weak cell of high pressure at the surface[7] should be a reflection of the 850 mb. ridge that Griffiths (op cit) talks about.

Under such anticyclonic conditions at the Accra Plains relative extremes of temperatures are also to be expected since the relative calm weather conditions associated with high pressure cells would promote added surface radiational cooling - intense enough to possibly exceed the warming that could result from the vertical subsidence at night.

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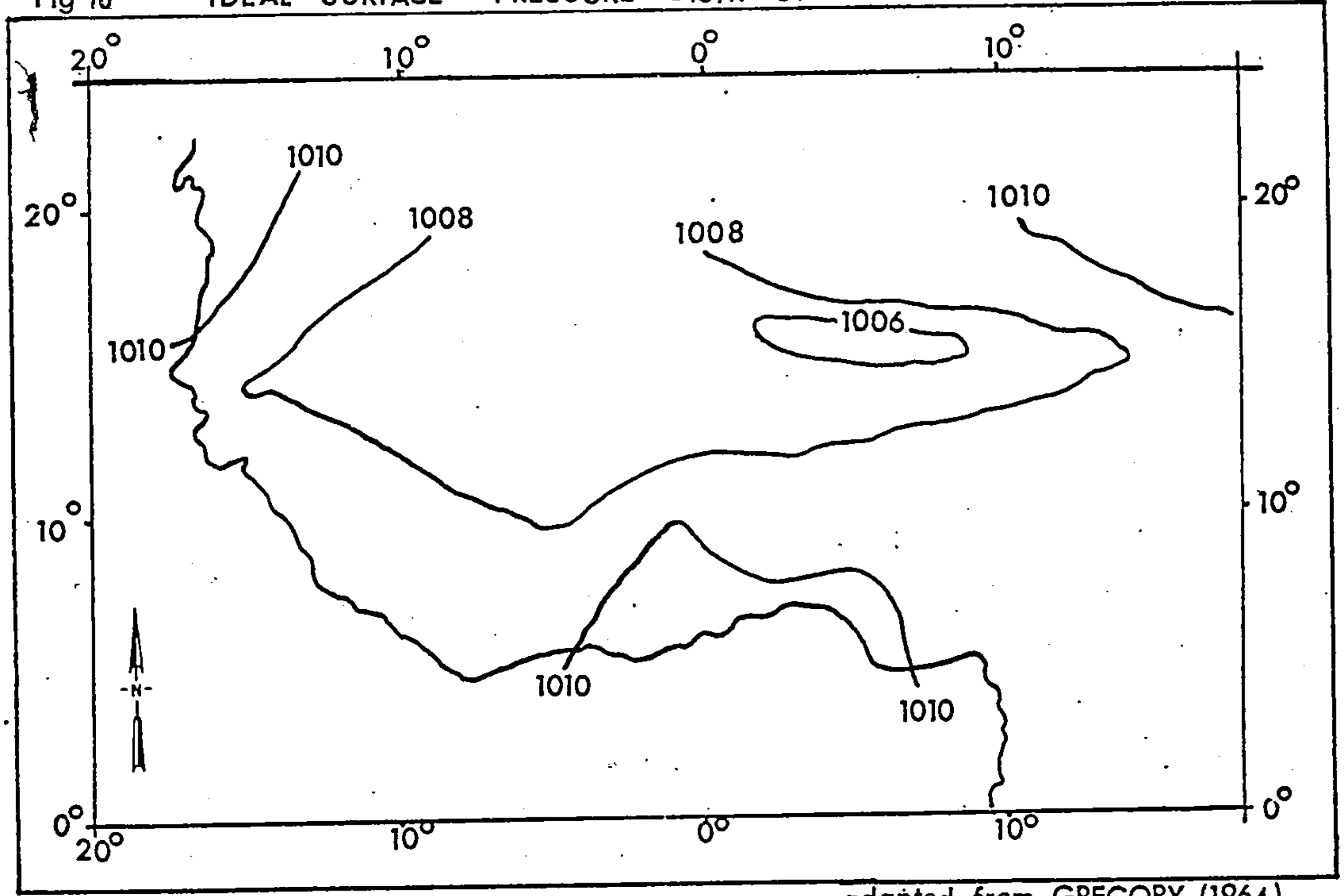
[7] From the Equation of Continuity it would be expected that where there is "Vertical Contraction" of the surface - 850 mb. ridge at the surface would be more conspicuous. Where there is "vertical stretching", on the other hand, and the depth of the layer expands a condition of low pressure at the surface should be expected as faintly represented on Gregory's (op cit) daily surface weather map of 24th February, 1961.

During the day, on the other hand, the combined effect of the solar radiation warming and the warming resulting from the vertical subsidence would generate highest surface temperatures within the anticyclone. Along the coast of Ghana, therefore, the Accra Plains have the lowest minimum temperatures (Fig. 13) and the highest maximum temperatures (Fig. 11). However, it is seen that the spatial variation in the mean minimum temperatures were not remarkably different. Consequently the highest mean annual temperatures here (along the coast of Ghana) during the 1960-74 period was highest almost by 2-3°C at the southeast Accra plains. (Fig. 12). This does contradict Trewartha's (op cit) claim that temperatures in the dry Ghana coast are the lowest and thereby creates doubt as to the validity in his inference that an upwelling of cold current occurs at the southeast coast of Ghana which, as he has suggested, should be causing the anomalous climate. In effect, therefore, the analysis of the mean annual minimum and maximum temperatures provides another indirect evidence to the hypothesis of the existence of above-surface (850 mb) ridge that, compounding the effects of the vertical circumpolar subsidence in the tropics (Riehl, 1951) would be responsible for the existence of the dry equatorial climate of the Accra Plains.

WEST AFRICA:

Fig 10 'IDEAL' SURFACE PRESSURE DISTRIBUTION PATTERN IN SUMMER



adapted from GREGORY (1964)

Fig 11 AVERAGE ANNUAL MAXIMUM TEMPERATURES ALONG THE COAST OF GHANA (1960 – 1974)

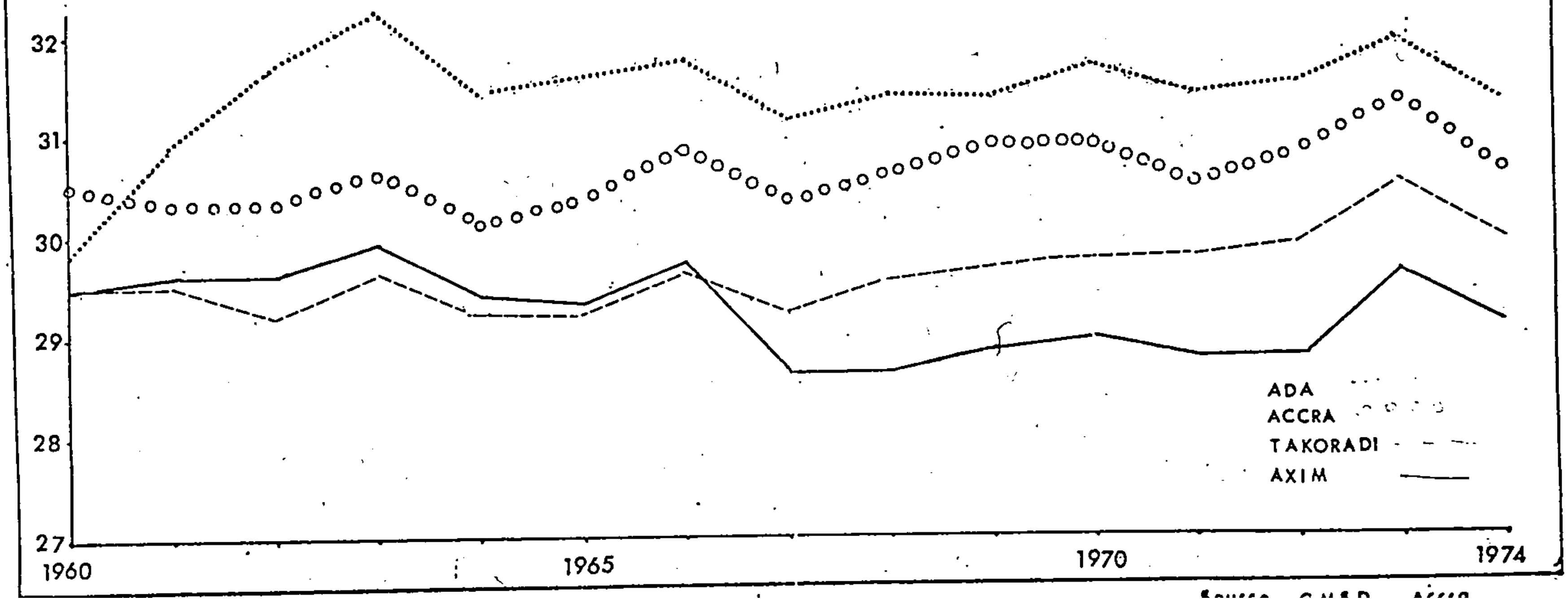
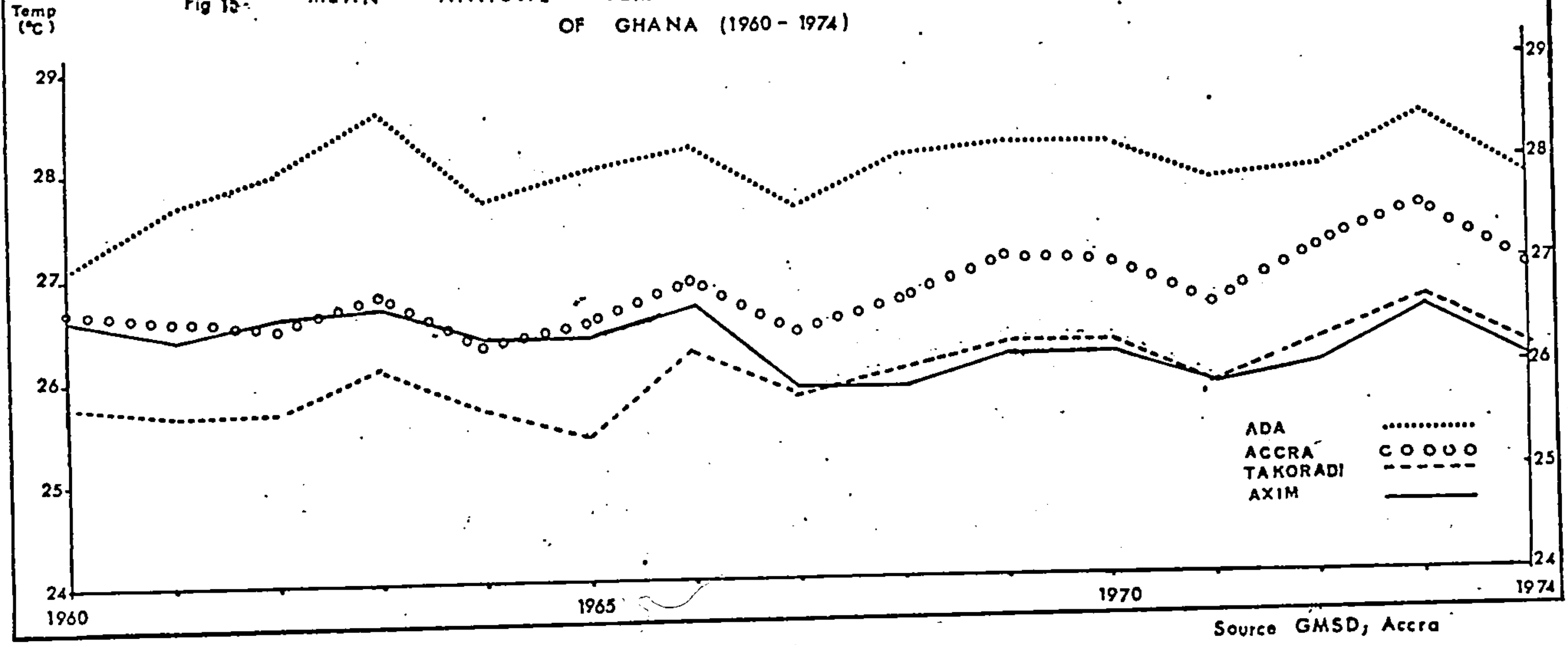
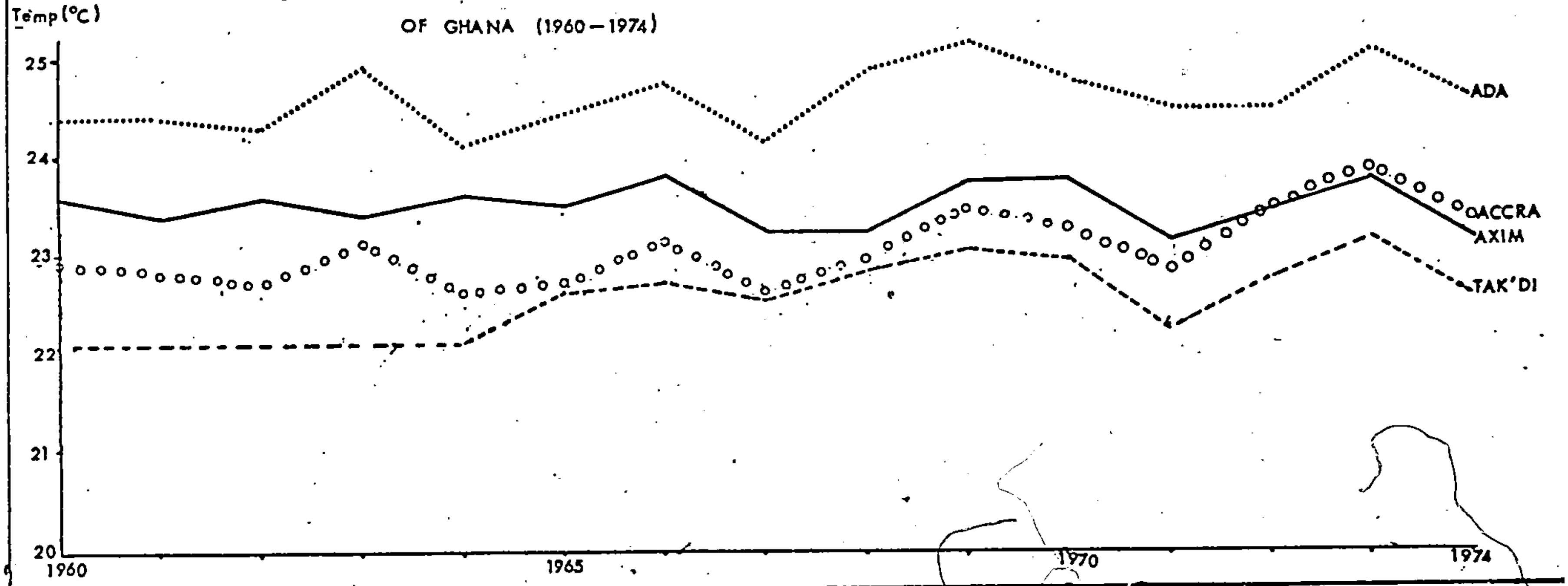


Fig 15 17B MEAN ANNUAL TEMPERATURES ALONG THE COAST OF GHANA (1960 - 1974)



Source GMSD, Accra

Fig 13 AVERAGE MINIMUM TEMPERATURES ALONG THE COAST OF GHANA (1960—1974)



Source GMSD, Accra

It needs to be emphasised that subsidence may be found within the trades throughout the year, ie. it is not a July (summer) phenomenon only. To refer to Table 3 again it is seen, for example, that mean vertical motion was still negative even when the ITD was overlying the ATEX area though the magnitude was very small. The additional presence of the 850-mb ridge in July-August, therefore merely reinforces the existing subsidence in the affected regions at this time of the year, making the mid-summer drought in these areas to be more severe than the neighbouring regions to the west and east. (Trewartha. 1962, Griffiths. 1972).

Finally it should be noted that subsidence within the trade wind belt shows considerable spatial variations. For many areas within the belt the observed subsidence appear to be stronger than the climatic average for the circumpolar trade wind belt (Brummer, _et_. _al_., 1974). Considering the extreme dryness of the Ghana dry belt and in view of the strong objections offered against Trewartha's 1961 explanations (See p. 44) it is being suggested here that the existence of this anomalous climatic region may be due to the effects of one of these cells of above-normal subsidence within the tropics. On the basis of this speculation it is shown in Chapter 5 that our suggested model is able to account for all of the features of weather and climate of West Africa within its framework without invoking any extraneous parameters for the said purpose.

To summarize the arguments thus far:

(i) Large-scale subsidence within the trade wind belt conjectured by Riehl in 1951 has now been shown to exist in the course of the ATEX investigations.

(ii) This tropical subsidence appears to extend to far lower elevations within the northern trades than within the southern trades. Thus its presence within the harmattan tends to be more obvious than it is within the monsoons.

(iii) However, the intensity of the subsidence in the monsoon airmass tends to increase the farther away from a locality the ITD is situated. In July-August when the ITD has reached its farthest position to the north, subsidence is strongest and it becomes so intense as to reflect on the rainfall amounts received at the southern margins of the region. As a result of the general northward displacement of the general circulation the 850 mb level high pressure ridge centered south of the

5

equator is able to reach the West African coast which further intensifies the intensity of subsidence around this region. Thus, the July-August aridity at the Accra plains tend to be more severe than in the adjacent regions to the east and west (Trewatha, 1962).

(iv) It is thus suggested that any rainfall model based upon the general circulation can never be complete unless it is linked up with the large-scale downward- moving vertical currents within the monsoon.

Before we show how we have managed to fit these facts into a comprehensive and interlocking whole, the suggested model, we may first discuss the specific climatological significance of the vertical subsidence on rainfall.

Climatological Significance of the Monsoon Subsidence:

Since subsidence involves adiabatic warming it tends to suppress rainfall (McIntosh and Thom, 1973, p. 144, 146, etc.) Subsidence also damps out the vertical motions from lower layers of the atmosphere and prevents drift situations in depth to occur. In the West African situation where a dry airmass overlies the moist airmass there is also the added possibility that subsidence would result in the entrainment of drier air from the upper levels of the

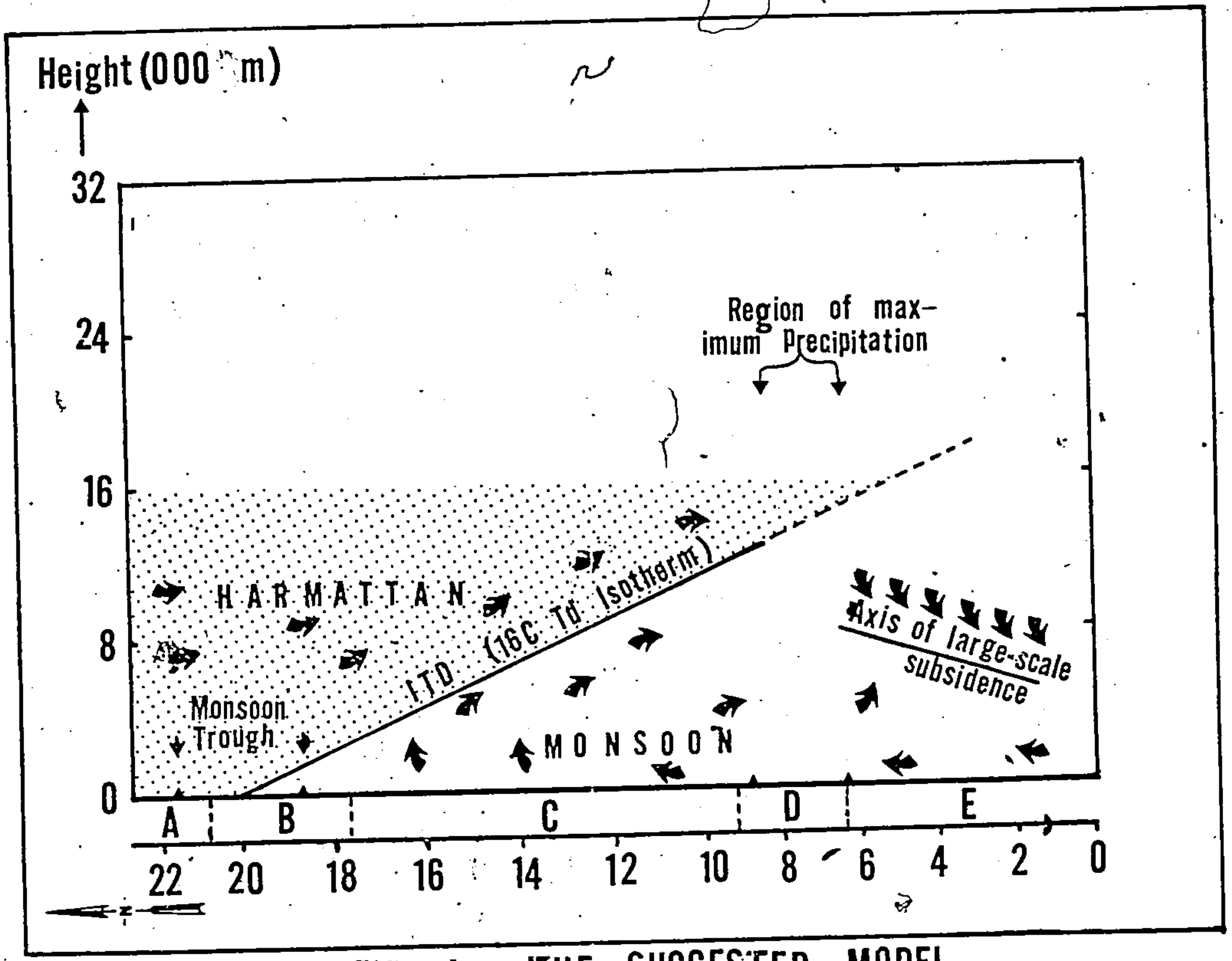


Fig 14 THE SUGGESTED MODEL

atmosphere and thereby reduce the relative humidity at the lower layers of the atmosphere. Thus the season and regions of strong subsidence will tend to be drier.

Subsidence is therefore very significant in relation to rainfall and cannot thus be excluded from any rainfall model of an area where its existence has been established beyond doubt.

The Suggested Model

The suggested rainfall model for West Africa follows from or organizes various facts about the structure of the West African atmosphere and its horizontal and vertical circulation into a coherent whole. The principal aspects of the model are shown in Figure 14.

Into a region of lowest atmospheric pressure referred to as the Monsoon Trough, the two tropical trades flow from opposite sides of the equator. On meeting, they are separated from each other by a region of steep moisture gradient otherwise referred to as the Intertropical discontinuity (ITD) and defined by the mean 16°C dewpoint temperature. The ITD slopes upwards and equatorwards, with the moist monsoon undercutting the harmattan. Consequently, the depth of humid air subjected to convective activities and rainfall similarly increases from the surface position of the ITD southwards. At the southern end of the ITD, is an axis of <u>subsiding currents</u> which slopes in the opposite direction to the slope of the ITD, ie upwards and northwards. The presence of this large-scale subsidence act as a suppressive mechanism which check convection and inhibits rainfall. As a result of the nature of the slope of this axis of the monsoon subsidence, the incidence of <u>dryness</u> resulting from its presence would <u>increase</u> southwards.

Together the whole system migrates slowly up and down across West Africa in perfect harmony with the apparent movement of the sun with a lag of 4 to 6 weeks. The southbound movement of the ITD tends to be nearly one and a half times faster than its northbound rate of movement as explained above (see p. 29).

Simple as the model is, it enables us to account for all of the apparent seasonal and spatial "anomalies" of rainfall distribution (and seasonal variations in weather) in West Africa.

CHAPTER FOUR

HOW THE MODEL EXPLAINS THE NORMAL RAINFALL (WEATHER) PATTERNS OF WEST AFRICA

The annual march of rainfall amount, i.e., the onset, advance and retreat of the rainy season in West Africa depend primarily on the position and seasonal replacement of the discontinuity (ITD) relative to a station, Fig. 18 (Illesanmi, 1971). This indeed, is the most obvious fact from the suggested model and stems from the peculiar arrangement of the dry and moist airmasses that circulate over the region (West Africa).

At any given moment and for any given location in West Africa, then, the position of the ITD is very important. This, as Clackson (1957) had cause to point out, is not because there is any particular weather activity at this airmass boundary, as it is usually the case at the boundary region's of airmasses (fronts) in the temperate region. In its (ITD) special circumstance its sole significance lies in the fact that it serves as a reference line for the normal weather system and structure associated with the three-dimensional boundary between the harmattan and monsoon. To the north of the ITD, i.e. within the harmattan airmass, the weather is entirely dry and rainless.

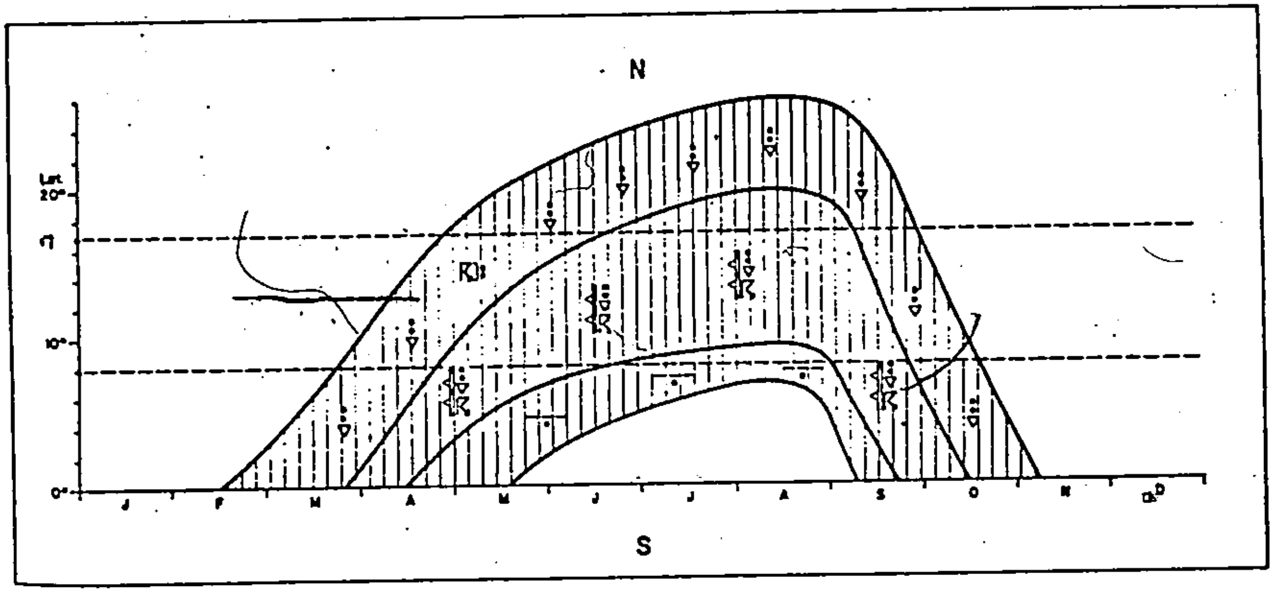


Figure 15 - Diagram showing the north-south movement of the monsoon weather zones during the twelve months of the year. The semiarid area lies between the two dotted lines. An arbitrary distinction is made between zones of scattered showers ($\dot{\nabla}$) and thunderstorms (☈), of disturbance lines (☈|), and of more continuous rain with overcast (-•-). The time lag relative to the zenithal position of the sun causes maximum northward displacement to occur in August.

Source WMO TECH. NOTE NO. 86

Within the monsoon, on the other hand, the weather as described by the amount (and frequency) of rainfall is determined by the depth of monsoon airmass below the ITD as well as the horizontal surface position of the ITD to the north of the station. In view of the slope of the ITD it is immediately obvious why the distribution of mean annual rainfall is heaviest in the south and declines steadily northwards except where local relief such as the Futa Jalon highlands (Gregory, 1965) distorts the general pattern.

As the depth of the monsoon overlying a given location steadily increases the location subsequently comes to experience different phases of weather, or what Walker (1957) refers to as Weather Zones, (Fig. 15) defined primarily by the variations in atmospheric dryness, amount of land cover, frequency and intensity of rainfall.

The characteristics of the various weather zones (shown in Fig. 7, 15) have been extensively described elsewhere (Hamilton and Archbold, 1945; Garnier, 1967; Walker, 1957, 1960; Trewartha, 1961). We shall therefore merely point out their principal features and show how our suggested model clarifies them (weather zones). Based primarily upon the depth of monsoon under the ITD and on the passage

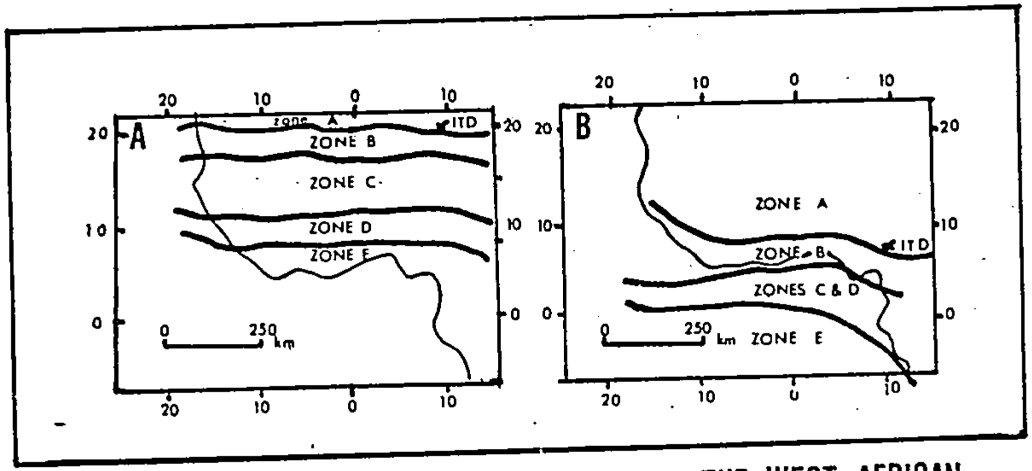


FIG 16 GENERAL LOCATION OF THE WEST AFRICAN 'WEATHER ZONES' IN SUMMER (A); WINTER (B) (After Walker, 1960)

of the DLs as well as the incidence of the monsoon subsidence five weather zones, A-E, may be identified in West Africa. It is clear from Fig. 15 and 16 that the weather types of zone D and E may be experienced only in the southern parts of West Africa, ie. south of about 9°N. (zone E is experienced only in areas to the south of 6°N (Fig. 16)). The Zone A or dry harmattan weather has its southern boundary marked by the farthest southward surface penetration of the dry harmattan air. Being completely under the influence of the dry harmattan airmass, this weather is "dry and rainless" with very little cloud, usually the cirrus type, found at great heights. Occasionally extensive haze caused by the fine dust suspended in the atmosphere may be observed. The absence of clouds and moisture encourage intense, radiative cooling at night, 18-21°C (65-70°F in northern Ghana) but intense warming at the daytime 40-43°C (104-110°F).

Zone B: This weather extends from the Zone A weather through 2-3° southwards, however its exact southern boundary tends to be ill-defined. This weather occurs at the wedge-end of the monsoon so that vertically the bulk of the atmosphere is primarily taken by the dry harmattan aloft. Consequently the weather is mainly dry though relatively more humid than Zone A. Generally speaking, it is a zone of scattered showers , the total rainfall in the month being usually less than 3 inches. Due to the presence of shallow depth of monsoon air at the lower layers of the atmosphere the amount of cloud cover tends to exceed that of Zone A weather as patches of fog of low stratus cloud develop usually at night.

Zone C: is bounded to the north by the Zone B weather and extends through 9-10 degrees (1055 km) to the south where the depth of the monsoon is on the average, betweeen 10-12.000 meters (Fig. 7). This is a zone of scattered showers and thunderstorms and of disturbance lines. The disturbance lines and the thunderstorms are however the most significant features. North of 8°N, ie. in the semi-arid West Africa, over 90% of the mean annual rainfall is accounted for by May to September and by the Zone C weather (Fig. 15 and 16). The depth of the monsoons under the ITD is sufficiently high.(Fig. 7) hence rainfall tends to be heavy, with the monthly total hovering around 127 mm (5 inches). Rainstorms are of high intensities (and are generallv of short duration) due to the influence of the disturbance lines.

Zone D: The zone D weather extends through 3-4 degrees southwards from Zone C. It coincides with the areas of the greatest depth of the monsoon airmass under the ITD. As seen from Fig. 7 the depth of the monsoon everywhere within this weather zone exceeds 4 kilometers reaching even 6 kilometers at the very southern portions of the weather. Within this zone therefore the ITD loses its significance, for all intents and purposes, as a controlling factor on the amount of rainfall received sinceit is then so high that maximum convection is possible within the monsoon airmass. (In our suggested model (fig. 9) therefore the ITD over these regions has been represented by the dashed line instead of the firm line in the B and C Zone. This is to underscore the fact that despite its presence maximum convection of the moist air is possible here). Thus, within the Zone (D) "days with rain are the rule rather than the exception" (Walker 1957). Rainfall also tends to be more prolonged and less intense than in Zone C due to the absence of the DLs. Thus in the coastal regions where it is referred to as "monsoon rain", for example, rain may occur in showers for periods of up to twelve hours and bring substantial amounts.

The most northern extent of the weather zone D is about 8^{O}N in July-August but during the rest of the rainy season the Zone D weather may be experienced only in the southern parts of the region. This situation is due to the fact that the most northern position of the ITD extends only to20-22^{O}N whereas the B and C weather zones extend from the ITD southwards through about 10-12 degrees as indicated above. This then, should clarify why maximum rainfall tend to be situated between 10-13^{O} south of the surface position of the ITD as stated by the various descriptions of the climate and weather of West Africa. These regions (of maximum rainfall) coincide with the areas where the greatest depths of the monsoon airmass under the ITD are to be found. Further south, however, rainfall begins to decline as we shall soon explain. Further northward, too, rainfall again decreases in gradual gradations in accordance with the decreasing slope of the ITD, as we have explained, through the C and B weather zones until a totally dry and rainless harmattan weather is encountered farther to the north, ie. beyond the surface position of the ITD.

ZONE E: This is the most southerly zone of all the weather zones of West Africa. It penetrates a relatively short distance inland even in July and August. The weather is relatively dry and cool with day temperatures in Ghana between 80^{O}F and 85^{O}F and night temperatures about 70^{O}F. This weather zone coincides with the periods

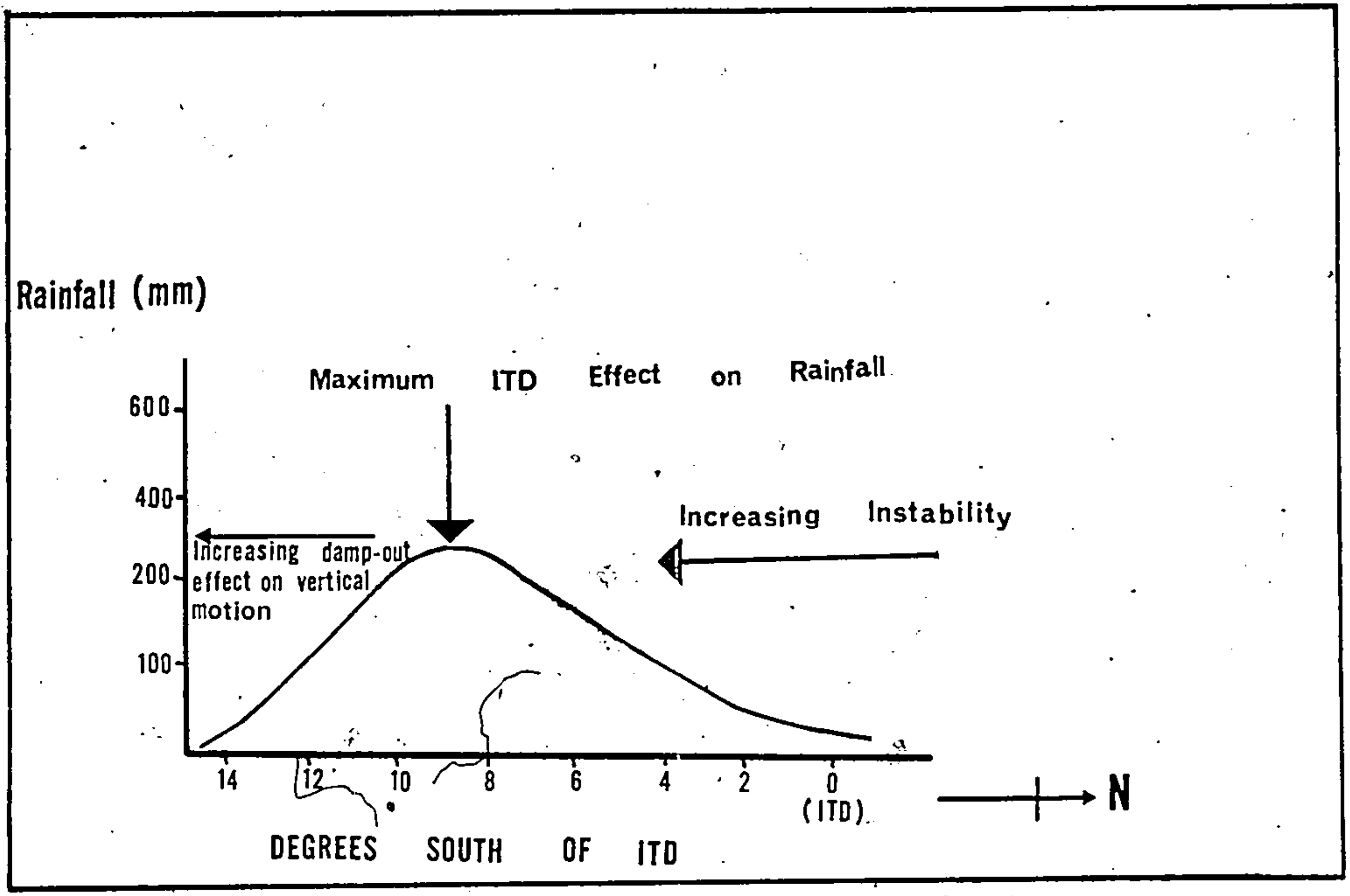


Fig 17 Rainfall distribution over West Africa in August (After Illesanmi,1972)

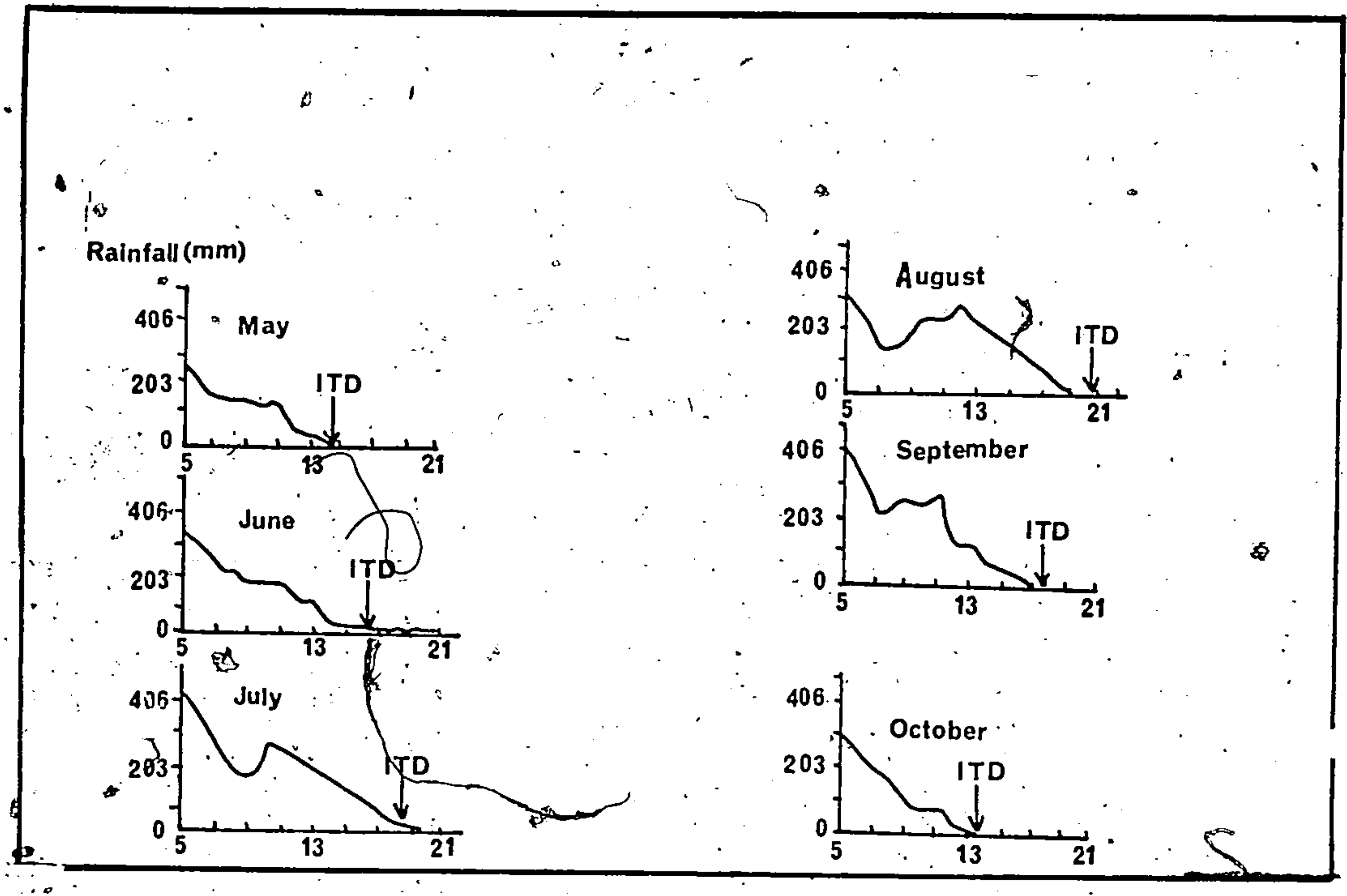


FIG 18 Spatial variation of rainfall in relation to the seasonal movements of the I T D

of July and August when the influence of the subsidence in the monsoon is at its peak. Conceptually, the axis of the subsidence may be said as having been 'pulled' northwards as to make its presence to be felt in the southern (coastal) regions. (Fig 9).

Due to the peculiar nature of this slope, decreases in rainfall in the Zone E weather tend to be greatest toward the equator (Chapter 2).

Summary:

The suggested model is therefore able to rationally explain all the significant features of the normal rainfall (weather) distribution in time and space over West Africa. At any given instant maximum rainfall should be received in 10-13° south of ITD and decrease both to the north and south. (Fig. 17).

In July and August, south of 9°N but particularly south of 6°N, rainfall totals drop sharply as a result of the increasing 'damp-out' effect of the large-scale subsidence on low-level vertical motion during this season. This is the basis of the anomalous situation whereby there is a break in rainfall totals in mid-summer in the presence of abundant moisture and maximum solar energy.

Partial support for this hypothesis attributing the "little dry season" to the intensification of upper-level subsidence within the monsoons may be seen from Fig. 6. It is seen that the mean monthly dew-point temperatures for both of the stations south of 6½°N <u>decline</u> during July-August which means that the atmosphere here was drier. This can only be attributed to the mixing of drier air from higher layers of the atmosphere, or to the drying of the atmosphere as a result of the adiabatic warming of the atmosphere, both of which phenomena should be the result of large-scale subsidence in the affected region (as explained in Chapter 2). It is interesting to note that Navrongo (11°N, 0°W) where the influence of the monsoon subsidence is not felt has higher relative humidities than the more southern stations as the mean dewpoint values indicate.

Hence our model is able to account for all the seasonal and spatial features of rainfall except the presence of the dry equatorial climate which we have deliberately left out of our discussion to date. It is felt that it need be treated separately.

Climatic Regions of West Africa

By a combination of the frequency of the weather zones experienced across the region three main broad climatic types may be identified in West Africa. The <u>Sahel Climate</u> north of 15-17°N is basically composed of the A and B weather zones (though the very southern parts receive small amounts of the C weather).

The semi-arid climate (comprising the Sudan and Guinea Savannah's) and lying between 8-15^{O}N consists of A, B and C weather zones. A and B weather constitutes the DRY season and C. the WET season.

The Humid Tropical climate experiences all of the five weather zones. Two very distinct seasons the dry and humid seasons, may be identified (See Fig. 3, 15, 19) but the dry season tends to be short. Besides the Wet Season (C.D,E) is such that there is sufficient moisture for greater part of the year. This climate is thus generally characterised as a Wet climate (Fig. 19).

The Anomalous Dry Equatorial Climate

As early as 1957 Walker (1957), writing for the Ghana Meteorological Services Department attempted to rationalize the existence of this climatic region outside the framework of the ITCZ model. Trewartha (1962) endorsed Walker's argument suggesting that the real causes of the aridity of this area are: "(1) the winds are parallel to the shore so that frictional divergence occurs; (2) there is a cool pool or current of water in the region, an idea borne out by the lower August temperatures here than along the rest of the Guinea Coast."

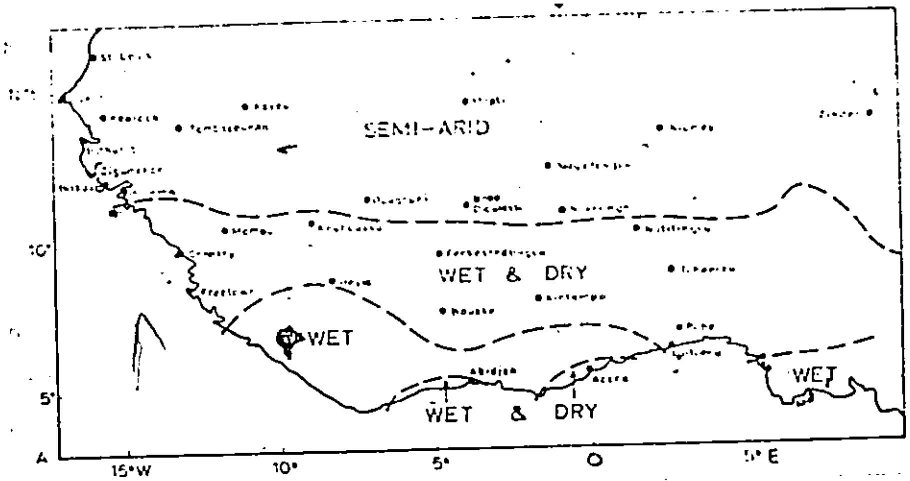


FIG 19 CLIMATIC REGIONS OF WEST AFRICA

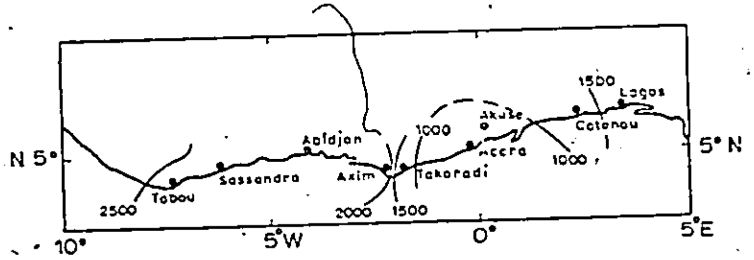


FIG 20 Mean annual isohyets (mm) along the coast of central west Africa.

source Griffiths (1962)

Rejecting the assumption about the direction of winds in relation to the reduced mean annual rainfall, Dickson and Benneh (1972) have pointed out that winds are generally onshore everywhere along the coast of Ghana.

As to the argument about the presence of cold water and the upwelling of cold currents may be disputed as follows. From Dankwa 's (1974) rainfall distribution maps of Ghana and Griffith's (1972) map of mean annual isohyets along the coast of central West Africa (Fig. 15) it is seen that the Accra plains, the dryest part of Ghana, receive only about a third of the mean annual rainfall total at the adjacent areas to the east and west. If we are to attribute such a drastic (67%) decline in mean annual rainfall to the existence of a cold body of water then the water temperature would be expected to be sufficiently low as to drastically reflect in the temperatures of the stations in the coastal dry belt. Yet temperatures throughout Ghana are virtually the same (Dickson and Benneh, 1970). (Fig. 12) It's evidently on this realization that prevented Walker (1957) himself to press this explanation any further and to concede that this explanation 'is less likely' (Walker, 1957 p. 7)

Indeed as Dickson and Benneh pointed out, none of the explanations offered [illegible] account for the Accra Plains is entirely satisfactory. As a temporary solution to the problem, therefore, this dry belt was merely branded "anomalous" and left to stand as if it were beyond rational explanation.

Within the framework of our suggested model we have hypothesised that the dry equatorial climate of the Accra plains could be the consequence of above normal subsidence. In other words it is caused by subsidence. . . . We are, in effect saying by this that no climatic region nor season in West Africa is anomalous to the circumstances of the circulation patterns and structure of the region's atmosphere.

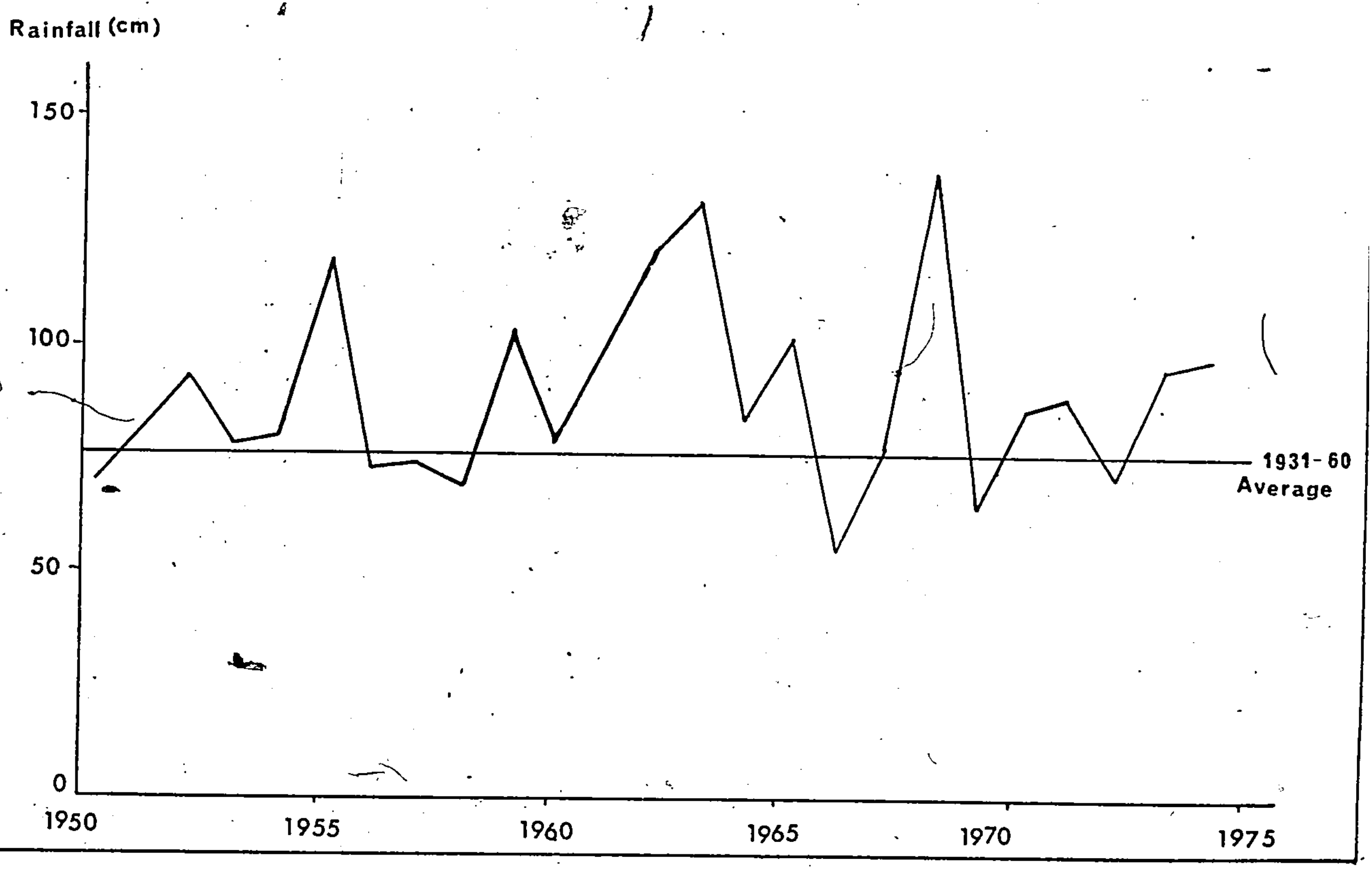
CHAPTER FIVE

A FINAL TEST OF THE MODEL

The purpose of the preceding chapter was to demonstrate the validity of our suggested model by using it to explain the normal spatial distribution patterns of weather in West Africa as well as the variation or zonation of the weather as the whole system migrates across the region. By that we have been able to confirm our first operational hypothesis that every significant feature of weather is explainable in terms of the circulation of the region, which led us to our conclusion that no climatic region nor season in West Africa could be said to be anamalous. But more important perhaps, from the point of view of making some contribution to the climatology of the region is our inferential statement that the Dry Equatorial Climate (otherwise referred to as the "Accra Plains" climate) should be due to the presence of above-average subsidence.

In this final chapter we shall complete our efforts to establish the validity of the model by examining the second of our fundamental hypotheses (see pp. 4, 5) namely that abnormal southward shift of the main features represented by our model would generate drought in the Sahelian Zone but increased

Fig21: MEAN ANNUAL RAINFALL DISTRIBUTION, ACCRA (1950– 1974)



rainfall in the very southern margins of West Africa. (Fig 21).
The method of analysis and the rationale behind this method have already been described in chapter one. We shall thus only present our results here.

Table 5 provides the mean monthly and annual rainfall data of some 18 stations in Ghana. Table 6 gives the mean rainfall distribution of these same stations for the 1961-74 period, whilst Table 7 represents the mean 1961-74 rainfall totals expressed as a percentage of the 1931-60 means. The map of the percentage change in the mean annual rainfall (Fig. 22) shows that our expectations are largely supported by the analysis. It is seen that over a greater part of the country to the north, the mean annual rainfall showed deficits in the range of about 2%. From these regions, of rather low net deficits, the magnitude of the negative change in the mean annual rainfall increased farther northwards, to the Sahelian Zone where really large deficits occured to constitute the Sahelian drought. The lower absolute values of the negative change index in northern Ghana is thus to be expected since the net deficits should steadily decline from the main center of the drought in the Sahel southwards to areas with zero deficits (index of 100%) where no change was experienced during the time of the shifts. Further south from these areas, then, positive changes should be observed, as seen from our map.

The negative change over Ghana however shows that the Sahelian drought extended farther to the south (affecting the whole of the Sudan and Guinea Savanas), than it has ever been recognized.

The 100% index of the mean annual rainfall (the thickened isoline on Fig.22) runs through southern Ghana southwest from around Half Assini to the northeast through Ho. To the south and southeast of this isoline, i.e. towards the equator, positive changes are observed reaching as high a magnitude as 130% which implies an increase in rainfall of as much as one-third of the normal.

At the northeast corner the Gambaga scarp is seen to have distorted the general pattern; a similar distortion is seen in the central part of the country along the Mampong-Scarp. This highland regions were responsible for inducing about 10% more rain than is expected. However, this notwithstanding, the general pattern is largely preserved.

We are primarily concerned with the ITD rainfall. For a more valid picture, therefore, we could exclude the rainfall during the dry season (November - April) from our analysis since rainfall in the dry season

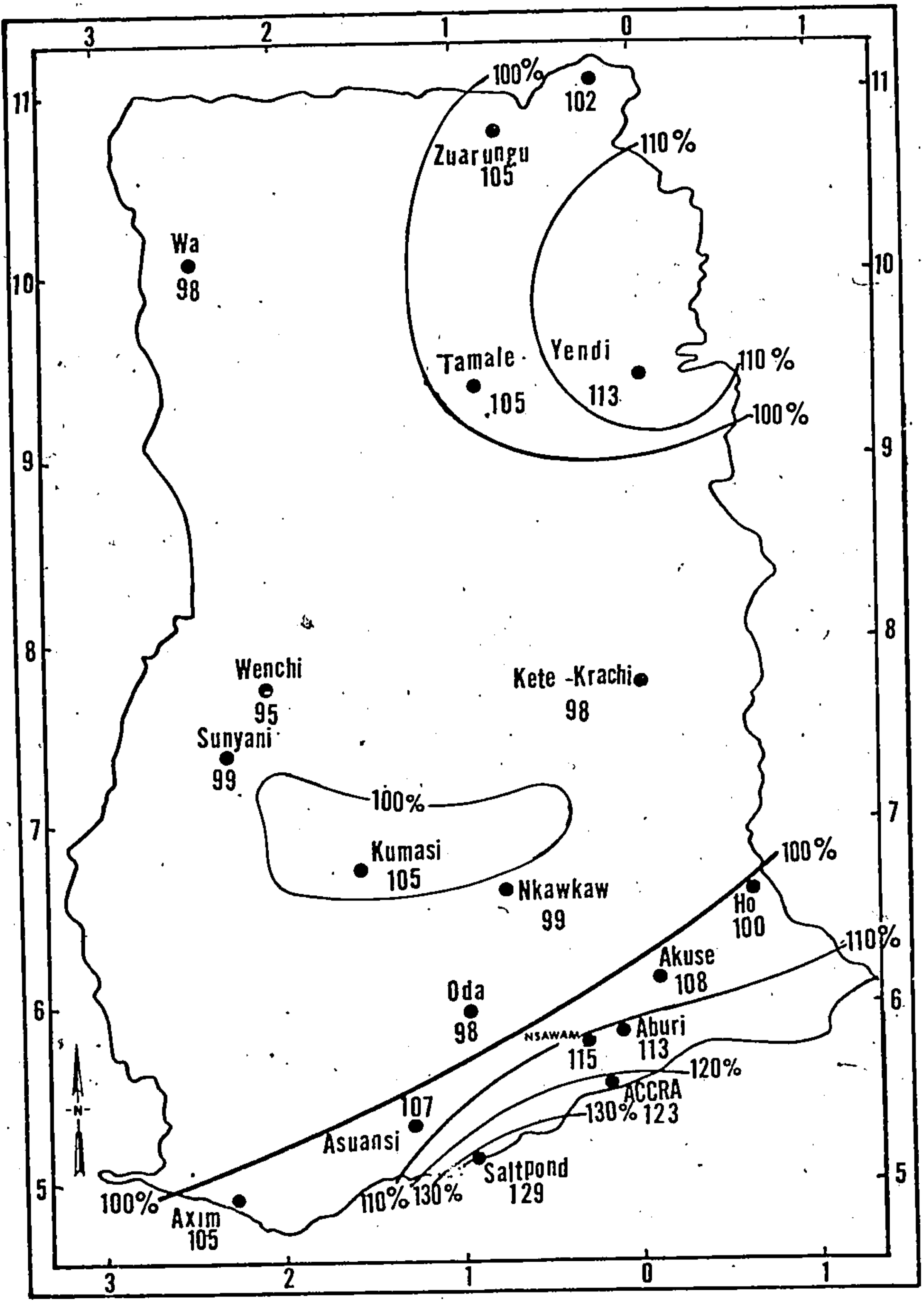


Fig 22 Index of climatic variation (in %) in Ghana during the 1961 – 74 period as measured by the net variation in the normal mean annual rainfall

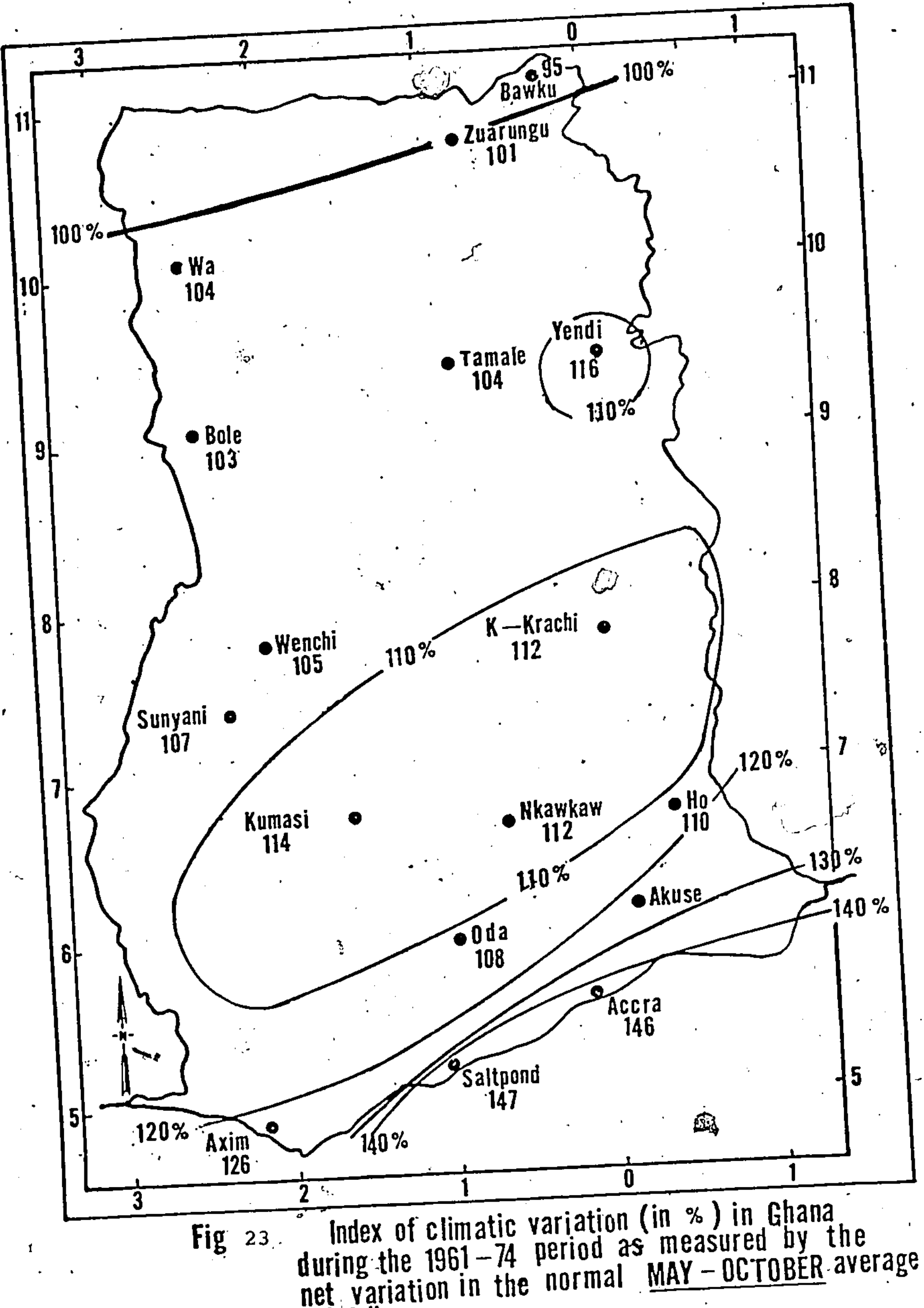


Fig 23. Index of climatic variation (in %) in Ghana during the 1961 – 74 period as measured by the net variation in the normal MAY – OCTOBER average rainfall.

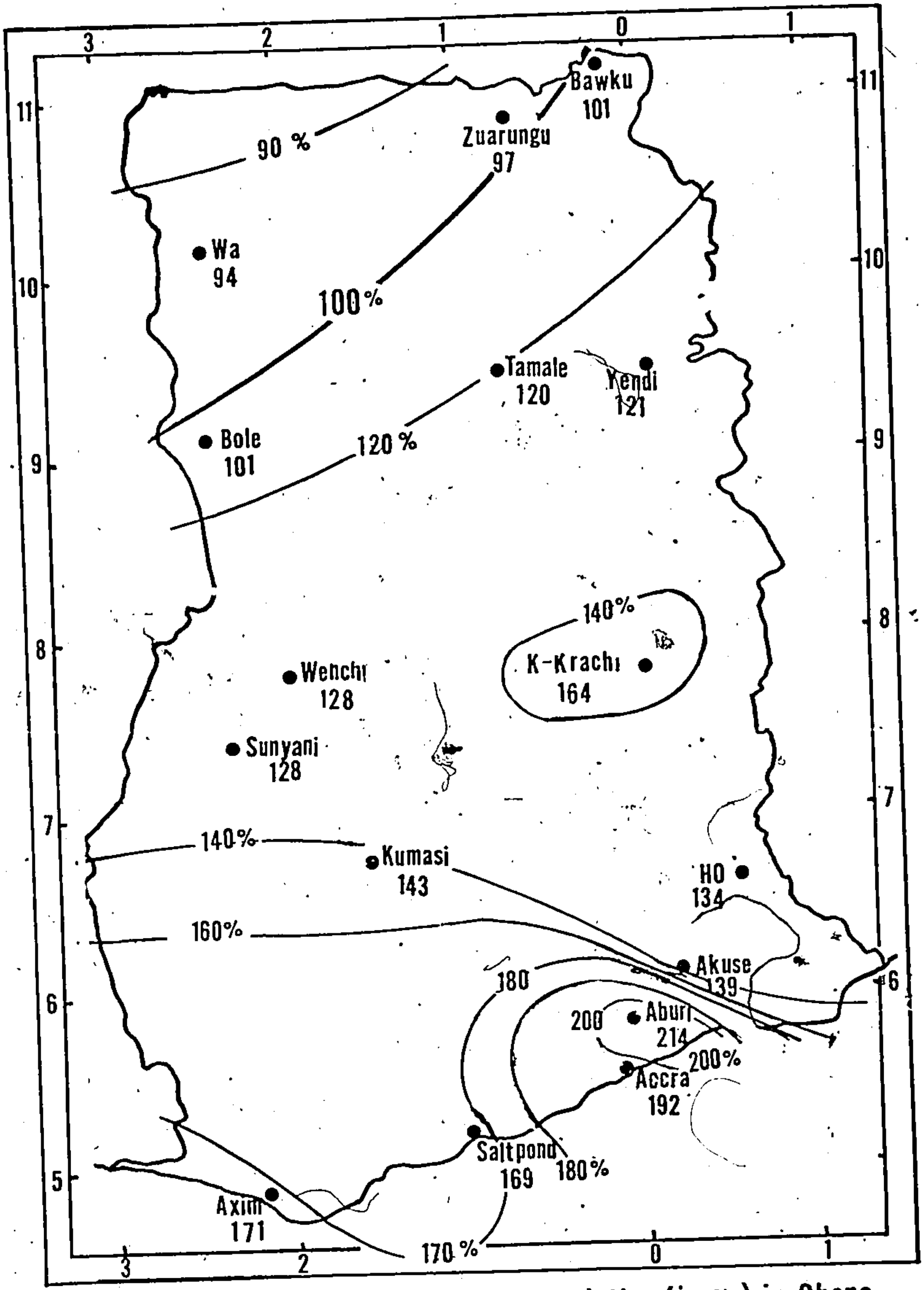


Fig 24 · Index of climatic variation (in %) in Ghana during the 1961–74 period as measured by the net variation in the normal mean August rainfall is not necessarily due to the influence of the ITD but may be due to other factors (Illesanmi, 1971). Fig. 23 shows the average change for the rainy season (May to October). It is seen that the expectations of the model are more clearly portrayed as the local relief effects in distorting the areal pattern, which aremore apparent during the dry season, are now eliminated.

It will also be observed that the 100% index which marks the limit of the Sahelian drought was again running from the southwest to the northeast and it was still as far south as 11°N. Northern Ghana is seen to have experienced some gain in rainfall of generally less than 5% so that for all intents and purposes this region could be regarded as having experienced no change in rainfall during the time of the shift. The main areas where substantial positive changes occured are to the south of 7°N, or thereabout. Here the indices of net rainfall are as large as 140% which represent an increase in rainfall in the recent period of nearly 50% over the 1931-60 normals. Thus, the net percentage change in both the mean annual rainfall, but particularly during the rainy season, sufficiently confirm the validity of our suggested model.

It has also been shown from the nature of the model that an abnormal southward shift in the model should result in decreased intensity of the monsoon subsidence as the horizontal divergence at 1.5 km height declines and the 850 mb. ridge contour fails to reach the West African coast. This would thus result in increased rainfall in August particularly in the region of the Accra Plains. The percentage change in August mean monthly rainfall was thus analysed. (Fig. 24)

A look at this map eloquently confirms this fact. It is seen that the greatest increase in rainfall with indices ranging between 140% and 214% occured within this dry belt.

To further bring out this point, the monthly zonal averages were computed for the three rainfall regions of Ghana (Table 10). The zonal average for the dry belt region (Southeast Ghana) was 169% for August.

CHAPTER SIX

CONCLUSION

Simple though this method of analysis may seem to be, we have shown sufficiently well that, in so far as net changes in rainfall are concerned, the hypotheses derived from our model are supported by the rainfall data of Ghana (see Appendix 1). Thus it may be concluded that the recently observed changes in weather and circulation pattern over West-Africa are related to the generally recognized (Lamb, 1972) weakening of the mid-latitude upper-level easterlies. and the resulting southward shift in the general circulation.

Omerod (1976) has attempted to attribute the Sahelian drought to the destruction of vegetation due to the increased cattle (and human) population which has resulted in high surface albedo (and hence, reduced energy for convective activities). However, since he did not present the model he claims to have used to arrive at his conclusions, it is not possible for a thorough evaluation of his work here. It may however be safely affirmed in view of our results, that the Sahalian drought was indeed caused by the shift in the ITD as previously suggested by earlier workers. (Bryson, 1973, for example)

The model also confirms Griffith's observation that the little dry season in July- August is attributable to enhanced subsidence. But more important than that it also attributes the so-called "anomalous" climatic region of the Accra plains also to a locally large degree of subsidence, and thereby shows that no climatic season nor region in West Africa could be said to be anomalous - they are the perfect expression of the characteristic features of the horizontal and vertical components of circulation of the region.

The model, it will be observed, achieves our objective of simplifying the facts about the climatology of the region into a coherent whole for the description and explanation of all the various features of the region's climatology. It's simplistic nature emphasises its great potential as a teaching aid.

That the model is highly "suggestive", to borrow Harvey's (1967) terminology, need not be over emphasised; in fact it does not take much effort for one to notice the very many areas it directs attention of researchers to for further study. For example, the determination of the exact empirical relationship between rainfall amounts and the depth of monsoon under the ITD; the direct measurement of sea temperatures along the Gulf of Guinea to resolve, once and for all, the existence or otherwise of the cold body of water here, the intensity of the coldness of this body of cold water (if it actually exists) and the extent to which it inhibits rainfall: the analysis of surface and upper-level weather charts on routine basis during the next decade at the standard contour heights and synoptic hours for the proper confirmation of the existence and nature of the above-surface ridge on the Accra plains; the mean monthly dew-point temperature maps for the whole of the sub-region to enable us to estimate more specifically the rate of movement of the ITD, etc. are seen as aspects of the West African climatology that the model readily isolates for further investigation. As an initial (and original) attempt, then, the proposed three dimensional model is obviously of great value. The student, teacher, and researcher will for a long time find it very useful. We should only hope that these and the many other aspects of the region's climate it isolates for further research would actually be taken up by other workers in order that the model would be improved upon and, ultimately, empirically formulated to allow more precise description and prediction of both the short- and long-term climatic fluctuations of West Africa.

APPENDIX 1

TEST OF SIGNIFICANCE BETWEEN THE 1931-60 ($\bar{x}$), and the 1961-74, ($\bar{y}$), ANNUAL RAINFALL MEANS AT ACCRA, GHANA.

A. 1. 1931-60 mean, $\bar{x} = 31.04$ in (Tandoh S.E., 1973, p. 11)

2. Standard Deviation, $\rho_x = 6.88$ ins. (Tandoh S.E., 1973, p.11)

3. Since $\rho_x = \sqrt{\frac{(x-\bar{x})^2}{n}}$ and n = 30 years,

4. ∴ $(x-\bar{x})^2 = 1420.03$

B. 5. 1961-74 mean, $\bar{y} = 38.03$ in. (from Table 11)

6. $\rho_y = 8.81$ ins. (from Table 11)

7. ∴ $(y-\bar{y})^2 = 1086.80$ from equation 3, and where n = 14

C. 8. The POOLED BEST ESTIMATE of the standard deviation of the populations, ($\hat{\rho}$) may be computed using the formula

$$\hat{\rho} = \sqrt{\left(\frac{(x-\bar{x})^2 + (y-\bar{y})^2}{n_x + n_y - 2}\right)}$$

$$= \sqrt{\frac{(1420.03 + 1086.80)}{42}}$$

$$= \sqrt{59.69} = 7.73$$

(see Hammond & McCullagh, 1974, pp. 162-164)

9. The standard error of the 1931-60 sample

$$SE_{\bar{x}} = \hat{\rho}/\sqrt{n_x} = \sqrt{59.69}/\sqrt{30} = 1.99^{\frac{1}{2}} = \underline{1.41}$$

10. The standard error of the 1961-74 sample

$$SE_{\bar{y}} = \hat{\rho}/\sqrt{n_y} = \sqrt{59.69}/\sqrt{14} = 4.26^{\frac{1}{2}} = \underline{2.06}$$

11. The standard deviation of the sampling distribution of the difference between means (i.e. the standard error of ($\bar{x}-\bar{y}$) is obtained from the formula

$$SE_{(\bar{x}-\bar{Y})} = \sqrt{\{(SE_{\bar{x}})^2 + (SE_{\bar{y}})^2\}}$$

$$= (1.99 + 4.26)^{1/2}$$

$$= (6.25)^{1/2}$$

$$= \underline{2.50}$$

12. ∴ the calculated value of 't' is given by

$$t = \frac{\bar{x}-\bar{y}}{SE_{(\bar{x}-\bar{y})}} = \frac{6.99}{2.50} = \underline{2.80}$$

13. At the 90% confidence level and a degree of freedom equivalent to 42, the Critical Value of 't' is read from the table to be equal to $\underline{t = 2.02}$

14. Since the calculated t is more than 2.02 it follows that the difference between the 1961-74 and 1931-60 means is significant QED.

TABLE 3: DAILY VERTICAL MOTION AT 500 m ($\bar{w}500$, in 10^{-3} m-sec^{-1}) OVER THE NORTH ATLANTIC DURING ATEX

DATE: FEBRUARY	$\bar{w}500(10^{-3}$ m-sec$^{-1})$
7th	-2.4
8th	-2.5
9th	-2.9
10th	-3.7
11th	-3.0
12th	-3.7
13th	-2.0
14th	-4.5
*15th	-0.2
*16th	-1.3
*17th	-0.8
18th	-2.9
19th	-3.0
20th	-0.8

Note that all values fit the time continuity well except for 14 February which appears too large.

SOURCE: Brummer _et_ _al_ (1974)

*when the monsoon trough touched the ATEX region (see discussion in text)

TABLE 4

MEAN MONTHLY AND ANNUAL RAINFALL (mm) ALONG THE WEST AFRICAN COAST

STATION	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	YEAR
Tabou	38	70	100	119	412	579	177	99	198	222	222	117	2,353
Sassandra	25	28	65	102	306	500	122	25	32	78	125	95	1,503
Abidjan	26	42	120	169	366	608	200	34	55	225	188	111	2,144
Axim	41	54	122	157	426	613	147	56	90	205	130	74	2,115
Takoradi	33	25	78	110	278	249	84	41	49	127	63	45	1,182
Accra	16	37	73	82	145	193	49	16	40	80	38	18	787
Akuse	20	41	129	107	167	152	69	32	94	197	115	36	1,159
Cotonou	36	51	104	134	201	338	120	22	82	164	68	19	1,339
Lagos	28	45	102	150	269	458	279	63	140	204	68	25	1,831

Source: Griffiths (1962, p. 226)

TABLE 5

MEAN RAINFALL DISTRIBUTION 1931-1960 AVERAGES

Humid Tropical	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
Axim	2.47	2.50	5.53	6.55	17.99	22.68	5.21	1.99	3.11	9.48	7.10	4.22	88.18
Kumasi	1.00	2.53	5.39	5.49	7.80	8.76	4.45	2.91	6.71	7.91	3.76	1.25	57.46
Nkawkaw	1.21*	2.54	5.02*	6.64	7.83	9.45*	6.28	3.83	8.35	9.79	4.96	1.97	68.41
Oda	1.42	2.94	5.86	6.74	7.61	9.39	4.40	2.65	5.51	7.42	6.56	2.51	63.05
Sunyani	0.51	1.46	4.34	5.97	7.28	7.41	3.66	2.42	7.14	7.91	2.81	0.83	51.69
Wenchi	0.34	1.72	3.94	5.82	6.60	7.64	3.60	2.83	7.68	8.58	3.09	0.86	52.70
Dry Savannas													
Bawku	0.00	0.19	0.51	1.92	3.99	4.56	6.52	9.53	8.36	2.29	0.27	0.05	38.17
Bole	0.19	0.44	1.99	3.58	5.70	5.83	4.86	5.84	8.69	4.00	1.22	0.43	42.77
Kete-Krachi	0.68	1.36	3.32	4.93	6.73	7.69	5.80	5.09	8.95	7.23	2.61	0.99	55.41
Tamale	0.08	0.36	1.99	3.46	4.76	5.20	5.86	7.45	8.55	3.86	0.51	0.18	42.26
Wa	0.11	0.38	1.78	3.17	5.18	5.50	5.27	8.29	8.78	3.16	0.73	0.10	42.41
Yendi	0.07	0.46	1.65	3.58	4.99	5.97	5.94	7.89	9.58	4.97	0.95	0.43	46.48
Zuarunga	0.03	0.17	0.55	1.44	4.50	5.20	6.51	9.66	8.68	2.57	0.38	0.06	39.75
Dry Equatorial													
Aburi	1.14	1.95	4.63	4.90	6.67	6.97	2.85	1.68	3.71	5.47	4.53	1.84	
Accra	0.63	1.47	2.89	3.22	5.75	7.58	1.95	0.62	1.56	3.14	1.51	0.71	31.03
Akuse	1.04	1.89	4.31	4.38	6.93	7.68	2.52	1.45	3.96	5.85	4.65	1.53	46.11
Asuansi													54.27(*)
Nsawam													54.99*
Ho	1.39	2.89	5.59	5.70	7.21	6.98	4.36	3.10	5.89	7.46	3.24	2.05	55.86
Saltpond	0.75	1.12	3.06	3.44	6.68	9.44	2.36	0.89	1.24	3.65	2.93	1.04	36.50

Source: J. B. Dankwa's (1974)

*estimates

TABLE 6

MEAN RAINFALL DISTRIBUTION - 1961-74 AVERAGES

Humid Tropical	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Axim	1.75	3.29	5.53	6.00	10.97	27.58	11.38	3.40	3.54	6.49	6.05	3.00	88.62
Kumasi	0.77	2.66	5.56	5.73	8.14	8.72	7.03	2.91	6.28	6.89	3.66	1.11	60.41
Nkawkaw	0.99	2.19	5.54	6.26	7.66	11.16*	8.01	6.17	8.20	6.94	3.41	1.50	68.02
Oda	1.11	1.98	5.80	7.23	7.39	9.61	5.39	3.66	5.30	7.09	5.13	1.99	61.66
Sunyani	0.23	1.79	5.12	6.10	7.75	8.60	4.62	3.10	5.90	6.43	1.70	0.28	51.60
Wenchi	0.10	1.36	3.76	5.37	7.47	7.32	4.08	3.62	7.00	7.77	1.65	0.82	50.32
Dry Savannas													
Bawku							7.18	9.70	8.14	1.73*	0.07*	0.01	38.77
Bole	0.01	0.52	2.16	4.26	4.96	5.97	7.02	5.92	8.16	4.00	0.95	0.45	45.56
Kete-Krachi	0.32	0.55	2.56	4.46	5 98	6.79	9.09	8.33	9.32	5.19	1.21	0.53	54.32
Tamale	0.13	0.31	2.47	2.98	4.40	6.10	6.07	8.92	9.33	3.03	0.52	0.06	44.32
Wa	0.07	0.47	1.84	3.27	4.78	5.90	7.27	8.08	7.58	2.83	0.43	0.43	41.42
Yendi			2.71	3.23	6.23	7.05	7.64	9.54	10.72	4.41	0.57	0.26	52.66
Zvarungu	0.09	0.64	0.76	2.78	4.16	5.69	7.72	9.39	8.32	2.34	0.18	0.21	41.93
Dry Equatorial													
Aburi	1.02		3.69	5.44	6.00	10.73	4.67	3.60	4.49	5.57	3.96	1.47	52.47
Accra	0.77	1.08	2.85	4.50	4.63	12.62	3.58	1.19	2.95	2.04	1.10	0.72	38.03
Akuse	0.87	1.99	3.56	5.91	6.41	9.69	4.12	2.02	5.50	5.20	3.69	1.01	49.99
Asuansi													57.85
Nsawam													54.99
Ho	1.04	2.08	4.85	5.35	7.44	9.56	5.89	4.16	6.37	5.86	1.76	1.84	56.20
Saltpond	0.83	0.95	2.30	4.85	7.96	16.37	4.15	1.50	1.97	2.94	0.48	1.06	47.25

SOURCE: Ghana Meteorological Services Department
(Hydro Division), Accra, Ghana

TABLE 7

THE 1961-74 MEAN RAINFALL EXPRESSED AS A PERCENTAGE OF THE 1931-60 MEANS

Humid Tropical	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
Axim	71	132	108	92	61	122	218	171	114	68	85	71	101
Kumasi	77	105	103	104	104	100	158	143	94	87	97	90	105
Nkawkaw	82*	86	110*	94	98	117*	127	161	98	71	69	76	99
Oda	78	67	99	107	97	102	122	138	96	95	78	79	98
Sundani	45	123	119	102	106	116	126	128	83	81	61	34	100
Wenchi	29	79	96	92	113	96	113	128	91	91	53	96	95
Dry Savannas													
Bawku							105	102	97	75	26*	29*	102
Bole	6	119	109	119	87	102	144	101	94	117	78	103	107
Kete-Krachi	47	41	77	91	89	88	157	164	104	72	46	53	98
Tamale	161	87	124	86	92	117	104	120	109	79	102	33	105
Wa	66	122	106	103	92	107	138	97	86	90	58	425	98
Yendi			164	90	125	118	129	121	112	89	60	61	113
Zuarunga	293	374	138	193	93	110	119	97	96	91	47	342	105
Dry Equatorial													
Aburi	90		80	111	90	154	164	214	120	102	87	80	113
Accra	122	74	99	140	81	166	184	192	189	65	73	102	123
Akuse	87	105	83	135	108	126	164	139	139	89	79	66	108
Ho	75	72	87	94	103	137	106	134	134	78	54	90	101
Saltpond	111	85	75	141	119	179	175	169	169	80	16	102	129
Asvansi													107
Nsawam													115

*estimate

TABLE 8

1961-74 MEAN ANNUAL RAINFALL EXPRESSED AS PERCENTAGE OF THE 1931-60 MEANS (also see fig. 16)

STATION	%
Aburi	113
Accra	123
Akuse	108
Axim	101
Bawku	102
Bole	107
Ho	100
Kete-Krachi	98
Kumasi	105
Nkawkaw	99
Oda	98
Saltpond	129
Sunyani	99
Tamale	105
Wa	98
Wenchi	95
Yendi	113
Zuarunga	105
Nsawam	115
Asuansi	107

TABLE 9

AVERAGE PERCENTAGE CHANGE OF RAINFALL DURING THE RAINY SEASON, MAY TO OCTOBER

Station	May	June	July	Aug.	Sept.	Oct.	Average
Aburi	90	154	164	214	120	102	141
Accra	81	166	184	192	189	65	146
Akuse	108	126	164	139	139	89	128
Axim	61	122	218	171	114	68	126
Bawku			105	102	97	75	95
Bole	87	102	144	101	94	117	103
Ho	103	137	106	134	108	78	110
Kete-Krachi	89	88	157	164	104	72	112
Kumasi	104	100	158	143	94	87	114
Nkawkaw	98	117	127	161	98	71	112
Oda	97	102	122	138	96	95	108
Saltpond	119	179	175	169	159	80	147
Sunyani	106	116	126	128	83	81	107
Tamale	92	117	104	120	109	79	104
Wa	92	107	138	97	86	90	102
Wenchi	113	96	113	128	91	91	105
Yendi	125	118	129	121	112	89	116
Zuarungu	93	110	119	97	96	91	101

TABLE 10

AVERAGE WET-SEASON MONTHLY RAINFALL FOR THE
1961-74 EXPRESSED AS A PERCENTAGE OF THE
1931-60 NORMALS FOR THE MAIN CLIMATIC ZONES

Climatic Region	Climatic Type	Mean Monthly Percentage Change					
		May	June	July	Aug	Sept.	Oct.
Northern Ghana	Savanna	96	107	128	114	100	90
S. E. Ghana	Dry Equatorial	100	152	158	169	143	83
S. W. Ghana	Humid Tropical	96	107	147	142	96	83

TABLE 11: MEAN ANNUAL RAINFALL (1950-60 and 1961-74)

1950	27.83	1961	40.38
1951	32.78	1962	48.40
1952	36.40	1963	53.12
1953	31.31	1964	34.08
1954	32.05	1965	41.47
1955	47.12	1966	22.61
1956	29.49	1967	31.94
1957	29.69	1968	55.68
1958	27.84	1969	26.25
1959	41.26	1970	35.18
1960	32.10	1971	36.18
		1972	29.14
		1973	38.60
		1974	39.30

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