MOISTURE CONDITIONS IN THE SAVANNA REGION OF WEST AFRICA

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ABSTRACT

This thesis examines the moisture conditions of the West African savanna from a climatic viewpoint. A literature survey established the extent of an "agreed" savanna area the moisture characteristics of which were investigated against a background of the region's climatology. Analytical procedures involved examining precipitation, the water balance, and atmospheric humidity at both the monthly and daily levels. The monthly investigations suggest that the savanna region is distinguished primarily in terms of wet and dry season contrasts and in the length, rather than the character, of the wet season. However, the analysis of daily conditions showed the savanna to differ markedly from the forest in the water balance of apparently similar rainfall days. These differences can be attributed to differences in the basic atmospheric conditions of the two areas and emphasise the importance of a detailed, climatological approach to the ecological appraisal of moisture conditions in the area.

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CHAPTER ONE

INTRODUCTION

The term savanna probably had its origin in Central America as a Carib word for marshes, scrublands, or any other area not covered with forests but consisting mainly of grassy plains (Richards, 1952). This origin of the term is reflected in general current usage in that "savanna" is widely used to describe particular aspects of tropical vegetation. Savanna vegetation is thus held to constitute a tropical plant community in which grasses and sedges dominate (Eyre, 1963), but in which the presence of various types of woody covering to this herbaceous undergrowth is recognised by the frequent use of terms such as "forest savanna", "woodland savanna", and "shrubby savanna", the shrubs being thorny or not.

Although savanna is most commonly used as a vegetative term, there is a tendency in some texts to attach it as an adjective to some other aspect of the environment. Thus, standard works such as "Physical Elements of Geography" by Finch, Trewartha, Hammond, and Robinson (1957), and Harrison Church's "West Africa" (Harrison Church, 1952), for example, contain maps depicting "savanna climates" and offer accounts of the character of such climates in the written part of their texts. Among geomorphologists too one finds reference to landscapes typical of savanna conditions. Thus, in Cotton's "Climatic Accidents", we read that the inselberg landscapes with their levelled smooth intermont plains are typical of the savanna and that such landscapes are "characterised by an alternation of wet with rather long dry seasons in which high temperatures occur; so that vegetation is scanty except along water courses. This is savanna climate." (Cotton, 1942, p. 90).

Despite such occasional uses of the word savanna, however, the expression remains basically a vegetative term which can be aptly summarised in Kimble's words as botanically consisting of "grasses, bushes and trees adapted to conditions of alternating wetness and dryness" (Kimble, 1960, p. 236).

Numerous writers have grouped this collection of "grasses, bushes and trees" into three categories on the basis of the height, closeness, and type of grass cover found (Molard, 1956; Keay, 1959; Church, 1952; Richards, 1952; Brian Hopkins, 1965; McGill University Savanna Research Project, 1962). Within these basic categories the amount of tree cover varies and an imperceptible grading from one vegetation sub-group to another is recognised, since clear distinctions in structure or species in the vegetation formations are absent. Shantz and Marbut, for example, in their study of the Vegetation and Soils of Africa (Shantz and Marbut, 1923) speak of "High grass, low tree savanna", "Acacia tall grass savanna", and "savanna comprising desert grasses with a scattering of small thorny bushes or trees covering the land."

The presence of woody species in most, if not all, types of savanna means that the term "savanna" used in its widest sense can also be thought of as applying to a variety of woody vegetation communities ranging from open bush at one end of the scale to woodland with a complete but light canopy of foliage at the other. These woody vegetation communities differ from a forest community because of the predominance of grass in the undergrowth and because of the absence of under-stories of other grasses or bushes. There may be evergreen or deciduous trees in the savanna (Michaelmore, 1939) and most of them display xeromorphic characteristics. Moreover, in almost any savanna region covered by savanna there are likely to be some components of other formations, like galeria forests, and forest mosaics (Hills, 1965(a)). Indeed, Clements (1949) considers that there are, in fact, only two major stable vegetation formations in the tropical world - the tropical rain forests and the hot deserts - and that the unstable ecotone between them is known as the "savanna". Although this may be thought a somewhat imprecise description of savanna, it does nevertheless make clear what seems to be a widespread recognition of this type of vegetation as being something less than tropical rain forests but more than what vegetation the deserts support.

Extent of the savanna

It has been estimated (Budowski, 1956) that about seven million square miles of the earth's surface are covered by savanna. This is a million square miles greater than the area of tropical rain forests and deciduous (monsoon) forests put together. Major regions of savanna vegetation are present in all the three southern continents, and smaller areas exist in Mexico, Asia and some of the islands lying within the tropics (Fig. 1).

In Africa the savannas extend in a great curve around the forest from the west through central and into south Africa. It is only in this continent that the savannas have such a vast and uninterrupted spread. Particularly notable are the Sahēlinne, Soudanaise and Guinēene belts stretching from east to west in West Africa, across the continent north of the equator from approximately 35°E to 15°W, with a small southward extension that reaches the coast in southern Ghana. Considerable areas of savanna are also found in South America

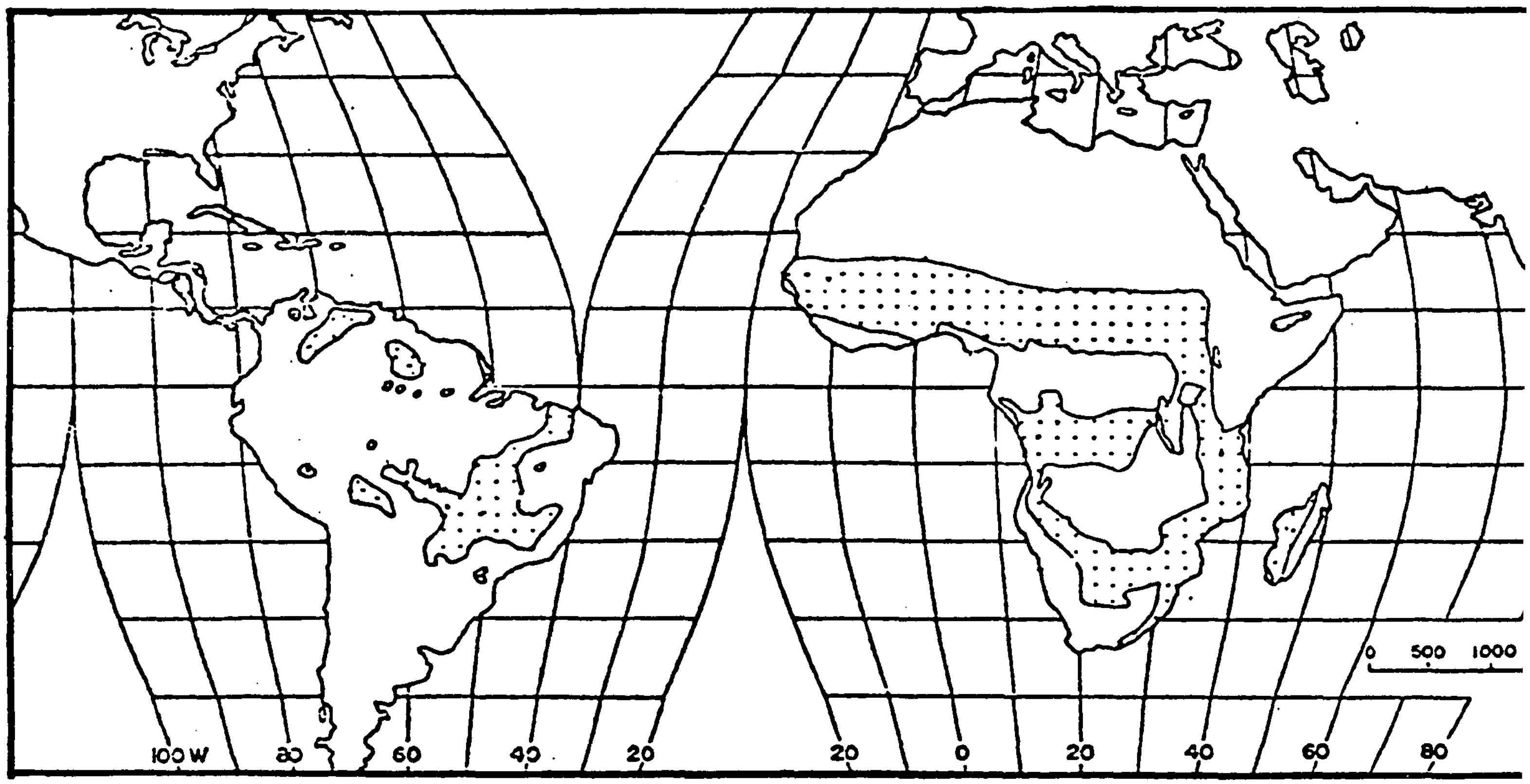

Fig. 1. The World Distribution o
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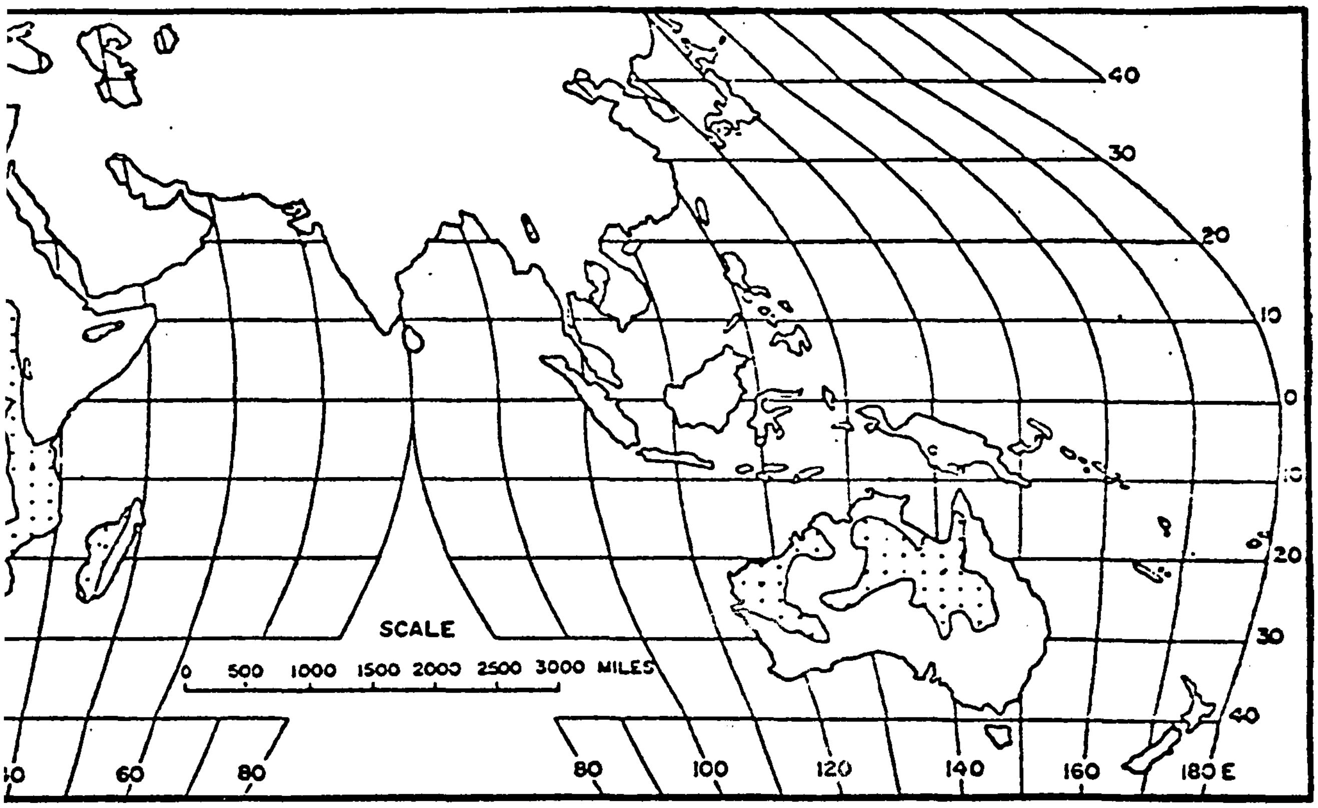


Distribution of the Savanna
from Hills 1965(a)

and Australia, but in both continents the extent is more limited and the distribution more fragmentary than in Africa. The principal areas of savanna in South America are the Pantanal and Planalto Central, which occupy most of Brazil. Other smaller areas are located to the west of Brazil and near the northern coastline of the continent. In Australia two main savanna regions are found as shown in Fig. 1.

Outside these three continents the distribution of savanna is highly localised, being confined to the smaller islands, to mountain tops, to level plains and to a few other areas suitable for such vegetation formations.

Savanna characteristics

According to Kuchler (Kuchler, 1951) there are four basic themes in the classification of vegetation: (1) regional, (2) physiognomic, (3) floristic, and (4) ecological. Of these the physiognomic and floristic approach are the two which concern themselves with plant characteristics per se without reference to potentially causal factors. Both these approaches have been used by different workers to establish the distinctive characteristics of the savanna.

The physiognomic approach uses the appearance of plants as a basis for differentiation of vegetation groups. This "appearance" may be considered in terms of the character of individual plants so as to distinguish between woody and herbaceous plants or tall and short plants for example, or one may consider "appearance" in terms of plant density and spacing (Kuchler, 1947). Such an approach has been used in respect to savanna vegetation by several writers, notably Aubréville (1949), Beard (1944), Schimper (1903), Warming (1909), and Richards, Tansley and Watts (1939).

In his study of tropical Africa, for example, Aubréville (1949, p. 256) classifies the vegetation by giving first importance to the density of vegetation cover, distinguishing between closed formations (formations fermées) and open formations (formations ouvertes). This yields contrasts in undergrowth. In the closed formation the soil is bare or has woody undergrowth (sous-bois composé surtout de végétaux ligneux), whereas in the open formation the soil has been invaded by grassland (une prairie de graminae). This open formation, according to Aubréville, has been given the name "savanna" in tropical regions. In areas where grass vegetation is rather sparse among a very open woody plant formation, Aubréville uses woody steppe (la steppe boisée) to describe the vegetation character.

The second descriptive physiognomic aspect used by Aubréville is the height of the woody plants, whereby he recognises different grades of forest or savanna: "une forêt sèche dense", "la forêt claire", "la savane boisée", and "la savane arbustive". Among these formations, "une forêt sèche dense" includes more or less continuous forest of relatively tall trees and a close undergrowth of woody shrubs (sous-bois arbustif). The "forêt claire" by contrast is more open, but nevertheless has relatively tall trees. There is a plentiful growth of grass in the undergrowth which distinguishes it from the "forêt sèche", where the grass cover is less, but where the coverage of trees is nevertheless sufficiently extensive to give the appearance of a forest. The wooded savanna (la savane boisée) differs from the three principal forest types in that the trees are shorter, many of them appearing stunted (rabougris), and the grassland is dense.

Floristic approaches to vegetation description analyse plants taxonomically (Kuchler, 1957). Such an approach does not appear to have been as widely used as the physiognomic one in the study of savanna characteristics but does, nevertheless, enter into a number of descriptions of vegetation character. Richards (Richards, 1952), for example, shows how the savanna of West Africa is distinguished in its sub-types by the dominance of a given species: Daniella oliveri and Khaya grandifoliola in the southern Guinean savanna; Isoberlinia doka, Monotes kerstingii, and Khaya senegalensis in the northern Guinean type of savanna; Adansonia digitata (baobab) and Lannea microcarpa in the Sudan savanna and species of Acacia in the Sahel savanna zone. Similarly, Aubréville lists and brings out the differentiation of species into his vegetation regions, even though he has given first place to physiognomy as a basis of description.

Causes of the savanna

It is generally observed that the plants individually or as communities forming the savanna display, show characteristics reflecting lack of moisture to some degree or another. The principal plants listed as being distinctive of the savanna have xeromorphic characteristics and portray varying drought resistance qualities. Physiognomically, the reduced size of the woody plants of the savanna compared with those of the forest, together with their wider spacing, point to the same conclusion that moisture characteristics, in some form or other, constitute an important element in the savanna ecosystem.

It is not surprising, therefore, that considerable attention has been given to the moisture element in works devoted to analysing and explaining the character and distribution of the savannas. In considering moisture in such a context, it must be recalled that water occurs in more than one form in the environment - in surface bodies as lakes and rivers, in sub-soil reservoirs, and also as precipitation. In the context of vegetation growth and requirements, the water in the soil is of great importance as it acts as a reserve for the future use of plants and controls the soil moisture character which is of such vital importance to plants as a factor in their growth. However, this important source of regulated water supply is, in the final analysis, controlled by the climatic element of precipitation. Many writers, therefore, realising this have examined it in terms of annual and monthly totals, seasonal distribution and the contrasts between the wet and the dry seasons.

Of the above-mentioned three precipitation categories, the seasonal distribution in particular, with extreme periods of excess water on the one hand and water deficit on the other, is regarded as having a profound effect on the characteristic landscape and vegetation of the savannas. Indeed, Aubréville (1949) in his summary of vegetation regions and their character in Africa relates vegetation types of Africa closely to the character and seasonality of precipitation. The wooded savanna, for instance, is considered as being related to a climate in which there are at least three dry months and seven or eight very wet months, whereas steppe formations (formations steppiques) exist under the influence of a long dry season and not more than three very wet months. Other writers have followed similar lines, either using precipitation directly or else considering it in terms of the water balance and of periods of water surplus and deficit during the year. Thus, Thornthwaite (1952) considers grassland climate to be marked "by a specific balance between moisture surplus and deficit which result as periods of very dry or moist soil conditions during the year" (Thornthwaite, 1952, p. 14).

Precipitation, however, only reaches plants through the soil. The nature of the surface, therefore, enters importantly into moisture as an element of the plant environment. This has given rise to a view of savanna causation from the standpoint of geomorphology and pedology.

Geomorphological studies of savanna regions suggest that they usually occur up to an elevation of 5,000 ft. and occasionally at higher altitudes (Hills, 1965(a)). Generally speaking, the land consists of smooth plains with wet season flooding or very wet conditions. Typical "inselberg landscapes" are often found. These consist of undulating topography dotted with the remnants of resistant rocks known as inselbergs (Cotton, 1961). Likewise, Tricart and Cailleux (quoted in Hills, 1965(a)) consider that the savanna landscapes are partial relict assemblages developed mainly by pediplanation in earlier semi-arid episodes which affected the equatorial regions.

However, whatever the cause, the flatness of the land surface and the importance of contrasting seasonal water relations appear to be the two principal elements dominating the "geomorphological landscape" associated with savanna vegetation. Thus, Cole related the distribution of "woodland savanna" to "pediplaned surfaces developed in the Tertiary and Pleistocene" on which, however, "water relations are vital" (Hills, 1965(a) p. 222).

The pedological approach to savanna vegetation characteristics is to examine the areas involved in terms of their soil fertility and drainage conditions. In comparison with soils of forest regions, the soils of the savanna are marked by an absence of humus and the formation of surface crusts through capillary action in the dry season (Waibel, 1948). In the forest, a closed nutrient cycle maintains a delicate equilibrium, whereas in the savanna the thin cover of vegetation enables serious soil erosion to take place (Mohr and van Baren, 1954; Richards, 1952). Moreover, the regular dry season burning of savanna soils does not enhance this fertility as only a few inches of the top soil are benefited. Mohr and van Baren (1954) have demonstrated that there is a difference in the moisture relationships in the top layers of soil between the forest and savanna. The friable nature of soil in the latter area and the readiness with which the grassy vegetation burns, contribute to the rapid dessication of the top soil after brief exposure to the atmosphere, whereas the forest soils take longer to dry out.

Another characteristic of savanna soils is the development of hardpans in association with the process of laterisation. This factor not only limits the depth of root penetration but also encourages the horizontal flow of water and strongly restricts the accumulation of water for use in the dry season (Bonazzi, 1968). Poor drainage, compact soils, and hardpans thus make for a difficult regime of moisture in the soil. Soil influences are, therefore, often invoked as a primary cause of the distribution and character of the savanna vegetation and the "soil climate", particularly in respect to its moisture characteristics, claimed as superseding in importance the atmospheric situation.

It is noteworthy that most studies of the savannas have tried both to describe and to explain the existence of the vegetation, and in trying to do so have tended to examine boundary situations. Particular attention has been paid to the forest/savanna boundary, and an excellent review of the contributions made by representatives of various disciplines on this subject is to be found in the Proceedings of the I.G.U. Symposium (Venezuela, 1964) of the Humid Tropics Commission on the ecology of the forest/savanna boundary (Hills and Randall, 1968).

A striking feature of the forest/savanna boundary is its sharpness over many areas. "The savanna forest boundary in West Africa is one of its most remarkable geographical features. The clarity with which the boundary is defined, whether from the air, or from the ground level, is throughout most of its length most striking." (Morgan and Moss, 1965, p. 286).

This sharpness is both intriguing and problematical. It raises the problem as to whether the forest/savanna boundary, and, therefore, the causes of the savanna can really be explained in terms of the physical environment. In particular it is difficult to see how so clearly marked a transition can possibly be climatically induced, for, in nature, abrupt changes in this condition are absent. Sharp changes in the underlying geological and soil character could, however, occur and so the nature of the forest/savanna boundary reinforces the view that the key to savanna distribution may lie in surface characteristics. However, its abruptness also opens up the possibility that a major factor which operates in the forest/savanna boundary lies in human interference. Thus, there is an important school of thought which centres on man as the major cause of much of the savanna. The particular expression of this is thought to be through the effects he has produced by repeated burning, shifting cultivation and grazing (Aubréville, 1949; Gourou, 1961; Waddell, 1963; Richards, 1952).

An approach different from any of those which have been briefly surveyed has recently been made by Van der Hammen (1968) who used the evidence of pollen analysis and carbon dating. Experiments were conducted using six cores from lakes within the Llanos Orientales. The results indicated that in the earlier part of the sub-boreal period the vegetation was that of open savanna but later, when the climate became wetter, the vegetation changed to woodland savanna or dry forest with *Byrsonima* extending up to the lake area. At the beginning of the sub-Atlantic period the character of increasing moisture was maintained but fires reduced the woodland vegetation to open savanna around the lake and since then, with the continued influence of man, the open savanna has spread to its present widespread locations. Thus, climatic change, rather than existing climatic character, has been injected as a further element into the whole controversial picture.

Contribution of this thesis

It will be clear from the foregoing brief survey of views concerning the causes of savanna vegetation that conflicting opinions exist. Some people emphasize the anthropic factor, especially the role of fire, while others consider the moisture element as a dominating force, either directly in terms of climate or through a combination of climatic, hydrologic and soil conditions (Eyre, 1963). In spite of these diverse opinions it appears to be commonly agreed that the moisture factor is extremely important: the arguments tend to centre upon the cause of moisture conditions and their expression, rather than upon the importance of the element itself.

This thesis attempts to offer its contribution to the controversy by trying to evaluate the moisture character of one of the world's major savanna regions - that of West Africa - in climatic terms. In attempting this, the emphasis will not be laid upon the savanna boundary and the differences across it, but the study will stress conditions within the savanna region in contrast to those outside. For this purpose, those areas will be established which have been studied in West Africa and about which all agree to be savanna as opposed to areas which are either clearly not savanna or about which some doubt exists because the savanna characteristics are either derived or mixed in with some other vegetation form. The moisture element within the different regions will then be examined. In this way it is hoped to show what kind of moisture differences, in a climatic sense, in fact exist between savanna and non-savanna areas, without being troubled by boundary problems, the particularities of which must clearly be due finally to non-climatic factors. However, one cannot have a basis for judging the relative importance of climate in comparison with the factors of surface and human activity, unless one has an idea of just how different "savanna climates" are from neighbouring ones. To get at this difference we must not be led astray by boundaries since climatic differences in their immediate vicinity are necessarily indeterminate. West Africa has been chosen for this sample analysis, firstly because here is one of the world's major savanna regions lying between forest to the south and desert to the north, and secondly because data on both vegetation and climate are readily available. Thus it provides a useful test area for the viewpoint on which this thesis is based.

CHAPTER TWO

THE SAVANNA REGION

For the purposes of the present study, West Africa has been defined as that part of Africa which lies west of 15°E longitude and south of 20°N latitude. This vast area of land stretching 1,200 miles north to south and 2,000 miles east to west has broad but simple physical and structural characteristics, which are in turn reflected in the large-scale zonation of the general environment.

Physical basis

West Africa's physical landscape bears the mark of age - a feature characteristic of the African continent. The region forms part of an ancient Gondwana shield, overlain by sedimentary deposits which themselves date mainly from early Paleozoic times (Strahler, 1954). Thus, old pre-Cambrian igneous and metamorphic base rocks are overlain by extensive sediments, largely Ordovician and Devonian in age, forming vast sandstone plateaux and tablelands. Younger sediments are mainly confined to coastal regions. Lower Cretaceous deposits, for example, are frequently encountered along the coast from Senegal to Nigeria, while in Ghana, near the coast, some early Mesozoic sediments have been faulted into pre-Cambrian base rocks (Morgan and Pugh, 1969). Younger material comprising marine sediments of Tertiary age, is practically confined to narrower coastal belts, with a particular widening in southern Nigeria where subsidence near the Niger Delta has resulted in the accumulation of thousands of feet of sediment (Morgan and Pugh, 1969).

There is little evidence of volcanic activity in West Africa. What exists is virtually confined to the east, more specifically eastern Nigeria and the Cameroons. Here Mt. Cameroon, rising 13,350 ft. above sea level and the highest mountain in West Africa, erupted in 1959, but most of the other volcanic sources ceased to be active in Tertiary or Quarternary times.

Mountain chains are conspicuously absent in West Africa. Notable highland areas are restricted to the Futa Jallon (4,000 ft.), the Nimba mountains on the Liberian, Guinea and Ivory Coast frontier rising to 6,083 ft., and the Jos Plateau, with a general elevation of 4,000 ft. and a summit height of 6,000 ft. (Fig. 2). In the east the Cameroon highlands are dominated by Mt. Cameroon (13,350 ft.). Except for the volcanic region represented by the latter mountainous area, these highland areas constitute relics of the ancient base rock that have withstood the levelling influences of weathering and erosion. They are not, therefore, parts of a mountain chain but represent only small, relatively elevated, relics of ancient land-forms and do not form barrier-like features affecting the large-scale characteristics of other conditions.

These basic geological conditions are reflected in the outstanding feature of West African physical landscapes: the presence of vast plains generally 2,000 ft. to 2,500 ft. above sea level. In some cases, these plains are formed by deposits over young surfaces and in others they are erosional features across older sediments. They are often dotted with isolated steep-sided hills, which rise sharply from the immense, flat area surrounding them (Bernard, 1939). In places in the tableland appear scarped edges and narrow strips of country, where the landscape has been carved and corrugated through erosion.

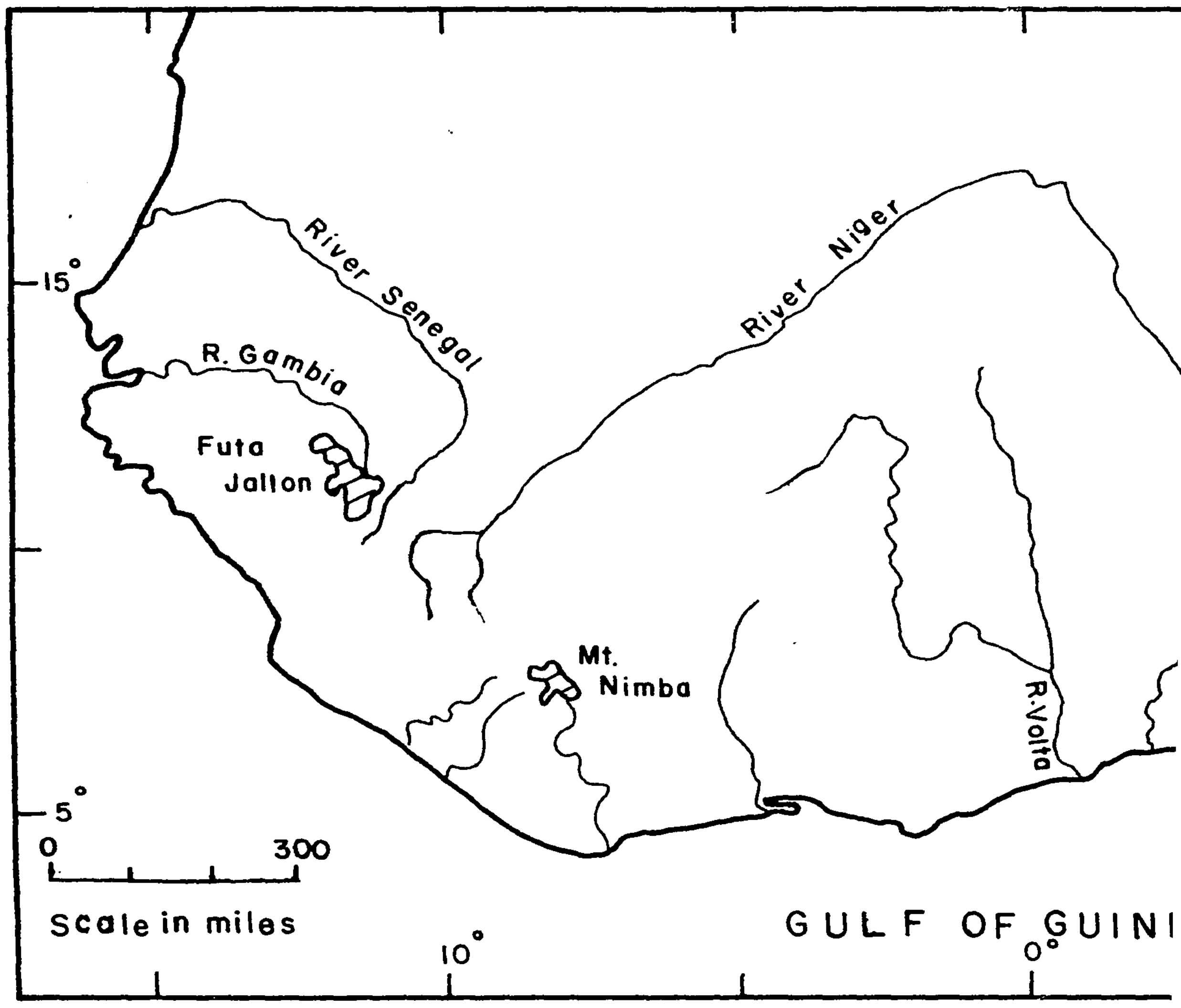
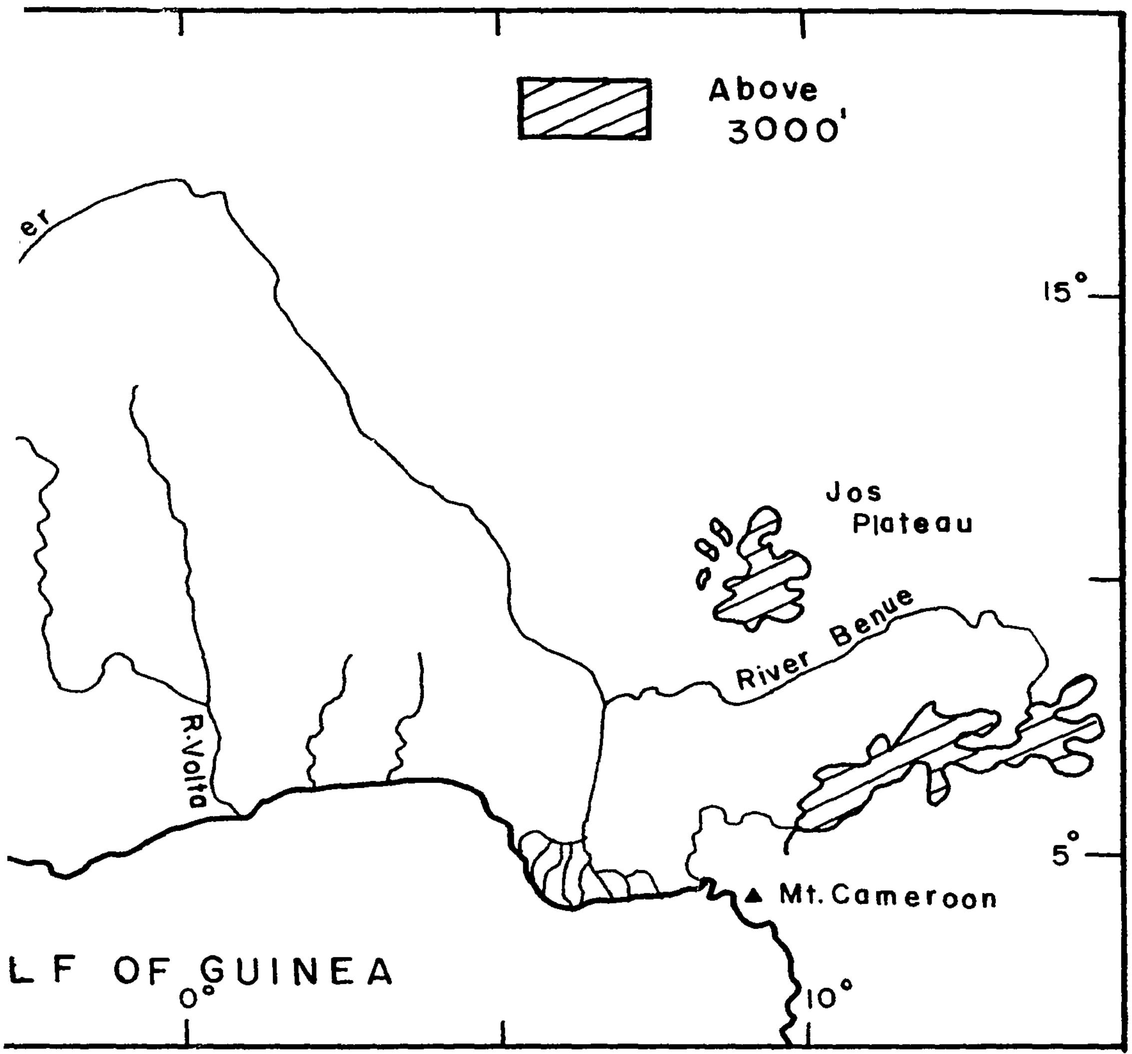


Fig. 2. West Africa - Phys:



: Africa - Physical Basis

This fundamentally table-like area is edged by a coastal zone the extent of which is wider to the east of Cape Palmas than to the west. A lagoon-fringed lowlying coastal region is succeeded inland by a belt of mangrove forests before the landscape changes to irregularly rising land towards the dissected edge of the tableland.

Across this series of wide plains, the rivers of West Africa have long winding courses, interrupted by falls and rapids as the nature of the ground changes. From the edge of the high inland plains several small streams flow directly to the sea. However, the main watershed lies parallel to the coast and is, indeed, not very far inland. From this watershed, the major rivers, with sources in the Futa Jallon and Cameroons, flow for great distances in a direction away or parallel to the coast before they finally turn to the sea (Fig. 2). Thus, the chief rivers, the Niger, Benue, Gambia and Senegal, have courses extending over several miles, providing a fundamental drainage system for West Africa which like the physiography and structure is large-scale.

Natural environment

The foregoing physical setting forms the stage on which West Africa's general environmental patterns of soils, climate and vegetation have developed. Their zonation is broadly latitudinal. Richards has described West Africa as having "a regular gradient from the climate of the wet coastal belt with a comparatively short dry season during which the humidity remains relatively high, to the arid and strongly seasonal climate of the interior culminating in the desert climate of the Sahara" (Richards, 1952, p. 335). This gradient of generally increasing aridity from south to north is reflected in well defined east to west bands of vegetation types parallel to the coast. In general terms, these latitudinal belts progress systematically from forest formations in the south through woodland savannas to grassland savannas and shrubby scattered forms of plant growth on to a gradual transition into the Sahara desert. Mangrove Swamp forests are found in places along the coast. The main forest formation of the region, however, consists of the luxuriant equatorial forests characterised by the dense growth of shadowy evergreen species of the "forêt ombrophile" as described by Richard Molard (1956). Between the main areas of high forest and the savanna, the forest changes in character with an increasing mixture of deciduous and evergreen trees. Riverine vegetation is also another characteristic of this area where, along the water courses, tongues of fringing forests extend into the dry forest zone.

Between the true savanna zone and the forests there lies a transitional area which is often referred to as derived savanna or forest savanna mosaic (Keay et al, 1959). This area is subject to varying influences of natural occurrences of fires (by lightening) and differences in soil and soil moisture character; it is also affected by anthropic activity such as repeated annual burning and shifting cultivation. The generally uneven character of trees at the zone's southern margin and an abrupt transition from forest to grassland distinguishes this area from its neighbouring vegetation types.

The continuing northward variation in vegetation characteristics expresses itself between the 7th and 14th parallels as broad belts of savanna grasslands with a narrow southward extension almost reaching the coast near southeastern Ghana. The main zone has three recognised sub-divisions from south to north, namely the Guinea, Sudan and Sahel savannas. Their differences are seen in contrasts in the general intensity of tree cover and herbaceous undergrowth.

Thus Guinean savanna is characterised in the south by undifferentiated relatively moist types of woodland in which such species as Lophira lanceolata and Daniella oliveri are found. A dense growth of tall grasses is not uncommon. In the south, scattered species of Isoberlinia doka and I. dalzielli, often associated with clumps of Uapaca togoensis, are characteristic and frequent. Tall grass savannas are features of wide valleys and strips of evergreen forest fringe the streams.

The Sudan savanna by contrast is made up of undifferentiated, relatively dry types of vegetation. Although Acacia are common, there are also other broad-leaved trees such as species of Combretum and Terminalia. Adansonia digitata and Sclerocarya are also characteristic of the area. Tall grasses with certain species of Acacia - A. polyacantha subsp. campylacantha and A. sieberiana - form part of the vegetation.

The Sahel savanna, on the other hand, consists of wooded steppes with abundant Acacia and Commiphora. It must be noted that the species of Acacia found here are ecologically different from the species of Acacia present in the Sudan savanna. The grass cover is usually shrubby and thorny (Keay et al, 1959; Richards, 1952).

Northward again the vegetation thins out into a region of annual and perennial species. Here solitary plants dot the area while patches of more dense vegetation are confined to places with a higher local rainfall. This whole area merges with the truly Saharan desert zone which, however, is for the most part outside West Africa as defined in the present context.

The latitudinal belting evident in the vegetation pattern of West Africa is also apparent in the distribution of soil types (Pugh and Perry, 1960). These change from coastal swamp soils in the south, northward through equatorial forest soils to a zone of lateritic soils, and finally to the northern sandy soils characteristic of the drier north.

The equatorial forest soils mainly comprise different kinds of sands and clays. The ground is well covered by vegetation and the dessicating effects of the Harmattan are rare. The forest soils are usually reddish in colour due to the presence of iron oxides. These soils have a high percentage of sesquioxides and silicious oxides. The forest latosols are of the zonal type of soil which develops over areas that are underlain by the basement complex. On some occasions, however, latosols are found over basic rocks. With particular reference to agricultural operations and fertility, the forest soils have been classified by Vine (1953) into two groups of moderately strongly leached soils and excessively leached soils. The former have been called forest oxysols and the latter forest ochrosols by Nye and Greenland (1965). The forest oxysols are brown or orange brown in colour and are characterised by open topsoils and compact sub-soils. The forest ochrosols which form the second group are normally found in areas where the rainfall corresponds to the moist semi-deciduous vegetation formations, as opposed to the areas of oxysols which are familiar in regions where the rainfall corresponds to the evergreen moist forests. The forest soils contain a slightly acidic topsoil with increasing acidity at depths.

Although conditions in the forest regions of West Africa are generally unsuitable for laterite development, nevertheless, local patches of lateritic crusts are occasionally found. The great area of laterite, however, co-exists with the savanna in a vast belt extending approximately south of a line from $14^{o}N$ in the west to $12^{o}N$ in the east, and north of a line from $8^{o}N$ in the west to $7^{o}N$ in the east. In West Africa laterisation can reflect deep weathering accompanied by the formation of hardpans at, or below, the surface, or be derived from alluvial or ferrous deposits covering any kind of Saharan drifts (Molard, 1956). The crusts are usually ferruginous with a rough red or black surface. They are found at various depths in different parts of the savanna. In regions with a double rainfall maximum the crust is located between 1½ ft. and 10 ft. below the surface whose top is covered by a thin layer of mobile soil over which the shallow rooted woodlands stand. Hardpans 10 ins. to several feet thick are found at the surface between the area $10^{o}N$ to $14^{o}N$. Between $14^{o}N$ and $16^{o}N$ the pans are restricted to those parts which have been exposed by rain or wind. It is also common to find semi-gravel and rock surfaces instead of crusts (Scaëtta as quoted in Morgan and Pugh, 1969).

The savanna soils are generally reddish in colour due to the presence of ferric oxide. The soils under high grass savanna are shallower than the forest soils. This is shown by the fact that rock rotting is found within 10 ft. below the surface in savanna soils, whereas in forest soils rotting extends to a depth of 20 ft. Moreover, in the savanna soils between the junction of the topsoil and the zone where disintegration of rock material takes place, there generally occurs a hardpan layer formed by the presence of indurated cemented iron oxide (Nye and Greenland, 1965).

The desert soils to the north are shallow, have poorly developed profiles and lack organic matter. Characteristic features of arid regions include areas of drifting sand, bare sand and pebbly reg, particularly in uplands where the soils are thin and stony (Vine, 1949).

Selected viewpoints on vegetation region

The foregoing broad and very generalised survey of environmental characteristics has been made in order to provide a setting for a more specific discussion of the character and distribution of the West African savannas. They are among the best known of the world's grassland regions and have been studied by numerous authors such as Richards (1952), Harrison Church (1956), Eyre (1963), Kimble (1962), Shantz and Marbut (1923), Philips (1958), Rattray (1960), Stamp (1964), Molard (1956), Brian Hopkins (1965), Aubréville (1949), Keay et al (1959), Boughey (1957), Kuchler (1960).

It is both impractical and unnecessary in the present context to discuss each of the above-mentioned works. What will be attempted is a study of some of them in order firstly, to show how authors with different viewpoints have approached the delimitation of the savanna region and secondly, to try to establish the composite region of savanna which will form the basis for a subsequent analysis of moisture conditions.

A recent and substantive study of African vegetation has been made by Keay et al (1959). In this work the term "savanna" is used to represent "a vegetation in which perennial mesophytic grasses (e.g. Hyparrhenia) at least 80 cm. high with flat basal and cauline leaves, play an important part; such vegetation is usually burnt annually; although most of the grasses form tussocks isolated from each other, the culms when fully grown form a more or less continuous layer dominating any lower stratum of plants." This definition serves to distinguish savanna from tropical forests on the one hand, and steppe on the other. The former are considered to be made up of evergreen, or partly evergreen species, forming a community which contains "several more or less distinct strata including an upper stratum of large trees which may be 40 to 60 cms. high", while the latter term is used for "vegetation in which annual plants are often abundant between the widely spaced perennial herbs" (Keay et al, 1959, p. 6).

The savanna, as mapped in terms of this definition, covers the area approximately between 7°N to 15°N latitude (Fig. 3a). A zone of transition in the south between the forest and regular savanna is recognised and this zone is referred to as the forest savanna mosaic. Degradation of the moist forest by the influence of fire is considered to be a factor of importance in the maintenance of this zone.

The savanna region proper is divided into relatively moist and relatively dry types of savanna. The subdivision recognises differences in the height of the grasses, which vary from 3 to 4 meters to 80 cms., and contrasts in floristic types. Thus the northern, or dry, savanna is dominated by xerophytic species such as Acacia with tall grass such as A. polyacantha subsp. campylacantha and A. sieberiana, whereas in the moist savanna the chief woody species are Isoberlina doka, Daniella oliveri, Julbernardia and Brachystegia. The northern limit of Keay's savanna region is located approximately 15°N on the west coast and 14°N near the eastern limits of West Africa.

The approach adopted in Keay et al (1959) is fundamentally physiognomic in its delimitation of savanna as a major vegetation community, the inclusion of floristic types being introduced to help indicate the general environmental conditions and differences within the region.

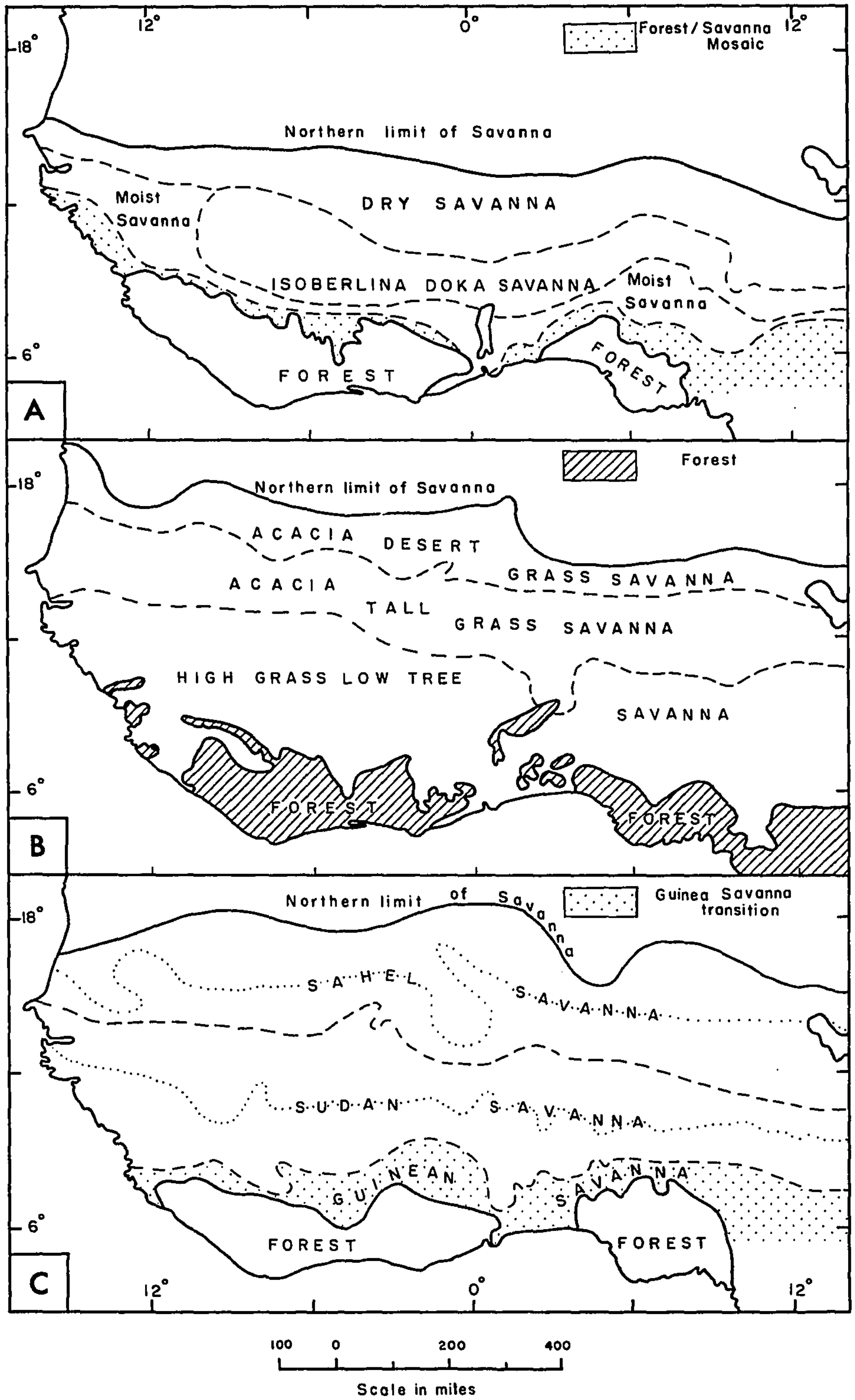


Fig. 3. West African Vegetation according to different authors

(A) Keay (B) Shantz (C) Molard

A basically similar approach was followed by Shantz (1923), the botanist who produced one of the earliest comprehensive vegetation maps of Africa, but one which is still being used as a basis by other authors like Stamp (1964) and Eyre (1963). Shantz distinguishes two major vegetation types in West Africa: tropical rain forests, which consist of closed formations, usually evergreen, with deciduous species associated towards the savanna borders, the trees forming a continuous canopy with two or three understories of woody growth; and savanna, which is differentiated by the general sparseness of woody vegetation and the presence of a herbaceous undergrowth. The principal factor used for identifying one savanna type from another is the intensity of grass cover they support. Thus, the map follows primarily the physiognomic approach to classification, although generic names or taxonomic terms form a basis for subdivision. Three divisions within the savanna are recognised: high grass, low tree savanna, *Acacia* tall grass savanna, and *Acacia* desert grass savanna. The southern limit of the high grass, low tree savanna is about 8°N on the west and 7°N on the east (Fig. 3b), but there is an extension to the coast in the area between Accra and Porto Novo (0° to 4°E). From these southern limits, this type of savanna is found to latitude 14°N on the west and 12°N on the east. The feature of a greater northward extension in the west is also seen in the case of the *Acacia* tall grass savanna, while a narrow belt of *Acacia* desert grass savanna brings Shantz's savanna zone to its northward limits in about latitude 16°N to 18°N. It is noteworthy that Shantz does not appear to have recognised zones of transition. Hence any specific area is considered to belong to one of a particular type of savanna and his map contains no intermediate areas in which vegetation is considered to be a mixture of two types.

Among geographers who have offered studies of West African vegetation, those of Molard (1956) and Harrison Church (1956) have been chosen as examples.

Molard defines the savanna as a light woody population which permits the development of a herbaceous undergrowth as opposed to the "forêt ombrophile" (rain forest), consisting in the south of evergreen species which are gradually replaced northwards by deciduous trees. Though his classification of the vegetation follows physiognomic principles, his detailed descriptions of the vegetation regions include the ecological factors of climate, soils, and amount of precipitation. He also appears to recognise a transitional zone, the Guinea savanna, since on his map this part of the natural zonation is not included in the regular area but is classified as an intermediate zone where galeria forests occur, lateritic crusts are rare, and the oil palm (*Elaeis guiniesis*) flourishes (Fig. 3c).

The savanna proper for Molard constitutes two main vegetation types: Sudan savanna and Sahel savanna. The difference between the two is based both on density of vegetation covering and on the types of vegetation, more particularly the amount and type of woody vegetation present. The distinguishing feature of the Sudan savanna is emphasized in Molard's quotation of an African proverb "Lã oũ apparaît le Karitē commence le Soudan". (Molard, 1956, p. 44). This quotation emphasizes the presence of the "Karitē" (shea butter tree) as a distinguishing characteristic of the Sudan savanna in contrast to the Sahel region where the tree disappears and the woody vegetation is dominated by the *Acacia*. Both regions are, however, sub-divided by

Molard into northern and southern types. Thus, he recognises a southern Sudan savanna containing a luxuriant vegetation ("une puissante végétation") of trees and tall grasses, in contrast to a northern Sudan savanna in which the baobab (Adansonia digitata), tamarind (Tamarindus indica) and other similar species become increasingly important, and where the undergrowth of grass decreases.

Similarly, the Sahel savanna is divided into northern and southern types. In the southern part certain species of baobab in local spots of deeper and wetter soils exist along with the predominant Acacia trees, but the shea butter tree has totally disappeared. This woody savanna (savane arborée) gives way further north to a savanna dominated by shrubs ("savane d'arbustes") and increasingly sparse grasslands.

The vegetation regions of West Africa as presented by Harrison Church (1956) result from an approach essentially similar to that of Molard. A primary differentiation between forest and savanna is made on the basis of tree height, of the density of herbaceous undergrowth and on whether the plant or tree is deciduous or not in the dry season. The generally familiar term of tropical rain forest is substituted by the expression "lowland rain forest" (as in Keay et al, 1959). This forest consists of dense vegetation. There are high trees with woody climbers, and a rich flora and undergrowth.

The change from forest to savanna vegetation is found in what is essentially a transition zone which Harrison Church includes as a narrow belt fringing the lowland rain forests. This is considered to be a region of "derived savanna", the term being used to imply the reduction of forest vegetation to savanna types by the influence of man's cutting, burning and cultivating activities. The savanna region as a whole is sub-divided into three: Guinea savanna, Sudan savanna, and Sahel savanna (Fig. 3d).

The Guinea savanna is found about $8^{o}N$ to $13^{o}N$ in an area where annual rainfall averages 40 ins. and 55 ins., and there are four to five months with less than 1 inch of rain. Harrison Church recognises a general contrast in the area between the south and the north. In general, the southern zone has a more luxuriant vegetation than the north. In the south, the grasses are taller and fire-resistant trees like Daniella oliveri, Lophira lanceolata, and Detaruim microcarpum are present. The tall tussoky grasses associated with this woodland are mainly species of Andropogon, Hyparrhenia and Pennisetum. The northern Guinea savanna, by contrast, has vegetation of a similar physiognomy to the south, but the coverage is poorer and the tree species differ. Thus, Isoberlinia, Karité and Tamarindus are the common types of trees here, and the grasses are shorter and shrubs are not uncommon.

The Sudan savanna vegetation is found in a belt, some 120 to 240 miles wide, to the north of the Guinea savanna. Here the annual rainfall is between 22 ins. and 40 ins., with a dry season of seven months which may be virtually rainless. The trees dominated by the Dum Palm (Hyphaene thebaica), baobab (Adansonia digitata), and Acacia albida, are scattered and rarely occur in clumps. Low shrubby bushes with woody climbers occasionally occur, particularly on rocky hills. The herbaceous growth is less tussocky than the Guinea savanna and is more feathery in character.

The third category of savanna designated by Harrison Church is the Sahel savanna, which is identified by an open pattern of widely scattered species of Acacia which are both thorny and deciduous in character. The

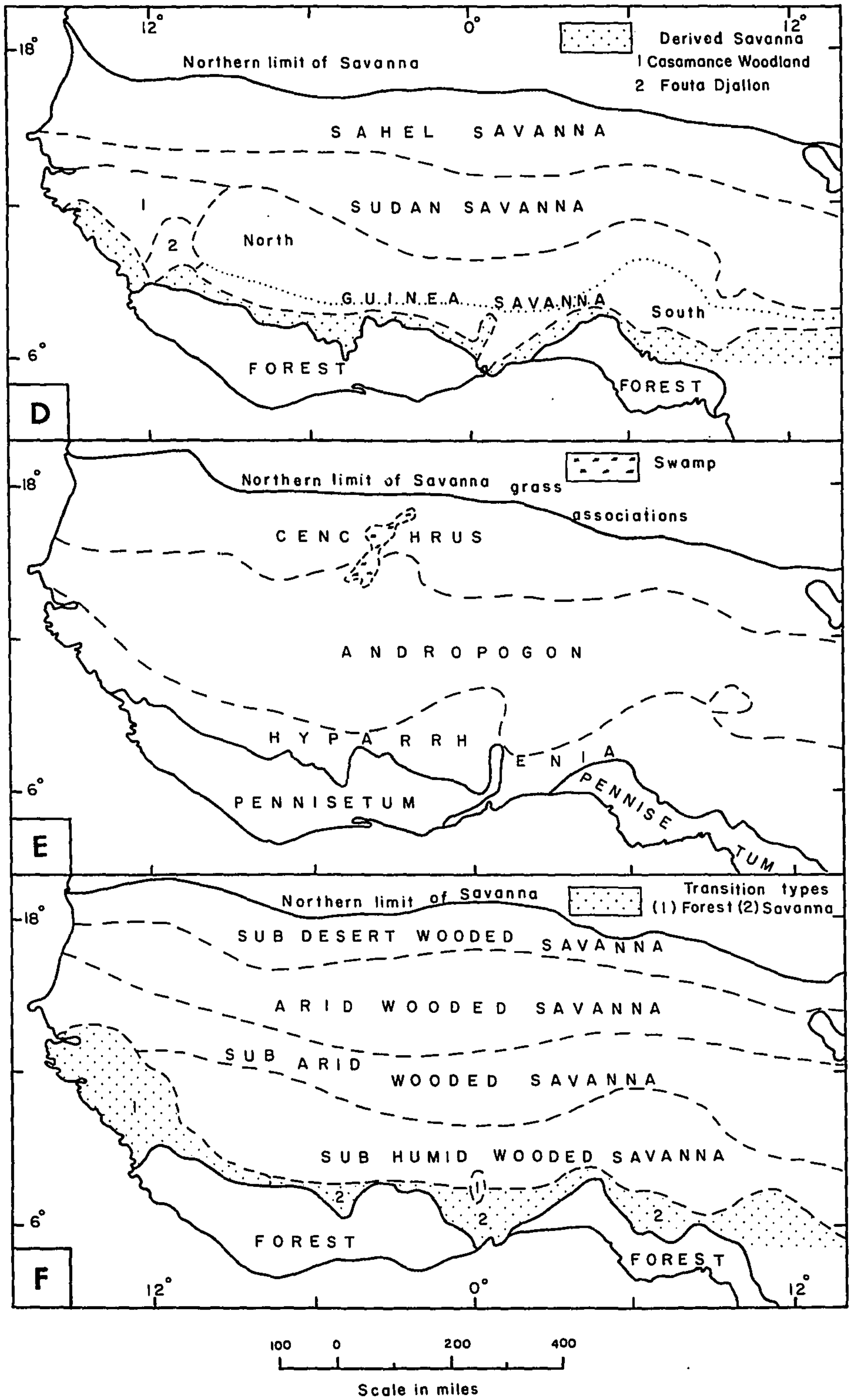


Fig. 3 (continued)

(D) Harrison Church (E) Rattray (F) Philips grass cover is short and discontinuous and, like that to the south, is used for grazing. The density of vegetation does not encourage fires and hence they are not as serious as in the Guinean and Sudan savannas. The northern limits of the Sahel savanna are located approximately at 18^{o}N on the west and 14^{o}N on the east.

The works considered so far have approached the question of vegetation distribution basically by looking at vegetation in its totality in terms principally of physiognomic characteristics. A somewhat different approach which is useful in the present context is found in Rattray (1960). This study concerns itself primarily with grasslands and it constitutes yet another way of showing savanna extensions in Africa, since it is a classification based on the major grass associations distinguished according to the dominance of one genus, and sub-divided according to the physiognomy of the vegetation in which a given grassland type occurs. Thus,the grasses are differentiated as "forest grasses" or "savanna grasses". The predominating species in the former category is <u>Pennisetum</u>, and <u>Hyparrhenia,</u> <u>Andropogon,</u> and <u>Cenchrus</u> are found in the latter. Viewed from this standpoint, Rattray distinguishes a predominantly forested region shown on his map as connected with woodland species of grass cover (<u>Pennisetum</u>). The savanna type grasses produce a savanna region of three kinds associated in a south to north progression with the species of <u>Hyparrhenia</u>, <u>Andropogon,</u> and <u>Cenchrus</u> respectively.

The <u>Hyparrhenia</u> dominated area forms a relatively narrow belt with its southern limits at about 8^{o}N (Fig.3e). North of this region is the area distinguished by the presence of <u>Andropogon</u> varieties. This is by far the largest of Rattray's grassland regions and comprises a more or less uniform belt of approximately 5^{o} of latitude wide , with northern limits in the vicinity of 15°N. Finally, there is the region characterised by <u>Cenchrus</u> species. It has a narrow but uniform latitudinal distribution in the vicinity of 16° or 17°N and separates the savanna grasses from the region of drier <u>Aristida</u> steppe grasses towards the Sahara desert.

A final study to be considered here is that of Philips (1958). His approach is ecological and aims at showing the agricultural potential of different parts of Africa. In this connection he has produced a map of bioclimatic regions which are based on a combination of potential or actual vegetation, rainfall, humidity and temperature conditions. The bioclimatic regions are, however, essentially vegetation zones. He identifies forests as occupying areas where the climate is highly humid, or humid in contrast with the deserts where the bioclimate is arid. Between these extremes lies the savanna which is sub-divided into "sub-humid savanna", "mild sub-arid wooded savanna", "sub-arid wooded savanna", and "arid wooded savanna"(Fig. 3f). Each one of these vegetation types expresses a particular bioclimate. However, "grasslands" or "open savanna" are also recognised, which are vegetation complexes lacking woody growth and which are interspersed within the different areas of "wooded savanna". The existence of these open areas is explained as a result of variable local edaphic controls or due to man.

The terminology used to designate each type of savanna shows that Philips has based his divisions on changes in vegetation types which he considers due to changing moisture conditions. There is some correspondence between the location and size of his zone and those of some of the other authors discussed. Thus, the sub-humid wooded savanna of Fig. 3f approximates to the area of Guinea savanna in Harrison Church's classification (Fig. 3d), while the sub-arid wooded savanna zone corresponds roughly to Keay's undifferentiated, relatively dry type of savanna (Fig. 3a). However, Philips's emphasis on a bioclimatic base for the differentiation of his regions implies a different point of view from that of the others, even though the resulting areas may be similar.

The savanna region

Each of the authors whose work has just been discussed were concerned either directly or indirectly with the common problem of delimiting the different vegetation regions of West Africa. From whatever point of view this question was approached, and whatever the actual definition used, each has produced a map or classification indicating areas of forest, areas of savanna and areas of desert. Taken together it can be said that their work represents the results of applying the major points of view in studying vegetation communities to the West African scene. The physiognomic viewpoint, the use of a floristic or taxonomic approach, and the ecological point of view, are all represented. In the context of the present thesis, therefore, it seems reasonable to combine the results of each author's work to see if it is thereby possible to achieve agreement on a savanna region of West Africa as distinct from other vegetation zones. Fig. 4 has been prepared to show the extent of the similarity and differences in the savanna boundaries as given by the different authors. This figure was used as the basis for preparing the composite map of the savanna region and the non-savanna regions shown in Fig. 5. The map indicates that it is possible to find an area which each one of the six authors whose work has been considered would

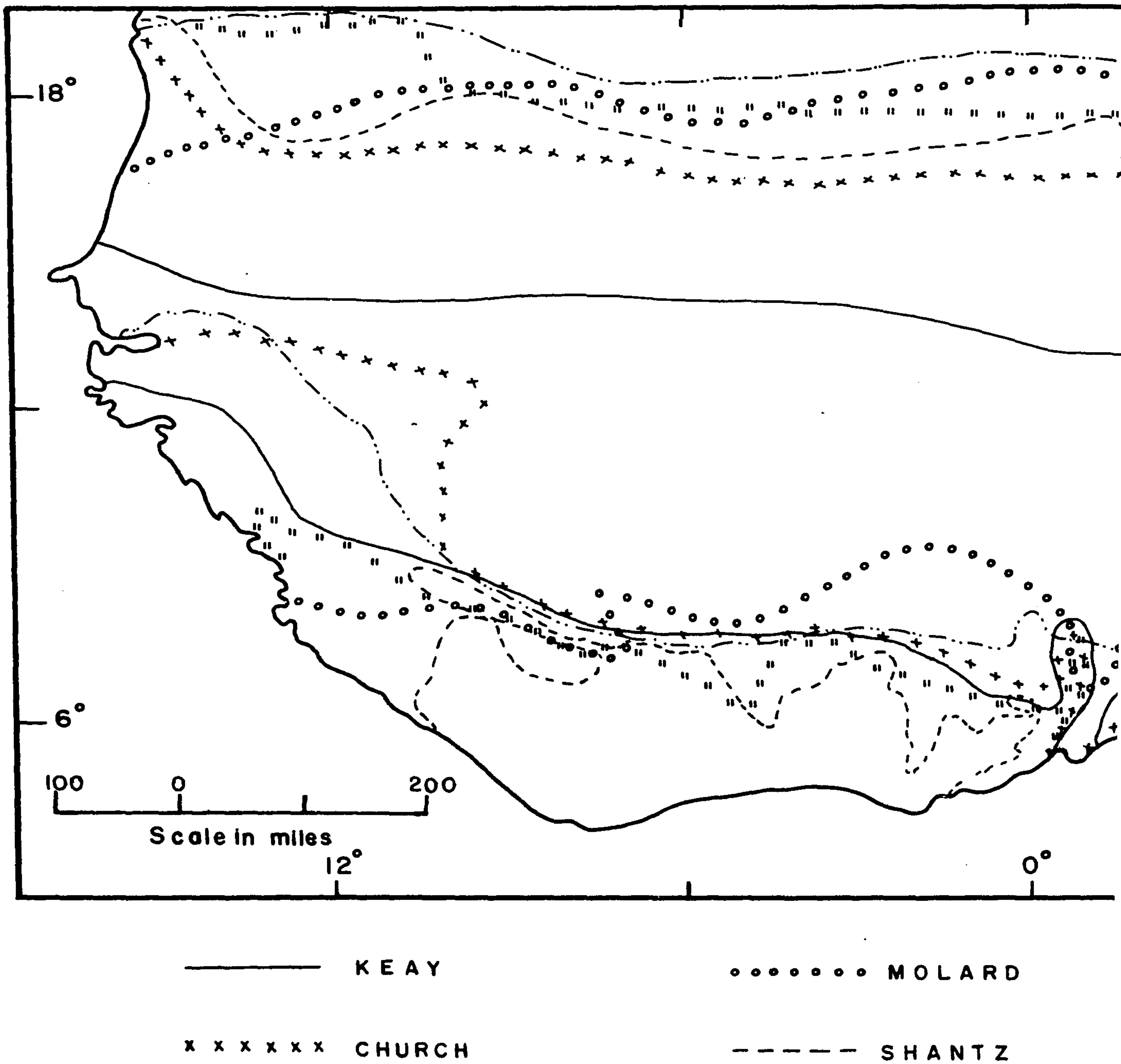
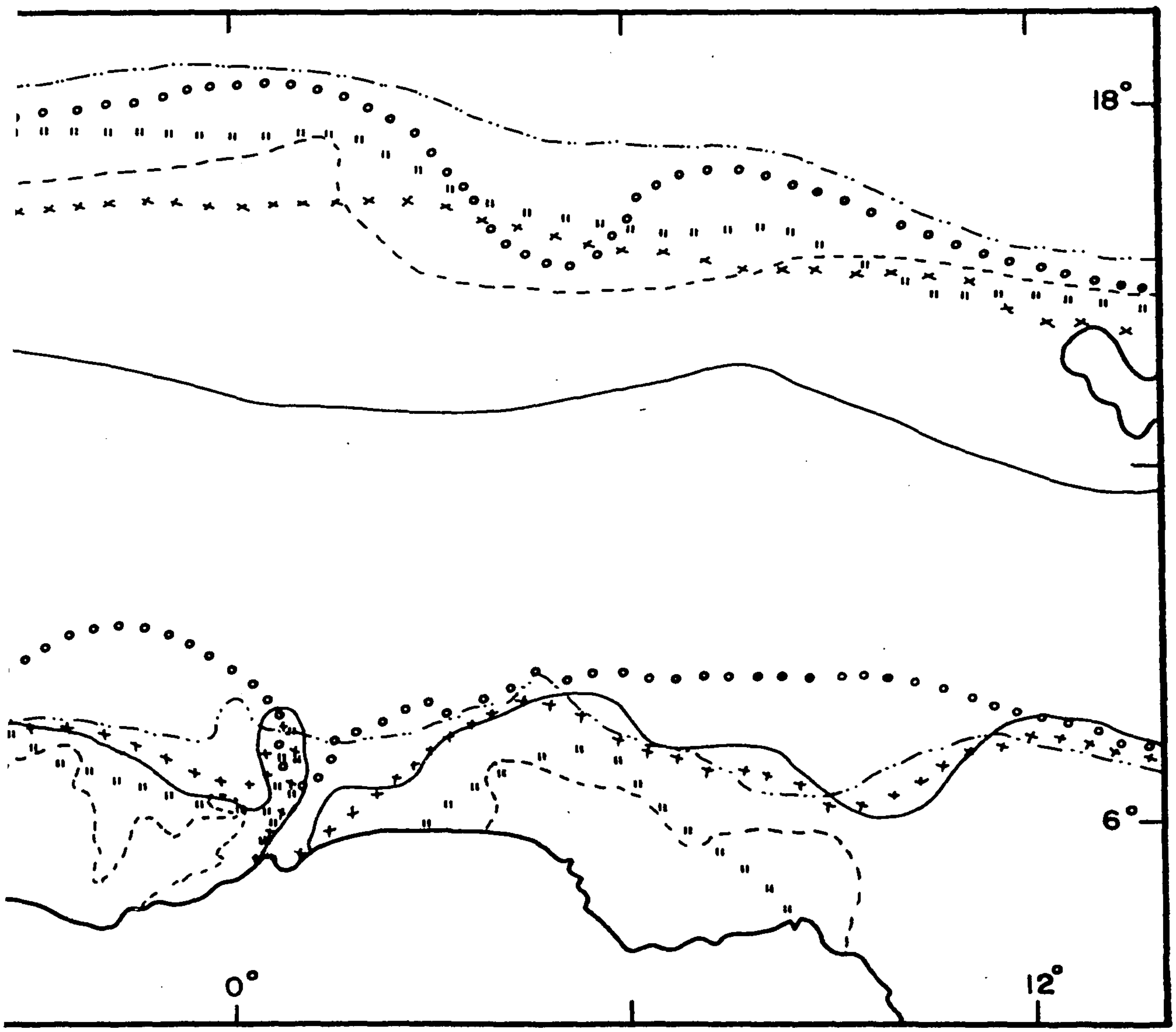


Fig. 4. Boundaries of the Savanna accord



∘ ∘ MOLARD

" " " " " " " PHILIPS

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ıe Savanna according to different authors

4

agree to be savanna. Equally, there is an "agreed" region of forest and an "agreed" region of desert. Between these regions lie other areas which can be termed "transitional", either between forest and savanna (southern transition) or between savanna and desert (northern transition). These transitional zones come about partly because of different boundary delimitations and partly because they have been designated as "transition" by one or other of the authors concerned.

The "agreed" savanna area thus determined occupies approximately 550,000 to 600,000 square miles and stretches 1,750 to 2,000 miles from west to east, and 425 to 450 miles north to south. Its southern boundary is the combination of the northern limits of the Casamance woodland type of vegetation as recognised by Keay and Church, the humid, sub-humid bioclimatic region as defined by Philips, and the northern boundaries of the derived savanna or zones of transition recognised by the other authors. The southern boundary of this zone is for the most part at about latitude 9^{o}N and the northern limits approximate to latitude 14^{o}N. A notable feature of the area is its well-established position east of longitude 10^{o}W. West of this longitude, the "agreed" savanna region is narrow and insignificant in size compared with non-savanna areas owing to the special and variable characteristics of montane vegetation (the Casamance woodland of Church and Keay, and the particular bioclimatic region of Philips) inland from the coastal region between Conakry and Bathurst.

Method of moisture analysis

Since this thesis aims to establish the distinctive moisture characteristics of the savanna area by showing how they compare or contrast with those of non-savanna areas, attention will be paid particularly to locations inside each of the regions shown in Fig. 5. This will be attempted by examining conditions at individual, or groups of stations which are clearly within each given region, and comparing the results. The different stations have been chosen on the basis of their location and the reliability and availability of statistics in terms of the different time-scales of the analyses which will be undertaken. The location of the stations used is given in Fig. 12 and they are also indicated in Table I where they are classified in terms of the regions they represent, the data available, and the type and time-scale of the analyses made.

It can be seen from this table that the basic methodology of this study is strictly climatic. Moisture is looked upon as an element of climate, whether directly in terms of precipitation and atmospheric humidity, or indirectly through the factors involved in evapotranspiration and the water balance. Clearly, this does not cover the element of soil moisture, which is recognised to be an extremely important part of any consideration of moisture as a factor of plant growth and characteristics. There are two principal reasons for this omission: firstly, to introduce it in definitive terms would greatly extend the scope and length of this thesis, and could indeed become the subject of another thesis in itself; secondly, the aim of this thesis is specifically to try to contribute to the discussion on the causes of savanna (briefly outlined in Chapter One) by concentrating on moisture as a climatic factor - perhaps atmospheric factor is a better term - in the hope of showing to what extent this particular element of the savanna ecosystem compares or contrasts with that of the ecosystem of other, non-savanna complexes. By so doing, it is

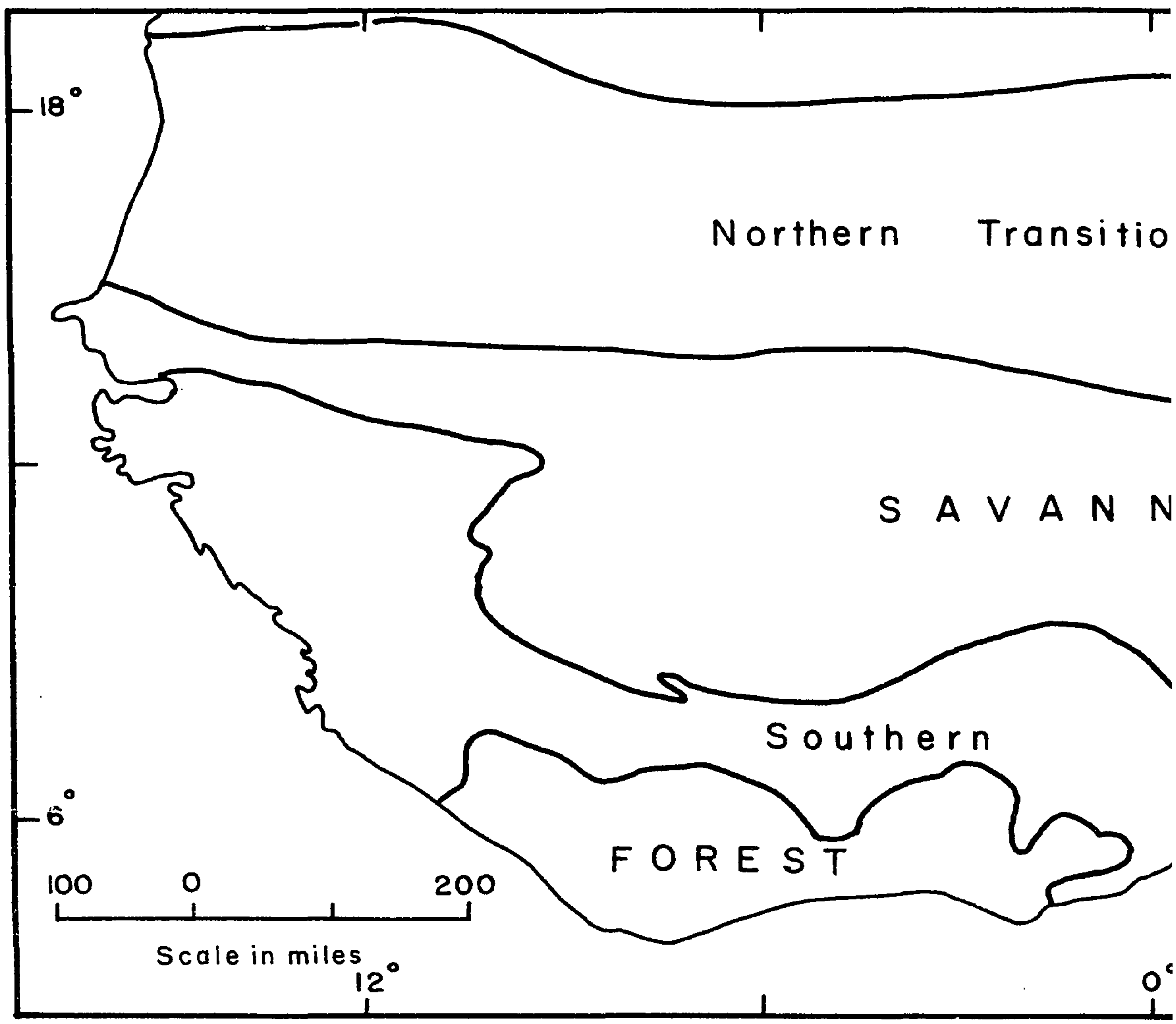
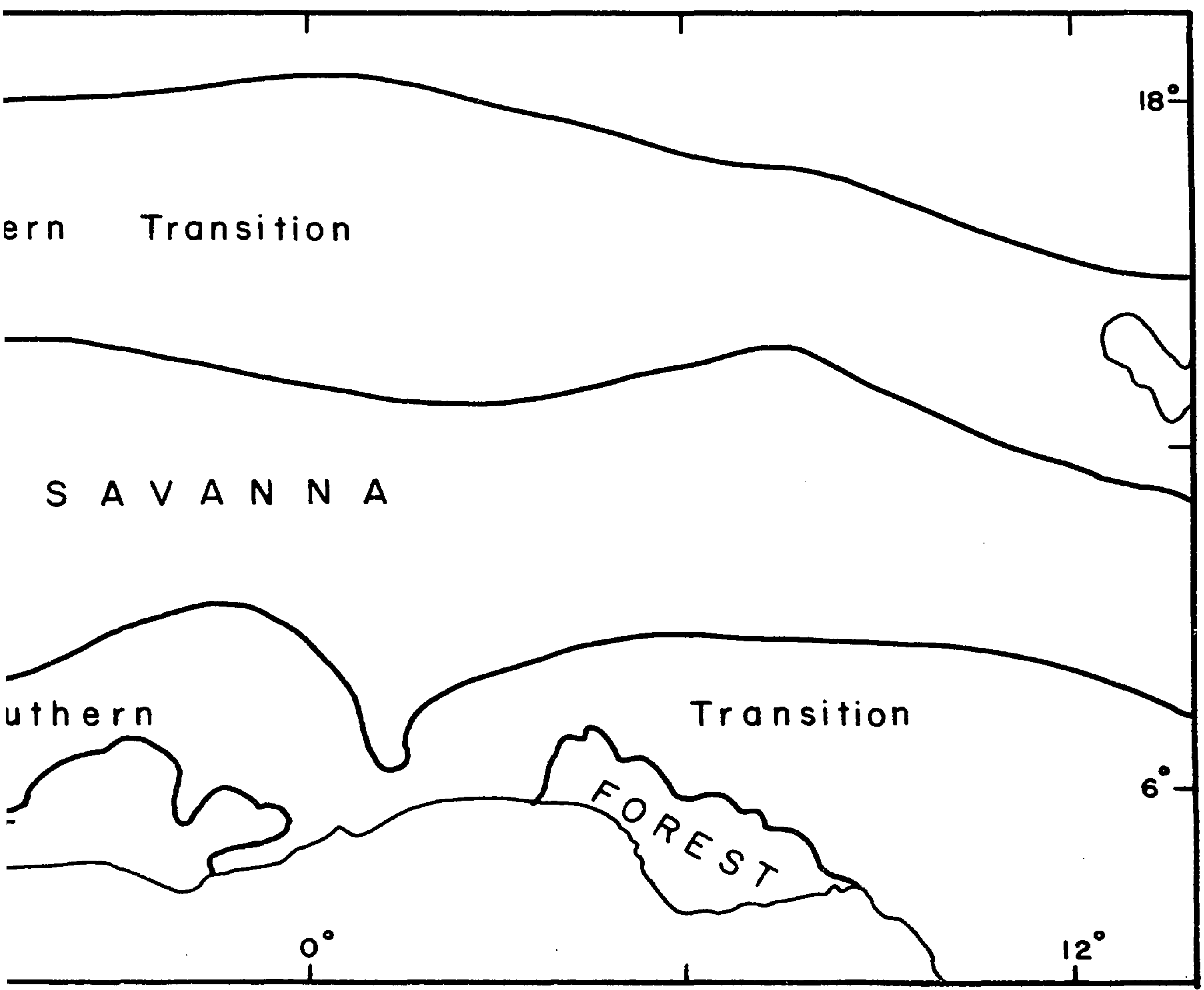


Fig. 5. Major Vegetation Regi



Vegetation Regions of West Africa

TABLE I

LIST OF STATIONS AND DATA USED IN THE ANALYSIS OF MOISTURE CONDITIONS

Region	Station	Mean Monthly			Monthly Variability			Daily Data					Hourly	
		P	PE	AH	P	WB	AH	P	PE	AH	S	W	P	AH
Northern transition	Kidal	*	*		*	*								
	Agadez	*	*	*	*	*	*							
	Timbuktu	*	*	*										
	Zinder	*	*	*	*	*	*							
	Mopti	*	*		*	*								
Savanna	Kayes													
	Niamey	*	*	*										
	Bamako	*	*											
	Sokoto	*	*	*	*	*	*	*	*	*	*	*	*	*
	Ouagadougou	*	*	*	*	*								
	Maiduguri												*	*
	Kano	*	*	*	*	*	*	*	*	*	*	*	*	*
	Bobo-Dioulasso	*	*	*	*	*								
	Kaduna	*	*	*	*	*	*							
	Natitingou	*	*	*										
	Minna	*	*	*	*	*	*						*	*
Southern transition	Mamou	*	*											
	Tamale	*	*	*										
	Ilorin	*	*	*	*	*	*	*	*	*	*	*	*	*
	Freetown	*	*											
	Ibadan	*	*	*										
	Bouaké	*	*	*	*	*								
	Kumasi	*	*	*										
	Enugu	*	*	*	*	*	*	*	*	*	*	*		
	Ikeja												*	*
Forest	Benin	*	*	*	*	*	*	*	*	*	*	*	*	*
	Warri	*	*		*	*	*						*	*
	Port Harcourt	*	*	*			*							
	Abidjan	*	*	*	*	*								

P=Precipitation
PE=Potential Evapotranspiration
AH=Atmospheric Humidity

WB=Water Balance
S=Sunshine Hours
W=Wind Miles Run

hoped to provide information which will help to throw further light on just how distinct a part this one factor plays in the complex of conditions which produce savanna characteristics.

CHAPTER THREE

GENERAL CLIMATOLOGY OF WEST AFRICA

The West African climate is strongly governed by the fact that the region lies between a vast expanse of heated land mass to the north and a warm equatorial ocean to the south. As a result, the general wind systems in the lower levels of the atmosphere consist essentially of two main air streams: the dry air from the north of continental (Saharan) origin, and the humid maritime air from the south, originating in the humid air masses over the Atlantic Ocean (Fig. 6). The surface boundary where the continental air meets the maritime air has been described as the Inter-tropical Convergence Zone (Trewartha, 1961; Flohn, 1960), the Inter-tropical Discontinuity (Walker, 1958), and the Inter-tropical Front (Hamilton and Archbold, 1945). A recent study by Garnier (Garnier, 1967), however, criticises the use of these terms on the grounds that since there is small thermal contrast between the two air masses, frontal activity in the zone of contact between them is absent, and the contact area does not necessarily separate two air masses of tropical origin as the term "inter-tropical" suggests. He therefore prefers to use the term Surface Discontinuity (SD), and this term will be adopted in the discussion which follows.

Winds and air masses

The dominance of planetary large-scale control of the wind systems across West Africa is further emphasised by the free latitudinal exchange of air over the area, in view of the absence of major relief features to act

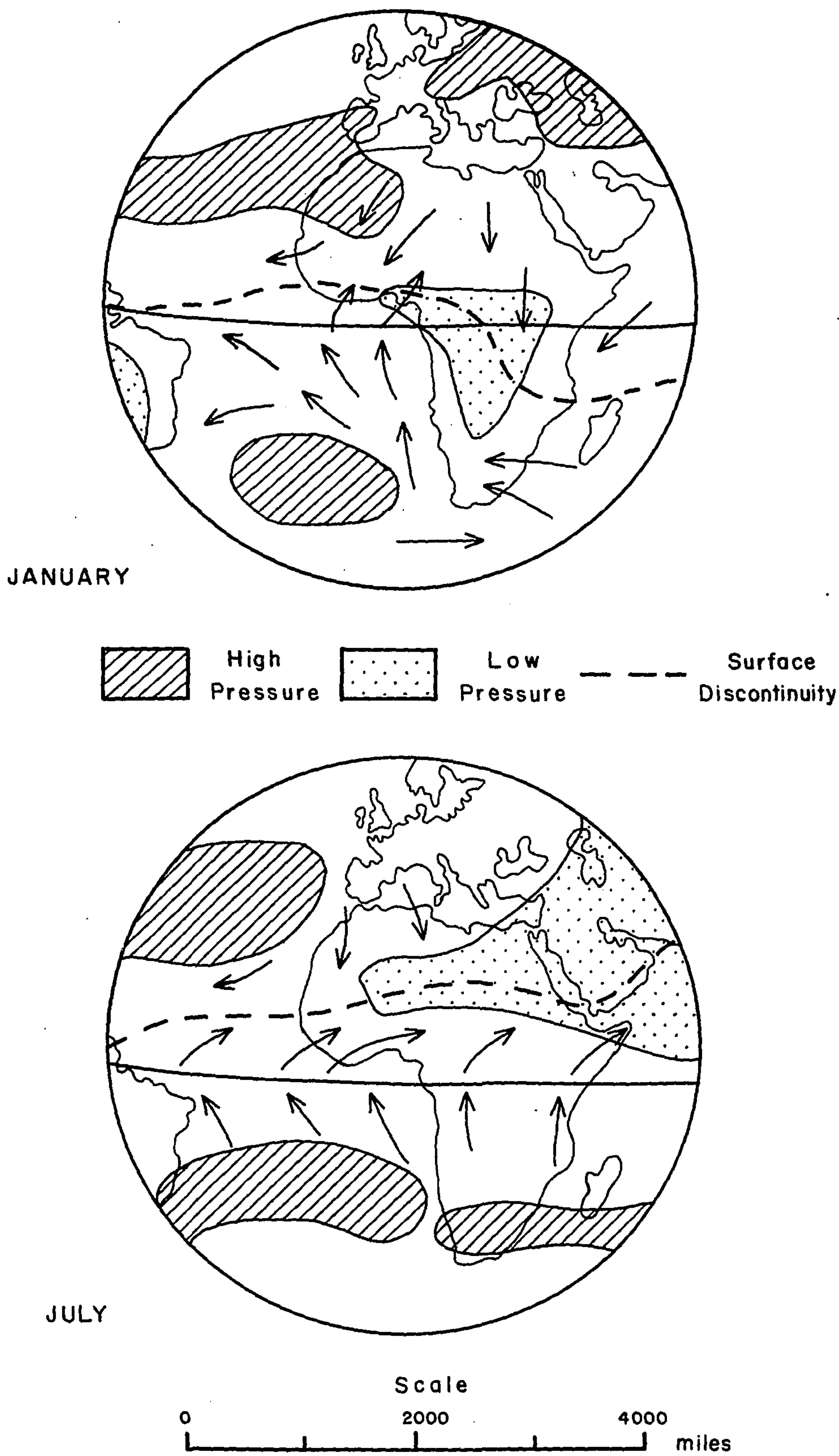


Fig. 6. Surface Pressure and Wind Systems over West Africa

as climatic barriers. The source region of the dry continental air mass is generally associated with the Azores sub-tropical anticyclone and its southward extension over the Sahara. It is a warm and dusty mass of air which has its maximum extension over West Africa in January, then reaching southwards to between 5^{o} to 7^{o}N. During this time the surface high pressure over the Sahara and the general trend of pressure systems show that the winds are north-east or easterly. By contrast, the moist maritime air streaming towards West Africa from the south probably has its origins in the south Atlantic. The surface winds carrying the air originate south of the equator where they are south-easterly, but after crossing into the northern hemisphere they veer to the south-west. These south-west winds have had a long history of sea track over warm waters before they reach West Africa and are, accordingly, heavily ladened with moisture. The Surface Discontinuity which indicates the zone of contact between these two major surface air streams has certain characteristics which, together with its migratory tendency, influence the climate of West Africa and its seasonal characteristics and variations.

Weather zones

The contrasting qualities of the tropical continental and tropical maritime air masses over West Africa result in a situation where the maritime air penetrates like a tongue into the dry air, thus forming a wedge which slopes upward towards the south (Fig. 7). The influence of this wedge of penetration over the region as a whole is marked between April and October, since it brings moist conditions well into the interior of the land mass. At other times of the year, the moist air is confined

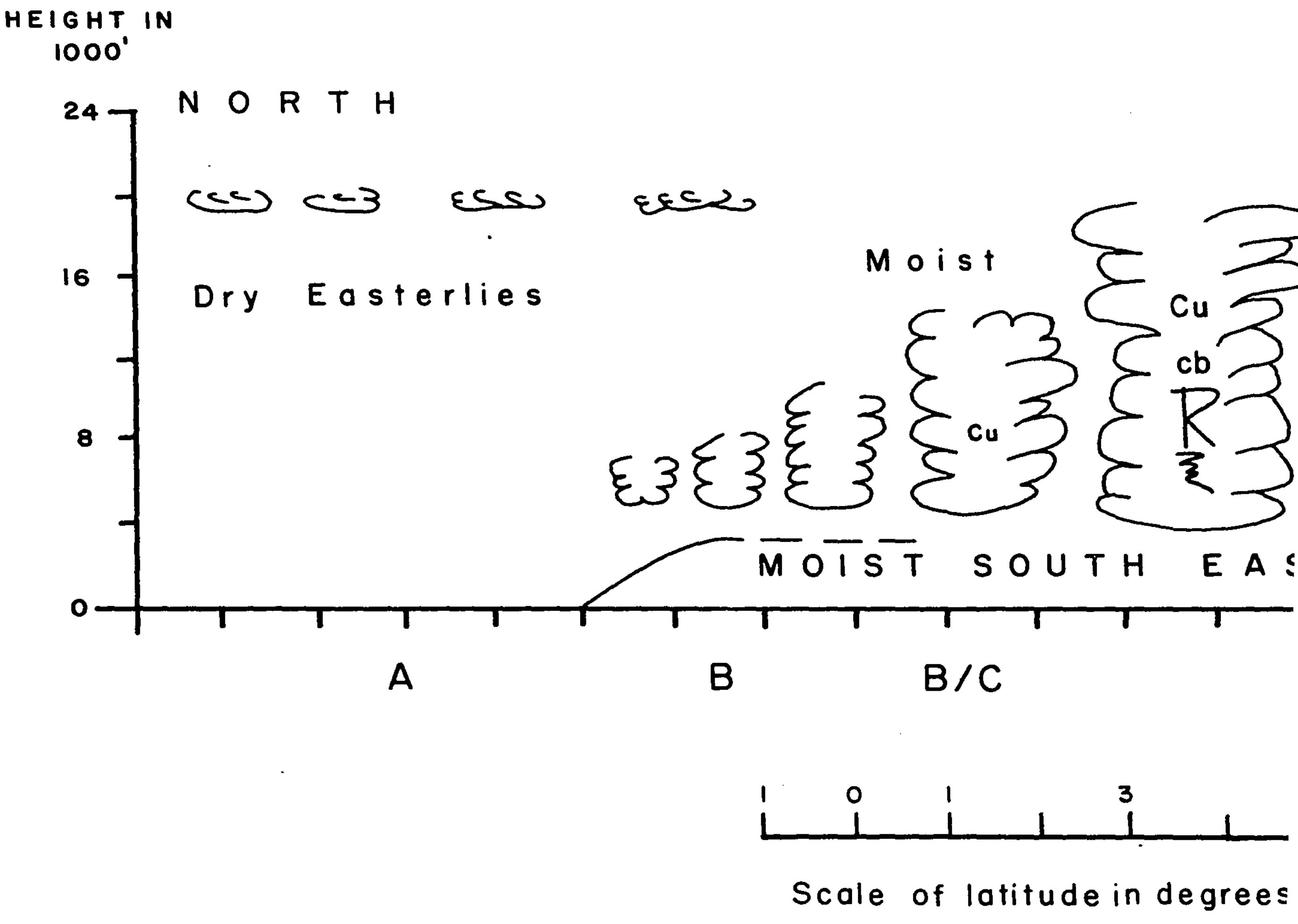
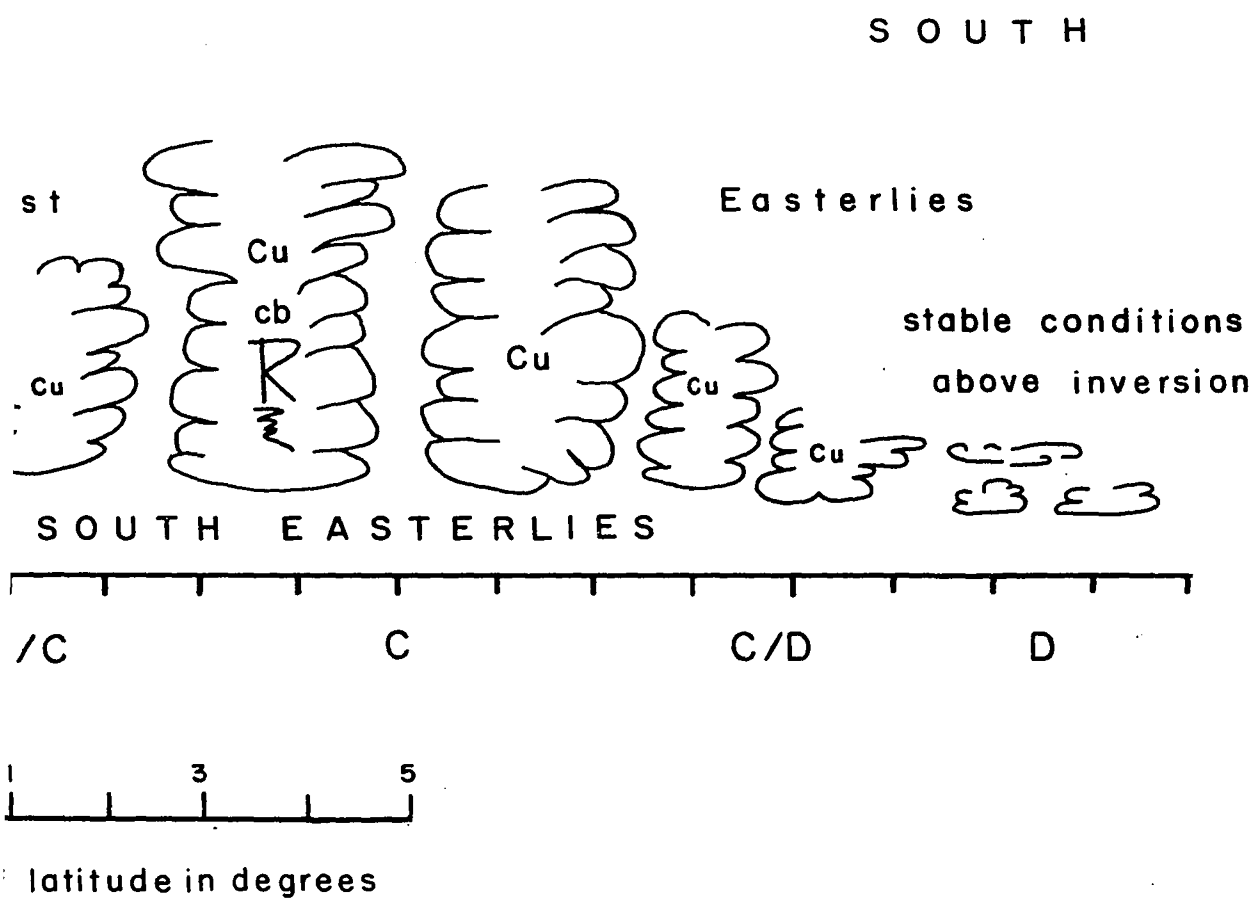


Fig. 7. Atmospheric Cross-sect
(adapted from Garn



ɔheric Cross-section over West Africa
adapted from Garnier 1956)

mainly to the south of latitude $8^{o}N$ or $9^{o}N$, thus limiting the area covered by humid conditions.

The migratory movement of the Surface Discontinuity, conditioned by the seasonal movement of the sun, strongly influences the regional pattern of West African climate. North of the SD lies dry easterly air with cloudless skies but rather dust-laden air, whereas south of it there are moist, south-west winds at the surface reaching a height of about 6,000 to 8,000 ft. but with easterly winds aloft. These contrasts, in both a vertical and a horizontal sense, lead to the formation of distinctive weather zones which fluctuate in relation to the varying position of the SD. It has been said that the rate of northward movement of the weather zones is at an average rate of a hundred miles a month and that the southward movement is much faster, at about two hundred miles a month (Walker, 1958).

The distinctive zonal weather patterns created by the contrasts across the SD, and the variations in its locations, have been most thoroughly studied in relation to conditions in Nigeria and Ghana, but very similar effects may be seen over West Africa as a whole. Four zones from north to south have been recognised (Fig. 7) by Walker (1958), Garnier (1967), Hamilton and Archbold (1945), and the Air Ministry, Meteorological Office (1944).

Lying to the north of the SD is zone A, a region of extremely dry air with a relative humidity of 30% or less and characterised by light to moderate, but steady and dessicating, winds. Though the skies are cloudless, the atmosphere is often hazy because of settling dust. The days are hot, with temperatures in the vicinity of $90^{o}F$, but nights are cool, at times seeming cold as the temperature drops to 60°F or less. When the SD is well to the south, the air immediately to the north of it is in contact with the forest and woody savanna or the numerous streams and other water bodies of the area. The consequent relatively high humidity content of the air near the surface, together with nocturnal radiation from the settling dust, thus results in early morning mist which lasts for a few hours before the warming effects of the sun are felt, and the mist dissipates. Any cloud likely to be found consists of broken cirrus high in the sky. During winter, in particular, much dust is often associated with this zone and surface blown dust is transported to great distances by gusty winds of more than 20 miles per hour. These "Harmattan" conditions are often accentuated subsequent to the passage of cold fronts in winter through the Mediterranean, which produce a synoptic situation encouraging a long trajectory of air across the Saharan sands (Hamilton and Archbold, 1945).

Zone B is found immediately to the south of the SD (which forms its northern boundary), but its southern limits are not too clearly defined, being some 150 to 200 miles south of the Discontinuity. Surface winds are light west south-west and the depth of the maritime air is shallow. Therefore, the surface atmosphere here is moist in its lower layers but dry above where east north-east winds persist. The low level dampness is expressed either as early morning mists, or as low morning stratus cloud, developing into scattered small cumulus clouds as the day progresses. This is more noticeable in the southern part of the zone than in the north where the morning mist or cloud is often absent. In general the cumulus clouds, with their bases around 2,500 to 3,000 ft., are unable to grow to great heights, owing to the overlying dry air into which the cloud evaporates as it grows. Rainstorms or thunderstorms in zone B are therefore uncommon, but isolated instances do occur. Sometimes in the afternoons or evenings thunderstorms develop but they usually bring little rain.

Atmospheric humidity is generally high. Relative humidity is in the vicinity of 90% to 100% at night and rarely falls below 60% by day. Warm nights (70^{o}F) and hot days (90^{o}F to 100^{o}F) create a hot, "sticky" atmosphere typical of conditions when the season is "building up" towards the rains.

South of zone B is zone C. It extends over a distance of between four and six hundred miles in a north-south direction, and has rather ill-defined north and south boundaries. The maritime surface air is deeper than in zone B and the overlying easterlies are moist rather than dry (Fig. 7). The depth of moist air permits the development of clouds in the unstable atmosphere so that rain showers and thunderstorms are frequent.

Reliable and persistant rain, however, is not necessarily characteristic of the zone. Periods of rainfall are short-lived with a good deal of sun in between times. Precipitation is associated with particular atmospheric situations, especially with disturbance lines oriented roughly north to south and moving in a westerly direction (Hamilton and Archbold, 1945; Eldridge, 1957). These constitute lines of thunderstorms which in general move from east towards west and provide a major source of rainfall in zone C. Such disturbance lines "may range from a well defined line squall through a line, possibly broken, of thunderstorms, to a heavy belt of cloud without rain" (Walker, 1958, p. 2). They travel at about 30 miles per hour and tend to occur regularly over periods of three or four days, followed by 24-48 hours without disturbance line activity (Eldridge, 1957).

A second cause of rain in zone C is the presence of ill-defined regions of local thunderstorm activity. These regions give to the area within their influence some widespread scattered rainfall. This is particularly the case in the south of zone C where widespread and fairly steady rains are common, with small changes in the generally high temperature and humidity. Daytime precipitation from rainstorms may cause big changes in temperature and humidity (Hamilton and Archbold, 1945; Garnier, 1967). With the onset of the rain, the temperature (80°F to 90°F before the rain) may fall by about 10°F and the relative humidity rises accordingly. However, if the rains occur during the night the influence on both temperature and humidity is less, which indeed may change not at all from the prevailing 70°F to 75°F and near 100% relative humidity (Garnier, 1967).

Zone D lies to the south of zone C and at a distance of about seven hundred to eight hundred miles from the SD. It has a latitudinal extent of some two hundred to three hundred miles with variable and ill-defined boundaries. The region is one of relatively low temperatures: by day the temperature is in the vicinity of 70°F to 75°F and by night it drops to about 65°F. The humidity is high at all times and vapour pressure is maintained at a level between 28-32 mbs. (Garnier, 1967). Relatively stable upper air conditions lead from time to time to an inversion (Hamilton and Archbold, 1945), although this is not always the case. But whether an inversion exists or not, the stability of the upper air tends to inhibit upward air movement and the consequent decrease in convection means that there is little rainfall in zone D. Low level stratus clouds with bases between 800 and 1,000 ft. are characteristic of this zone.

Moisture belts

The weather zones described above express the manner in which certain types of weather patterns are associated with the position of the SD at any particular time of the year. They also produce distinctive "moisture belts" which differ according to the nature of the zone. Thus, in zone A there is very little precipitation and such moisture as exists is expressed in the mist associated with the presence of dust particles and the light dew formed at times by nocturnal cooling. Zone B is similar to zone A in that precipitation is largely absent. However, the moist air of the lower levels of the atmosphere is expressed in high humidities giving rise to morning mists and considerable surface condensation, especially when the zone is over forest areas. However, the afternoon cumulus clouds, characteristic of the zone, may grow under the influence of topographic irregularities into moderate sized storm clouds. Nevertheless, the resulting thunderstorms do not necessarily produce much rain, and the zone as a whole is not characterised by more than scattered and irregularly-occurring precipitation.

The moisture situation in zone C is another story. Here the atmosphere is active, and in the moist unstable air the growth and development of cumulus clouds to considerable heights is readily achieved. This is expressed in the clearly defined pattern of thunderstorms associated with disturbance lines, or in the outbreaks of thundery rain which may cover a wide and somewhat ill-defined area. Zone C, therefore, is pre-eminently the zone of rainfall in West Africa, and the duration of this zone in a given area is closely associated with the duration of that area's rainy season.

By contrast, zone D, although extremely humid in an atmospheric sense, is one in which rainfall is infrequent. Morning mists, high humidities, and lack of sunshine all accentuate the dampness by which the moisture elements of this weather zone are characterised.

The north-south fluctuation of these moisture zones has a marked influence on the quantity, seasonal contrasts, and nature of the precipitation which arrives in different parts of West Africa. Since zone B is narrow, and since zone D affects only the southern part of the area, it is principally zone A and zone C which tend to dominate. This is expressed in the strong seasonal contrasts over the area. The study of the basic climatology also shows that the main precipitation belt is zone C, with its vigorous convection and characteristic disturbance lines. Its arrival in an area tends to mark the start of the rainy season, the upper air divergence in the zone - a divergence which may possibly be associated with an easterly jet stream (Hayward, 1968) - giving rise to the instability and rainfall present in the area.

Relation of vegetation region to weather and moisture zones

In view of the connection between the weather and moisture zones and the position of the SD, it seems reasonable to think that an analysis of the varying position of this discontinuity might produce an understanding of moisture conditions in the savanna region. With this in view, the daily position of the SD for the years 1958, 1959, and 1960, was mapped for the area of West Africa east of longitude 6^{o}W and as far north as latitude 20^{o}N. This area covers the main region of the savanna as given in Fig. 5. The information for this daily analysis was obtained from the daily synoptic maps prepared for 0600 GMT by the Nigerian Meteorological Service, supplemented by information obtained from the Ghana Meteorological Service. The position of the SD was examined on the basis of 2°latitude and longitude squares, and the zone within each square for each day was noted. For this purpose it was considered that zone A was north of the SD, that zone B was within 3°latitude south of it, that zone C lay from 3° to 10°latitude to the south of the Discontinuity, and that zone D was south of the latter latitude. The 2°square through which the SD passed on a given day was ignored in the analysis to allow for the potential daily fluctuation of the SD which Clackson has shown can be as much as two hundred miles (Clackson, 1957). In this way it was possible to express how frequently the different weather zones occurred in each 2°latitude and longitude square.

The four maps on Fig. 8 show this frequency averaged over the three years analysed. The isolines displayed on each map have been selected so as to portray the most noticeable features of the frequency distribution. They indicate the decreasing influence southwards of zone A, and show how zone D did not reach further north than latitude 8°N during the three years analysed. Zone B, being essentially an area of transition between zone A and zone C, did not occupy any part of the area for more than 25% of the year on the average, the major area of relatively long duration being between latitude 6° and 14°N. Zone C, on the other hand, had quite a widespread influence, divided essentially into two parts: an area north of about 12° or 14°N where its influence is apparent for between 30% and 40% of the year, and the region to the south where its influence is of greater duration, with a maximum of over 60% but less than 70%, just to the north of the limit of influence of zone D.

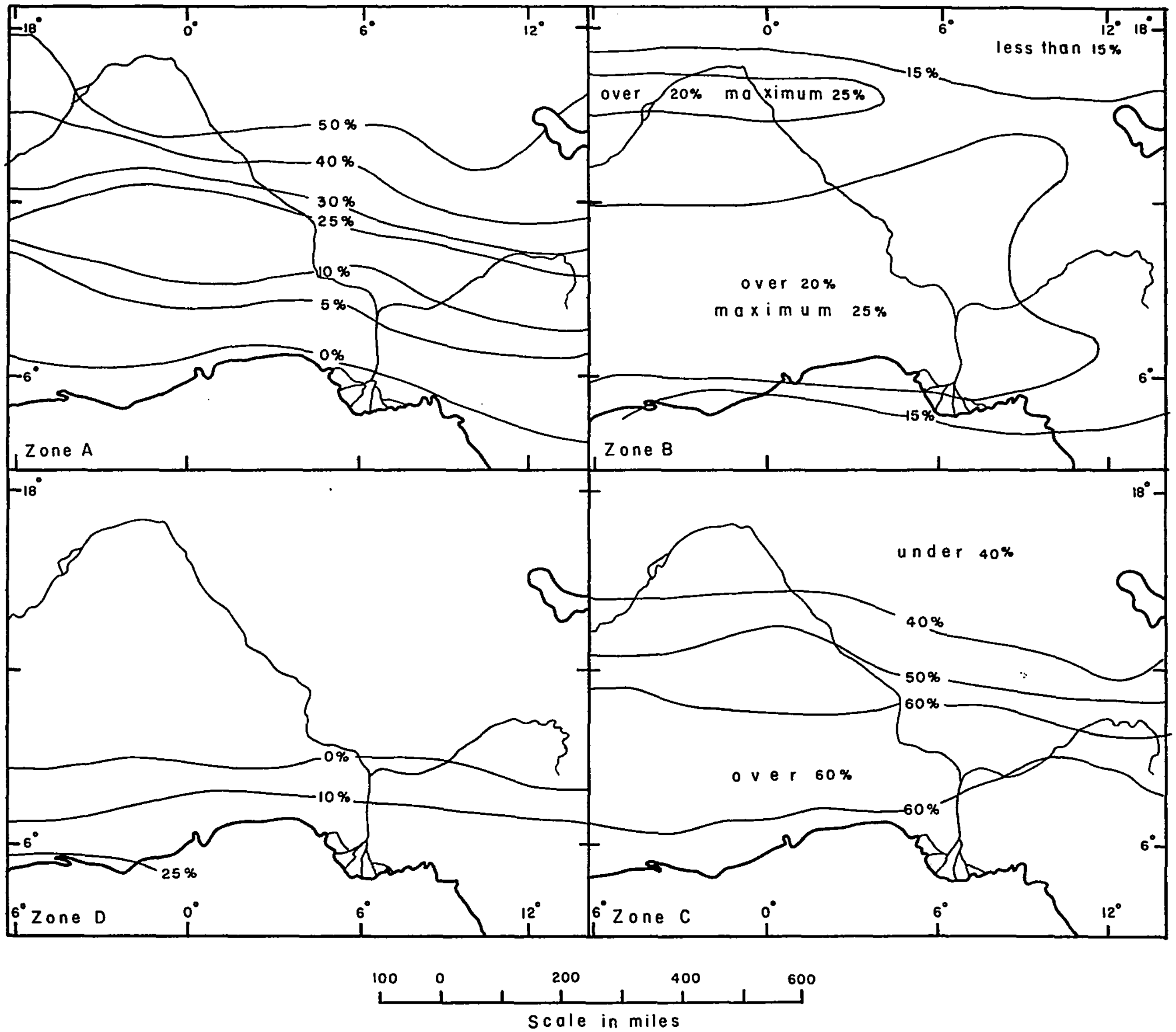
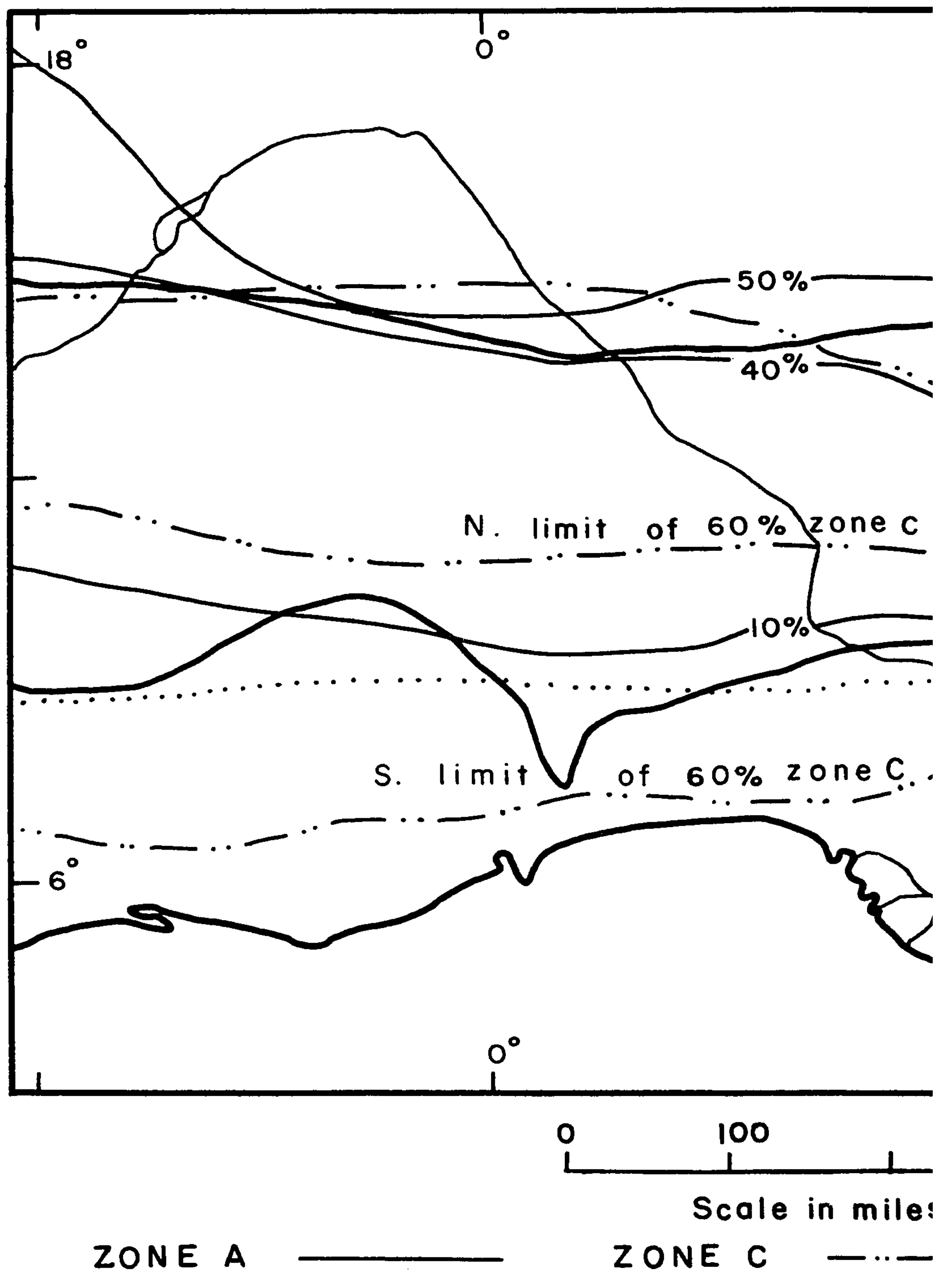


Fig. 8. Percentage Frequency of Weather Zones over West Africa

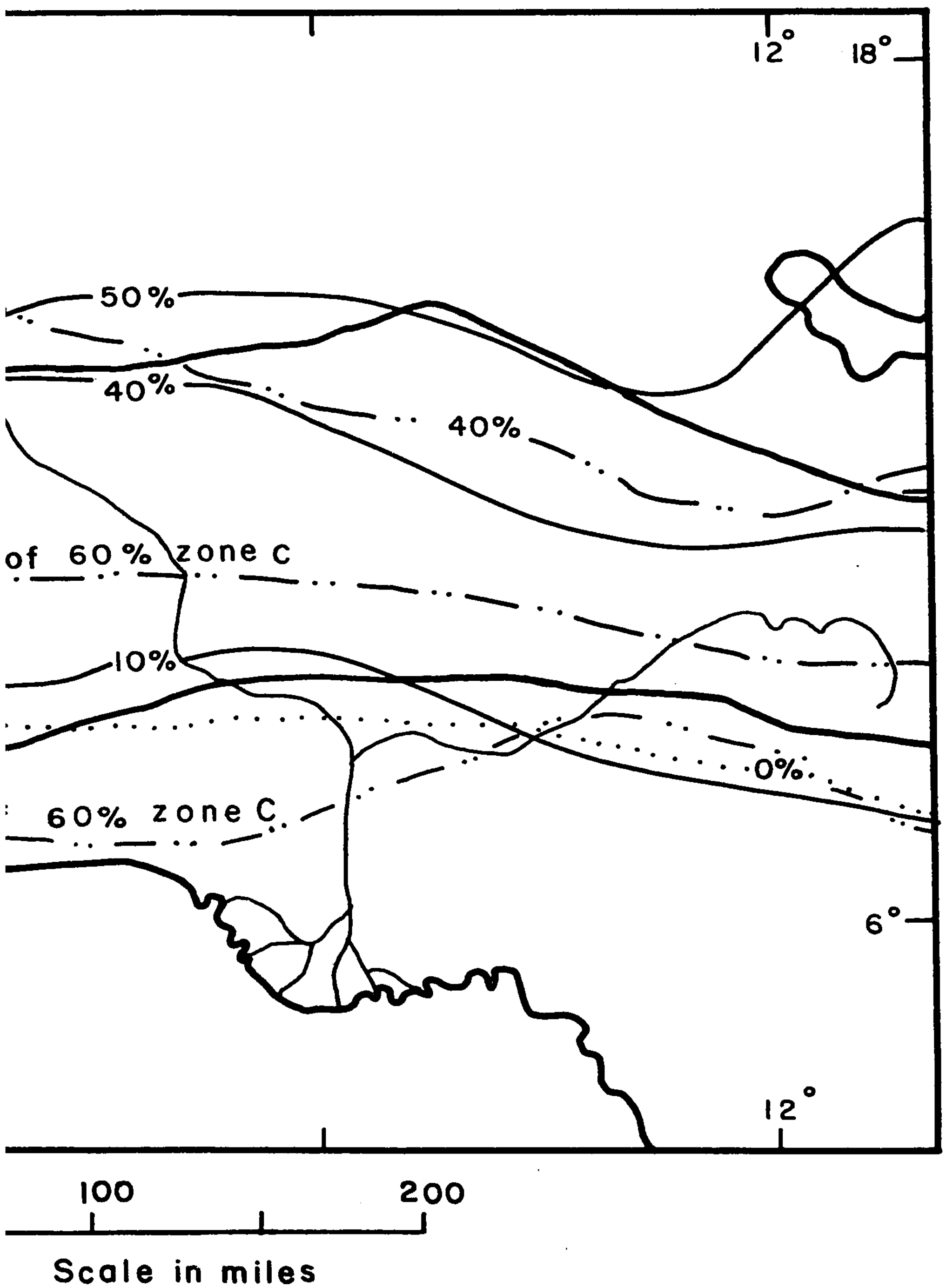
When these frequencies are related to the boundaries of the savanna (Fig. 9), it can be seen that the area is quite clearly distinguished from the regions to the north and south of it in terms of weather-zone frequencies. Zone A dominates the savanna for 10% to 40% of the year, except in north-east Nigeria where a small area experiences zone A for up to 50% of the year. Zone D does not reach it, and zone C is there for between 40% and 60% of the year throughout most of the region, but with a frequency higher than 60% in the southern part. These combinations of values separate the savanna from its neighbours. To the south the southern transition and forest lack a notable experience of zone A but are visited by zone D for some of the year, whereas to the north of the savanna zone A is clearly the dominant weather zone for over half the year.

As a first approximation arising from this chapter's examination of West Africa's basic climatology, therefore, it would appear that there is a *prima facie* case in which moisture conditions, as revealed through the weather zones, make the "agreed" savanna region climatically different from its neighbours. The remaining chapters of this thesis will try to see to what degree this may be true and how such distinctiveness may be expressed.



Savanna Boundary

Fig. 9. Relation of the Savanna Region to



ONE C —··—··—··   ZONE D ········

a Boundary ————

anna Region to Weather Zones in West Africa

CHAPTER FOUR

METHOD AND LEVEL OF INQUIRY

At the most general level the moisture characteristics of an area may be considered by referring to mean annual conditions, particularly mean annual rainfall totals. As a way of distinguishing the moisture conditions of the West African savanna, however, the approach is not particularly fruitful.

Aubréville, for example, has pointed out that in parts of West Africa, wooded savanna is found where the mean annual rainfall is in the vicinity of 2,000 mm., whereas in some areas of dense forests the mean annual rainfall is no more than 1,250 mm. (Aubréville, 1949, p. 65). Substance for such a view is given in Fig. 10. The figure shows the relation of the savanna and non-savanna regions established as a basis for this study (Fig. 5) to the distribution of mean annual rainfall over West Africa, as given in Jackson's recent treatment of African climate (Jackson, 1961). It can be seen that parts of the savanna core region have a mean annual rainfall comparable both with that of the southern transition zone and with that of some areas of forests. In the north, where the latitudinal zoning of the vegetation is particularly marked, the boundary of the savanna for most of its length has a closer correlation to mean annual rainfall than it does to the south. But taking the savanna region as a whole, it is difficult to find a value, or range of values, whereby the region may be clearly distinguished from the areas on either side of it. The best that can be said is that most of

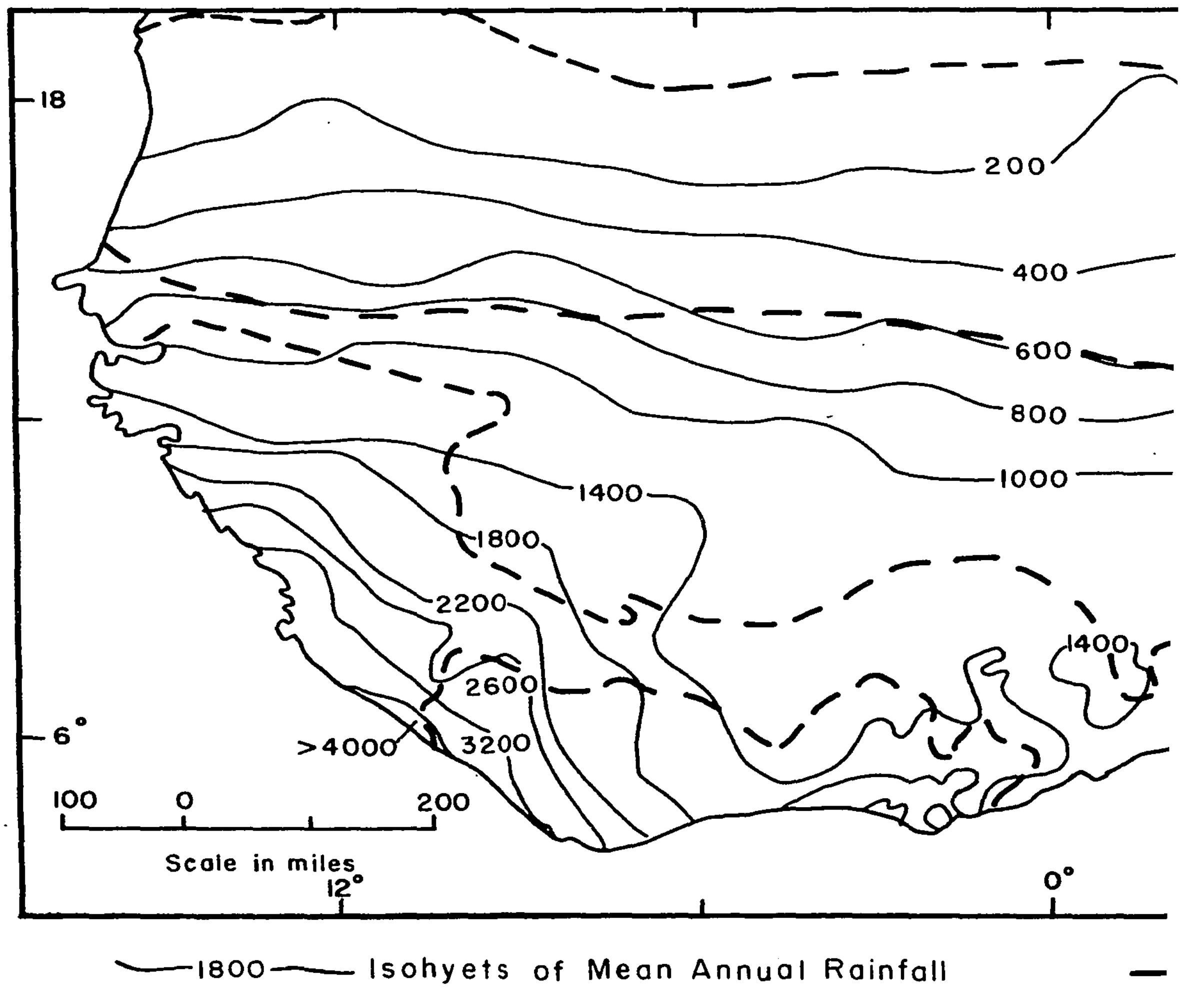
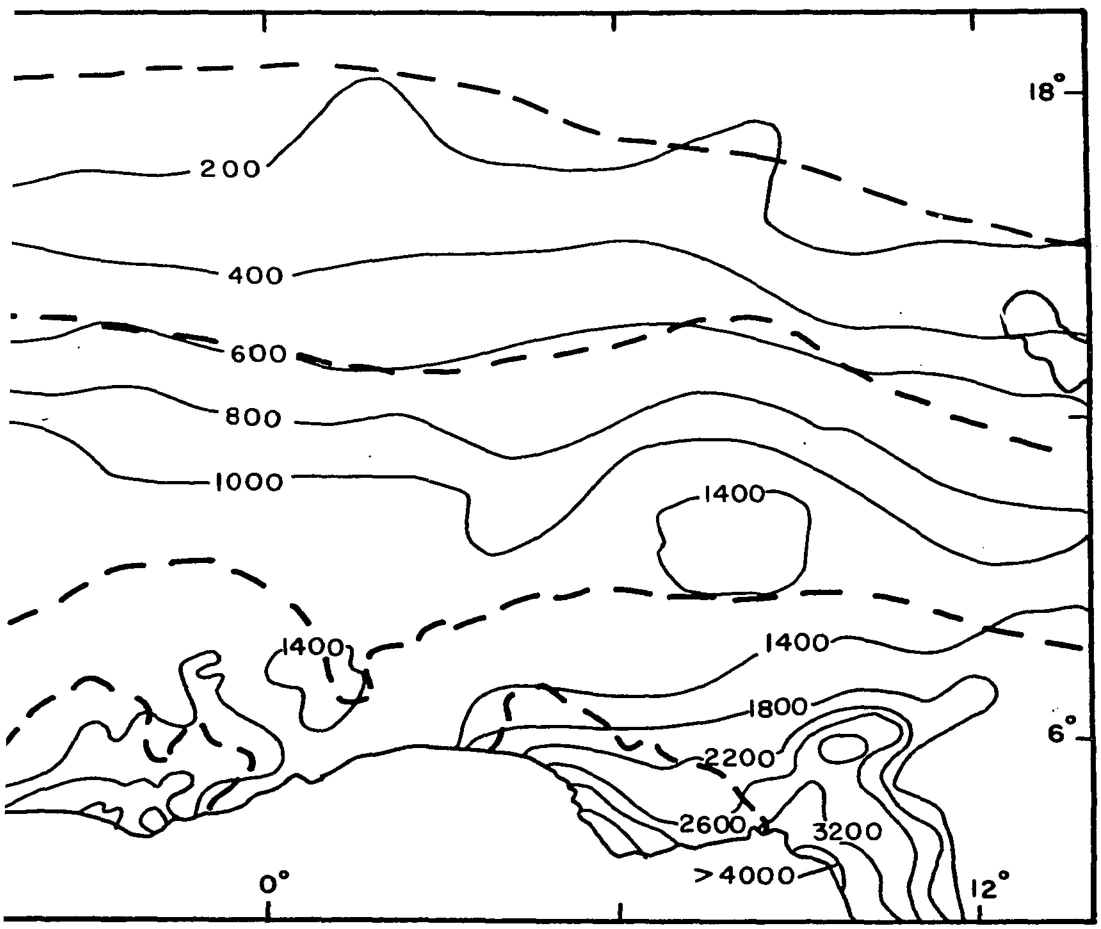


Fig. 10. Relation of Vegetation Boundaries to Me
(Rainfall from Jackson



ıl Rainfall — — — Vegetation Boundaries

Boundaries to Mean Annual Rainfall in West Africa
all from Jackson 1961)

the savanna has a mean annual rainfall of between 600 mm. and 1,400 mm., that the northern transition zone has less than this amount, and that the core forest regions and about half the southern transition have more.

A recent study of the moisture balance in Africa (Davies, 1969) runs into similar difficulties in trying to relate the savanna/forest boundary to mean annual precipitation and mean annual potential evapotranspiration. Although the data of individual stations suggested the possibility of locating the savanna/forest boundary by reference to stations where, on an annual basis, precipitation equals potential evapotranspiration, a plot of the data on the vegetation map of Nigeria showed that the relationship was not as clear as the evidence of the individual stations had suggested (Davies, 1969, p. 30). The data of Table II draw further attention to this discrepancy. The evidence in the table shows that the mean annual water balance in the savanna on the whole is negative, but negative over a very wide range which at one end of the scale links the area with the northern transition, and in the central portion of the scale (-350 mm. to -700 mm.), with the southern transition.

It appears clear, therefore, that any substantive and realistic appraisal of moisture conditions in the West African savanna must focus upon a shorter time interval than a year. To consider the matter in terms of monthly values seems logical and this level of analysis has, in fact, been adopted for the greater part of this thesis. However, as will be shown later, even this level is too general to provide an adequate insight into the peculiarities of the moisture conditions of the savanna area. Thus, daily conditions will also be examined, but only after a thorough investigation of moisture at the monthly level has been made.

TABLE II

MEAN ANNUAL WATER BALANCE AT WEST AFRICAN STATIONS

Savanna Stations

Kayes	-1172
Sokoto	-947
Bamako	-553
Ouagadougou	-922
Kano	-639
Maiduguri	-948
Bobo-Dioulasso	-416
Natitingou	-250
Navrongo	-723
Kaduna	-41
Minna	-298

Northern Transition Stations

Kidal	-1506
Timbuktu	-1567
Zinder	-1283
Mopti	-1090
Niamey	-1270

Southern Transition Stations

Tamale	-674
Ilorin	-376
Mamou	817
Freetown	1860
Bouaké	386

Forest Stations

Benin	435
Warri	1081
Port Harcourt	739

Note: Figures indicate Mean Annual Rainfall minus Mean Annual Potential Evapotranspiration.

Rainfall and water balance at selected stations

To provide a pointer to the nature of the discussion which will be undertaken at the monthly level, a presentation of monthly conditions at five stations is given in Fig. 11. Two of these stations, Kano and Natitingou, are in the savanna, Agadez is in the northern transition zone, Ilorin is in the southern transition, and Warri lies within the forest realm. Agadez in the north can also be thought of as representing conditions on the desert border.

On each of the diagrams the mean monthly precipitation and potential evapotranspiration are plotted, and an indication of precipitation variability is given by means of dots as used in standard dispersion diagrams.* It can be seen that the two savanna stations of Kano and Natitingou experience a short season of two to three months in which rainfall is well over 125 mm. per month. These few months comprise a wet season, in whatever terms such a season may be defined, whether as having a rainfall of over 100 mm., for example, or in water balance terms, as the period when precipitation is greater than potential evapotranspiration. Within this concentrated wet season the range of precipitation variability is comparatively high, but no higher than is to be generally expected in the tropics.

It is interesting to note that in spite of this variable wet season distribution of rainfall, none of the wet months proper has a rainfall which falls below potential evapotranspiration. The last of the generally wet

* The discussion on the nature of the water balance is reserved for Chapter Six, in which the different methods of calculating potential evapotranspiration and the relevance of using the mean monthly potential evapotranspiration as a guide to water balance conditions at the monthly level are outlined.

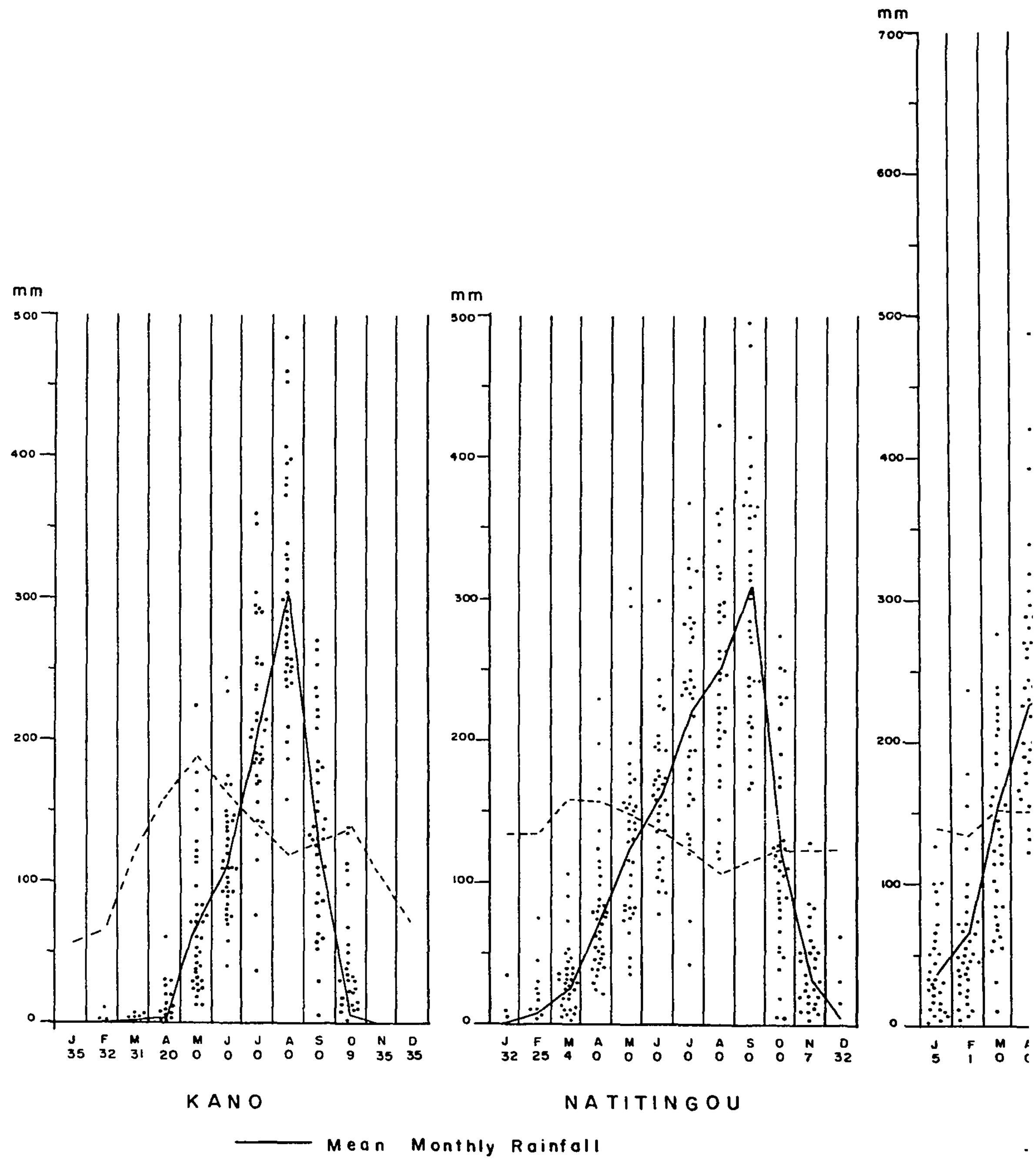
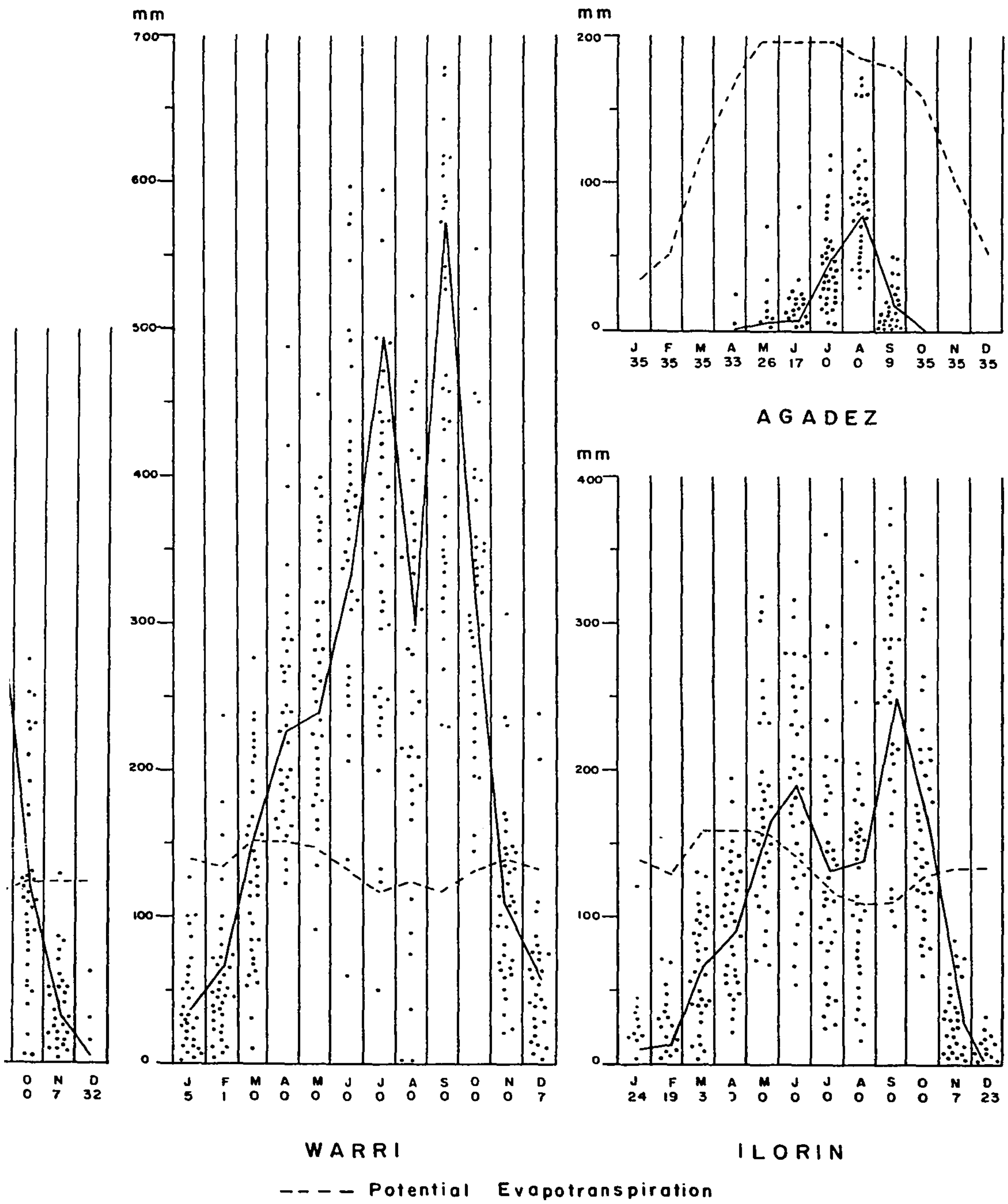


Fig. 11. Precipitation Variability and the Water

Note: A period of 35 years within the period 1921 to 1960 wa
below each month indicate years without rain.



and the Water Balance at Five West African Stations

1921 to 1960 was used according to data availability. Numbers
rain.

season months, however, has a balanced distribution of months above and below the potential evapotranspiration, and a somewhat similar balance is seen before the beginning of the wet season as well. Just as the wet season in the savanna is a brief period of reliable rainfall, so is there a longer period of markedly and "reliably" dry conditions in which the contribution of moisture as precipitation is almost totally absent and in which, with no exception, two to four months are below the value of potential evapotranspiration.

Comparing the conditions at Kano and Natitingou with those at Agadez in the northern transition, it is clearly evident that the latter station has a drier wet season than the former. Moreover, the season is very short, comprising only one month of reliable rain and with no months, even in the height of the rainy period, having a rainfall exceeding potential evapotranspiration.

The forest station of Warri is distinguished from the two savanna stations by its longer period of wetness coupled with higher rainfall totals. The variability of precipitation from year to year is, however, rather high, particularly in the wet season. The period of time when one might reasonably expect the precipitation to be greater than potential evapotranspiration is nine months. Of this period, however, only two months, September and October, are ones in which the rainfall total is consistently greater than the potential evapotranspiration. In all other months, precipitation is at times less than potential evapotranspiration: indeed, in January it is consistently below the latter, and in December and February it is similarly related to the potential evapotranspiration for 90% of the time. The general impression obtained from examining the diagram for Warri, therefore, suggests that the rainfall is less reliable here than either at Kano or Natitingou in the wet season, but that the longer length of the rainy season and the greater quantity of precipitation compensate for this situation.

Ilorin, an example of a southern transition station, lies between Warri and the savanna stations in its rainfall variability characteristics and in terms of the frequency of months less than potential evapotranspiration. The number of months when precipitation is greater than potential evapotranspiration is only slightly more than the number for the two savanna stations, but the station is more like Warri in having a wet season in which some months are above and others are below the potential evapotranspiration value.

Basis of regional investigation

This brief discussion of the precipitation characteristics of five stations offers guidelines for the inquiry which might be profitably followed at the monthly level on a regional scale: the quantities and frequency of occurrence of precipitation, together with an investigation of the water balance and how it varies from year to year each month. To put this into a regional context, a large number of stations over West Africa were chosen for examination (Fig. 12). From these stations a selection was made so as to provide a systematic study of conditions by means of cross-sections cutting across the different vegetation belts.

The stations chiefly used were chosen from two principal zones: an eastern zone extending from the Niger delta across Nigeria northwards

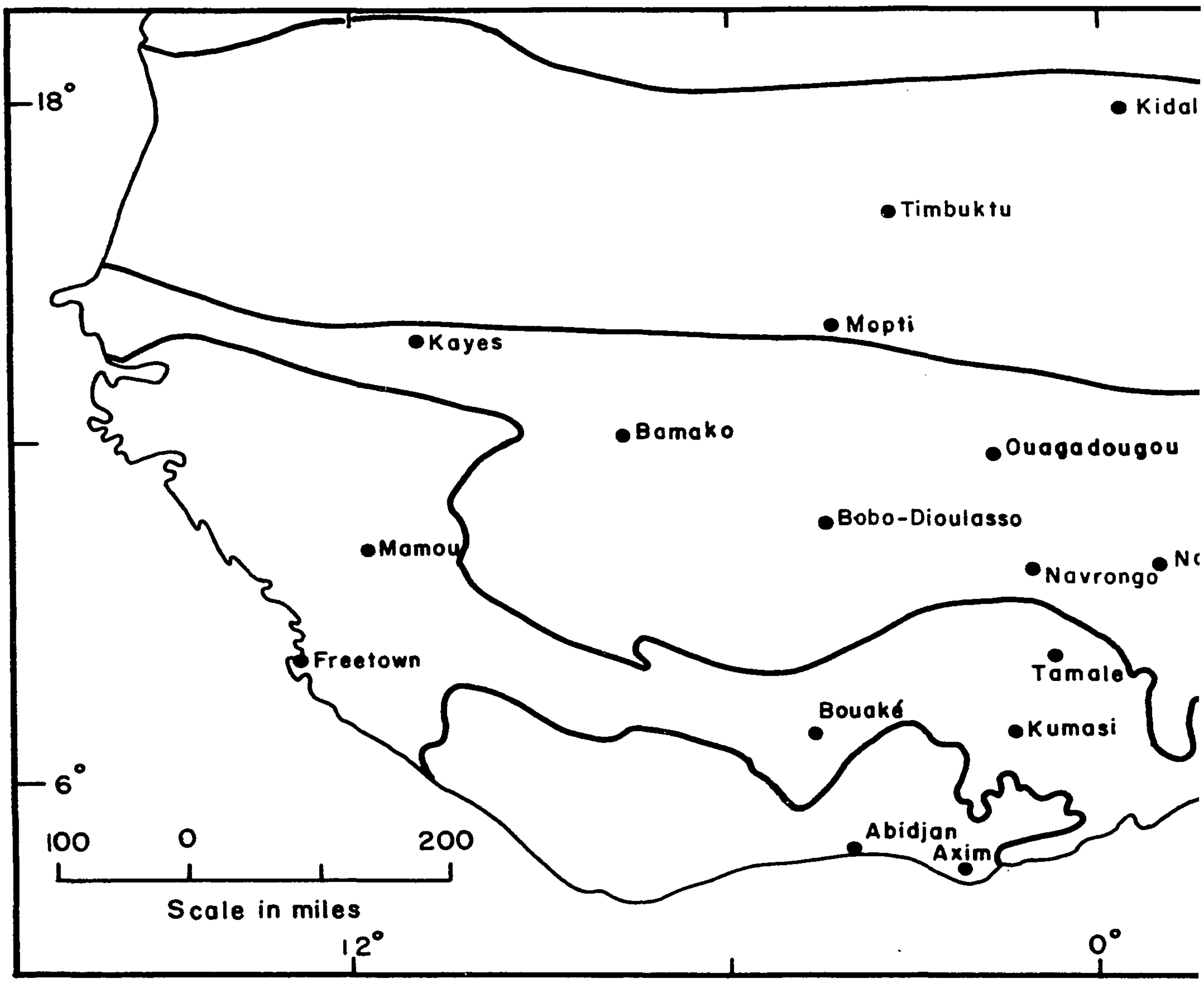
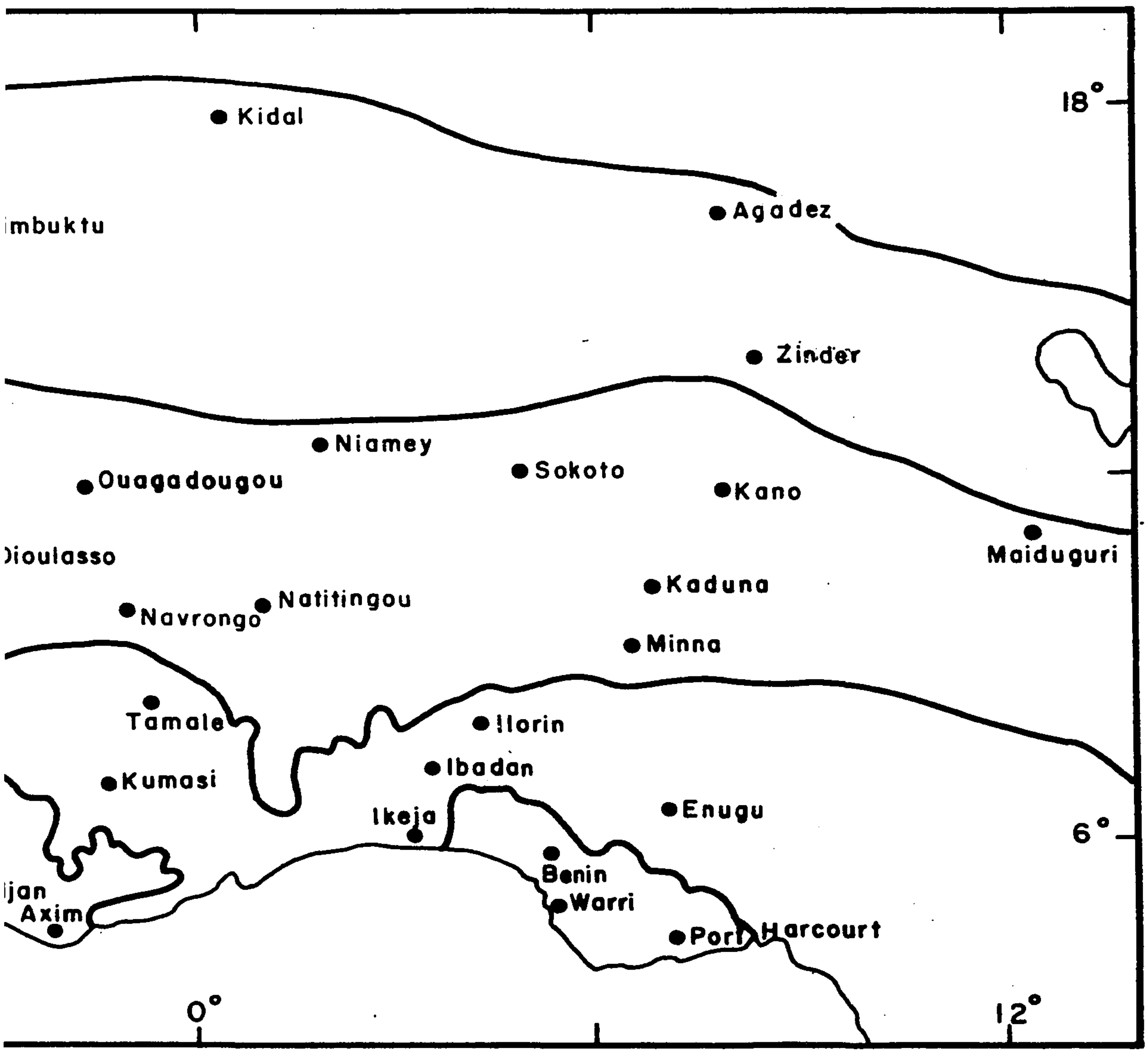


Fig. 12. Climate Stations of We



: Stations of West Africa

TABLE III

STATIONS USED FOR REGIONAL MATRICES

EASTERN ZONE	
Northern Transition	Agadez Zinder
Savanna	Sokoto Kano Kaduna Minna
Southern Transition	Ilorin Ibadan Enugu
Forest	Benin Warri Port Harcourt
CENTRAL ZONE	
Northern Transition	Kidal Timbuktu Mopti
Savanna	Niamey Ouagadougou Bobo-Dioulasso Natitingou
Southern Transition	Tamale Bouaké Kumasi
Forest	Abidjan
WESTERN ZONE	
Northern Transition	Kidal Timbuktu Mopti
Savanna	Bamako
Southern Transition	Mamou Freetown

to Agadez, and a central zone through the Ivory coast northwards to Upper Volta and into Mali. Some use was also made of a line of stations from the west coast inland. Table III indicates the stations used in respect to these three zones and their classification in terms of their location in the different vegetation regions. The latitudinal belting of the vegetation zones, as shown in the base map (Fig. 5), suggests that to use cross-sections of this type offers a reasonable way of examining the distinctive moisture characteristics of the savanna since contrasting aspects are more clearly defined in this direction than in an east to west direction. The similarity of conditions in the latter direction, and the north to south contrasts, are also brought out by the latitudinal belting of the weather zones discussed in Chapter Three.

Principal attention will be paid to the stations in the eastern and central cross-sections. There are two main reasons for this: the first is that the savanna core region is most clearly defined in that part of West Africa which lies east of longitude 10^{o}W; the second reason is that reliable statistics over a relatively long time period for an adequate sampling distribution were more readily available here than for much of the western area, where the station network is somewhat sparse.*

Much of the data on which the discussions of the next two chapters will be based is presented in the form of matrices. The arrangement of each of these is essentially the same. The stations used are listed on the left-hand side with the most northern station at the top. Horizontal lines group the stations into appropriate vegetation zones as indicated in Table III. This

* A description of data sources and the time periods of the records for different stations will be found in Appendices One and Two.

will provide a diagrammatic representation of moisture conditions in the savanna and show how they compare or contrast with the characteristics of the non-savanna areas on either side of them.

CHAPTER FIVE

MONTHLY RAINFALL CONDITIONS

The brief discussion of individual stations in the last chapter expresses in a general way how the quantity, character, and seasonal pattern of precipitation vary from the forest through the savanna to the northern transition zone. The purpose of the present chapter is to offer a more coherent impression in a regional setting by considering different aspects of precipitation over West Africa at the monthly level.

Mean monthly rainfall

Figure 13 is a matrix which refers to mean monthly rainfall in the east and central cross-sections, already mentioned, and also to that of four stations extending from the west coast inland in a north-east direction through the savanna. Isohyets on the matrix at 0 and 100mm. levels draw attention to the progressive northward decrease of abundant precipitation, with a consequent increase of months in which mean monthly rainfall is zero. In the forest and southern transition area some rain is recorded throughout the year. The savanna stations, however, have some months with an average of zero rainfall and some other months with more than 200 mm., whereas the northern transition stations have fewer months with over 200 mm. than the savanna, and more months which are on the average rainless. The chief distinguishing expression of the savanna in this matrix is thus seen to be in the strong "seasonality" which is more marked than in the forest with its steady record of rain, and also than in the northern transition in which the keynote is a

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	0	0	0	0	6	8	49	78	20	0	0	0
Zinder	0	0	0	3	27	55	153	232	71	7	0	0
Sokoto	0	0	0	13	51	80	205	268	143	19	0	0
Kano	0	0	2	8	71	119	209	311	187	14	0	0
Kaduna	0	2	13	69	147	180	218	312	279	76	5	0
Minna	0	5	22	58	138	177	210	241	276	140	10	4
Ilorin	12	5	68	93	167	193	131	138	251	171	28	11
Ibadan	10	23	89	137	150	188	160	84	178	155	46	10
Enugu	19	15	81	209	195	166	182	190	282	246	53	23
Benin	20	33	91	175	208	302	315	208	307	244	74	15
Warri	36	63	151	228	240	333	492	298	573	312	110	58
Port Harcourt	29	68	187	175	249	269	332	278	442	266	93	32
CENTRAL ZONE												
Kidal	0	0	0	0	4	8	38	51	28	0	0	0
Timbuktu	0	0	0	0	3	19	65	95	37	5	0	0
Niamey	0	0	0	3	19	84	181	206	101	21	0	0
Ouagadougou	0	3	8	19	84	118	193	265	153	37	2	0
Bobo-Dioulasso	0	3	20	47	116	132	229	336	211	75	13	2
Natitingou	3	8	26	75	126	162	221	254	311	118	33	5
Tamale	2	9	51	88	121	132	128	189	217	98	13	5
Bouaké	38	74	153	207	187	198	176	278	378	161	57	26
Kumasi	26	65	136	139	191	223	113	74	170	201	95	32
Abidjan	26	42	120	169	366	608	200	34	55	225	188	111
WESTERN ZONE												
Kidal	0	0	0	0	4	8	38	51	28	0	0	0
Timbuktu	0	0	0	0	3	19	65	95	37	5	0	0
Mopti	0	0	0	3	19	55	154	195	104	20	0	0
Bamako	0	0	3	15	60	145	251	334	220	58	12	0
Mamou	6	7	39	86	164	242	328	454	378	291	79	10
Freetown	17	8	32	65	226	389	730	800	528	301	171	54

Fig. 13. Matrix of Mean Monthly Rainfall (mm.)

(For Period See Appendix Two)

large number of rainless months with only one or two months of notable mean monthly rainfall in the middle of the year.

Further examination of the matrix indicates that the savanna is distinguished by having at least two, but not more than five, months in which the mean monthly rainfall is zero, and at least three, but not more than six months, with an average of 100 mm. At least one, but not more than three, of the higher rainfall month averages over 200 mm. falls into this category. About half the savanna stations also have one month with an average rainfall of 300 mm. or greater. These values differ noticeably from the stations representative of the other zones. Thus, southern transition and forest stations have, on the average, rain in every month, though not necessarily always more than the savanna, especially in the transition area and at Abidjan where "little dry season" characteristics are well marked in July and August. Unlike the savanna, however, these stations all have a plentiful average rainfall during most of the year and do not share, according to the evidence of the matrix, the strong seasonal contrast between a clearly dry season and a clearly wet season which appears to be a characteristic and distinguishing feature of the savanna. The limit to the savanna region in the northward direction, however, is given by the presence of a long dry season, scarcely offset by even two months of notable rainfall.

Monthly rainfall variability

Further insight into rainfall characteristics can be gained by looking at the year to year variation of totals in each month of the year. This has been done in respect to firstly, the presence or absence of recorded rainfall, and secondly, the amount of rainfall to be expected in a given month.

Figure 14 is a matrix illustrating the first point of view in terms of the percentage of years in which rain was recorded each month over the periods analysed. Significant differentiation of the savanna region in this respect is obtained by reference to two frequency levels: a frequency of 100%, and one of 20% or two years in ten. Using these thresholds it can be seen that the savanna region is distinguished by the combination of the duration of the two frequencies: rainfall being recorded ten years out of ten for a minimum of four months and a maximum of seven months; and a minimum of two months but not more than five months in which rain is not recorded for at least eight years in ten. That seasonal contrast is a distinguishing element of the savanna region is thus again emphasized by the fact that it is the combination of these two values which tends to differentiate the savanna climate from its neighbours, rather than either one of them taken individually. Thus, at Agadez, north of the savanna core region, there are five months only in which rainfall has been recorded two years in ten or less over the period analysed; but this is related to a period of only two months of rainfall having been recorded ten years out of ten. To the south of the savanna, on the other hand, 100% frequency for seven months is found at both Ilorin and Enugu, linking these stations to savanna stations such as Minna and Kaduna. But this value is associated with an absence of any months without rainfall eight years in ten, thereby bringing the transition zone more into line with the forest where in every month, even the driest, rain can be expected for at least seven years in ten.

The second view of rainfall characteristics, namely the amount of rainfall to be expected in a given month, is considered in Figs. 15 and 16.

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	5	3	0	60	58	79	100	100	84	16	0	3
Zinder	5	5	8	24	39	100	100	100	100	37	10	5
Sokoto	7	0	10	62	97	100	100	100	100	60	0	0
Kano	5	7	20	62	100	100	100	100	100	80	2	0
Kaduna	12	20	70	100	100	100	100	100	100	100	37	10
Minna	21	14	22	100	100	100	100	100	100	100	43	14
Ilorin	45	60	97	100	100	100	100	100	100	100	90	45
Enugu	63	84	97	100	100	100	100	100	100	100	97	66
Benin	79	100	100	100	100	100	100	100	100	100	100	72
Warri	83	97	100	100	100	100	100	100	100	100	100	85
CENTRAL ZONE												
Kidal	11	9	14	22	45	92	100	100	89	25	11	11
Mopti	9	3	14	58	94	100	100	100	100	92	25	6
Ouagadougou	6	16	52	94	100	100	100	100	100	97	32	4
Bobo-Dioulasso	15	36	80	49	100	100	100	100	100	100	80	19
Bouaké	71	97	100	100	100	100	100	100	100	100	94	80
Abidjan	88	96	100	100	100	100	100	100	100	100	100	100

Fig. 14. Matrix of Percentage Frequency of Years with Some Rain Recorded (Period of 35 years, within the period 1921 to 1960)

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	0	0	0	0	0	0	2	31	0	0	0	0
Zinder	0	0	0	0	0	0	64	48	21	0	0	0
Sokoto	0	0	0	0	0	10	61	114	38	0	0	0
Kano	0	0	0	0	10	38	76	99	31	0	0	0
Kaduna	0	0	0	0	43	112	66	117	122	2	0	0
Minna	0	0	0	17	45	64	86	123	182	50	0	0
Ilorin	0	0	0	23	66	61	0	10	104	61	0	0
Enugu	0	0	0	48	127	38	46	8	114	122	0	0
Benin	0	2	31	73	127	173	86	36	190	147	27	0
Warri	0	0	30	122	94	140	61	30	234	150	23	0
CENTRAL ZONE												
Kidal	0	0	0	0	0	0	3	19	0	0	0	0
Mopti	0	0	0	0	0	12	46	74	31	0	0	0
Ouagadougou	0	0	0	0	8	47	112	138	60	0	0	0
Bobo-Dioulasso	0	0	0	0	5	33	22	55	30	4	0	0
Bouaké	0	0	11	19	38	15	3	12	54	28	0	0
Abidjan	0	0	21	46	76	200	0	4	5	8	81	5

Fig. 15. Matrix of Lowest Rainfall (mm.) Recorded Each Month (Period of 35 years, within the period 1921 to 1960)

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	0	0	0	0	0	0	23	53	2	0	0	0
Zinder	0	0	0	0	0	20	117	150	37	0	0	0
Sokoto	0	0	0	0	13	53	107	162	77	0	0	0
Kano	0	0	0	0	26	74	155	250	66	0	0	0
Kaduna	0	0	0	30	94	135	166	218	232	31	0	0
Minna	0	0	3	36	76	127	147	152	228	61	0	0
Ilorin	0	0	17	55	110	132	50	47	185	115	3	0
Enugu	0	5	20	89	198	206	145	53	249	188	13	0
Benin	0	9	60	114	166	247	260	153	229	178	30	0
Warri	5	20	82	162	185	255	275	127	330	245	65	2

	J	F	M	A	M	J	J	A	S	O	N	D
CENTRAL ZONE												
Kidal	0	0	0	0	0	2	18	30	4	0	0	0
Mopti	0	0	0	0	2	35	101	112	52	2	0	0
Ouagadougou	0	0	0	5	45	80	149	210	105	8	0	0
Bobo-Dioulasso	0	0	2	16	65	97	145	210	155	35	0	0
Bouaké	0	8	50	80	93	93	35	62	145	78	15	2
Abidjan	2	25	60	70	240	375	30	10	25	93	125	40

Fig. 16. Matrix of Lowest Rainfall to be Expected Eight Years in Ten (Period of 35 years, within the period 1921 to 1960)

Fig. 15 represents the lowest recorded rainfall of each month during the period examined, and Fig. 16 shows the minimum value at the 80% level of frequency (eight years in ten).

Both diagrams are similar in their differentiation of the savanna in terms of the duration of dry conditions. Fig. 15 shows that there are from five to eight months in which the absolute minimum rainfall is zero, whereas Fig. 16 indicates that the same low value was achieved eight years in ten for some four to five months at the southern edge of the region, and for seven months at the northern limits. These figures serve to distinguish the savanna from the northern transition where at least eight months at the 80% level, or nine months at the absolute low level, are shown to be without rain. The southern transition is similar to the savanna in having five months in which the absolute minimum rainfall is zero, but at the eight out of ten years level two or three months with this low figure are characteristic. However, in the generally monsoonal conditions of West Africa, there is the occasional year, even in the forest, when one or more months lack recordable rainfall.

When the wetter months are considered, the high variability of rainfall over West Africa becomes apparent in the rather irregular pattern of values for the minimum quantities occurring. This is particularly apparent in the matrix of absolute lowest values. It can, however, also be perceived in Fig. 16. Nevertheless, in this figure the savanna stations are revealed as all having an expected rainfall of over 100 mm. eight years in ten. One can indeed say that this is a savanna characteristic in the wet season months. While this level of rainfall for an equal or greater number of months is common to most of the forest and the southern transition, the evidence of Fig. 16 suggests that it is not necessarily universal. It is not the case at Bouaké, while at Abidjan the regularly occurring high totals of May and June are separated from those of November by the possibility of distinctly low falls in July, August, and September. The relatively short wet season of the savanna, therefore, is shown up as both concentrated and reliable in contrast with the longer period of the rainy season to the south during which, however, periods of quite low rainfall seem occasionally to occur.

In view of the importance of precipitation in the wet season to the moisture characteristics throughout West Africa generally, an attempt was made to investigate the variability of precipitation in the savanna region at this time of year more closely by statistical analysis. Such procedure, however, needs to be used with considerable caution, especially when applied to rainfall, since standard statistical analysis of variability customarily assumes a normal distribution curve. This is rarely obtained for rainfall, except in the case of a very long series in which zero is not reached. The problem of skewness and variability in relation to rainfall have been treated in a number of publications, and a precise review of the difficulties involved with particular reference to Africa, has been recently published by Gregory (Gregory, 1969). It is there pointed out that a coefficient of variability greater than 35% implies statistical unreliability since it indicates that a normal frequency distribution is most unlikely to be achieved. However, the converse of the argument is that a coefficient of variability less than 35% suggests the possibility of the series approximating to a normal distribution (Gregory, 1969, p. 65).

With these limitations in mind the rainfall of a number of stations in West Africa for which records of thirty-five years or more exist were analysed, and from them the four stations shown in Table IV were selected. Only wet season months were analysed, and use of the "chi-square" test (Snedecor and Cochran, 1967) showed that, except in the case of Kano for July and Warri in June, the resulting analyses were significant at the 5% level.

The choice of months for representation in Table IV was also made because July and August are the peak wet season months of the savanna, whereas June and September are both high rainfall months at Warri. Thus, the table offers some insight into wet season conditions in the savanna as compared with the heavy rainfall months of a forest station. It seems reasonable to suggest from the results that they confirm the implications of the relative reliability of wet season savanna characteristics evident from the data in Fig. 16. The coefficient of variability in the savanna is seen to lie generally within a range of 25% to 35%, and the probability of the wet months reaching a total of 100 mm. is high. The big difference from Warri, however, is in terms of the quantity of rain rather than its reliability. In the savanna stations in July, the chances are that in eight years out of ten the rainfall will lie with a range of just over 100 mm. up to rather more than 300 mm., and at a 60% probability, the range will be between a minimum of 137 mm. (at Kano) and a maximum of 284 mm. (at Kaduna). The corresponding figures for August lie within the range of approximately 180 to 450 mm. at 80% probability and 210 to 410 mm. at 60% probability according to location. At Warri, by contrast, at the 80% probability level in June, the range of expected rain lies between 202 and 518 mm., and in September it is between 311 and 701 mm. From this we can surmise that the degree of reliability of the rainy seasons of the forest

TABLE IV

THE VARIABILITY OF PRECIPITATION DURING THE WET SEASON AT FOUR WEST AFRICAN STATIONS

Station	Month	Mean	SD	CV %	Range of Precipitation 8 years in 10	Range of Precipitation 6 years in 10
Kano	July	78	28.8	36.7	104 - 292	137 - 259
	Aug.	127	28.3	22.2	231 - 414	255 - 383
Kaduna	July	87	29.0	33.2	129 - 317	163 - 284
	Aug.	126	42.0	33.4	183 - 457	231 - 408
Ouagadougou	July	192	48.7	25.3	130 - 254	152 - 232
	Aug.	272	65.6	24.1	188 - 356	217 - 327
Warri	June	360	123.7	34.3	202 - 518	256 - 464
	Sept.	506	151.1	29.9	311 - 701	379 - 633

All figures in mm.

and the savanna are more or less equal, but that the savanna reliability lies around a lower mean level and represents a likely range of precipitation which is less than in the forest.

The foregoing analyses suggest that in terms of monthly precipitation the savanna is distinguished from the non-savanna, principally in regard to the strong contrasts between a dry season and a wet season. The latter is a single peak period of reliable rainfall lasting four to six months, which is shorter than the forest with its double peak rainy season of eight to nine months, but is somewhat longer and distinctly wetter than is found in the northern transition region. On the other hand, if the savanna resembles the forest in the wet season, its dry season adopts the severity of the northern transition in its highly reliably occurring absence of rain.

Rainy days and rain per rainy day

The occurrence of precipitation as expressed in the number of rainy days is an aspect of precipitation that has not been examined so far. Although a detailed examination of individual rainy days will be made in a later chapter, some consideration of this aspect of precipitation at a monthly level is relevant here to see what light it may throw on the generalisations on savanna and non-savanna characteristics reached by the rainfall analyses which have already been made.

The data of the matrix given in Fig. 17 reveal a similar pattern to that of monthly precipitation values. There is a concentration of rainy days within the short wet season in the savanna, an extended wet season in the forest and, by contrast, a very short period of rainy days in the northern transition. When the total rainfall of a particular month is divided by

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	0	0	0	0	1	2	6	10	2	0	0	0
Zinder	0	0	0	0	3	6	10	13	6	1	0	0
Sokoto	0	0	0	1	4	7	13	17	12	2	0	0
Kano	0	0	0	1	5	10	14	17	11	2	0	0
Kaduna	0	0	2	5	12	14	19	21	22	8	1	0
Minna	0	0	2	5	13	14	18	20	20	14	0	0
Ilorin	1	1	4	9	12	14	12	11	18	14	2	1
Enugu	2	2	5	8	16	19	19	16	21	17	2	1
Benin	1	3	6	11	15	19	23	17	23	18	5	2
Warri	3	5	10	13	19	23	23	19	25	23	10	3

	J	F	M	A	M	J	J	A	S	O	N	D
CENTRAL ZONE												
Kidal	0	0	0	0	1	2	5	7	3	0	0	0
Mopti	0	0	0	1	3	7	11	13	9	2	0	0
Ouagadougou	0	0	1	3	7	10	13	16	12	4	0	0
Bobo-Dioulasso	0	1	2	4	7	10	12	17	15	8	2	0
Bouaké	1	4	7	8	10	11	9	12	17	12	4	2
Abidjan	3	5	9	11	19	21	13	11	13	19	16	9

Fig. 17. Matrix of Mean Monthly Rainy Days (Period 1945 to 1964)

the number of rainy days of that month, however, another element of the precipitation situation is noticeable. This serves to show again, but in a different way, the similarities between rainfall within the savanna area and the region to the south. The evidence of Fig. 18 indicates that there is not much difference between the quantities of rain per rainy day in the forest stations and at the savanna stations. The characteristic range of 12 to 15 mm. per rainy day at savanna stations like Kaduna, Ouagadougou, and Bobo-Dioulasso, compares generally with the values found at the forest and southern transition stations. By contrast, looking at the situation to the north of the savanna we see that there is a marked decrease in the average rain per rainy day. The mean figure is less than 10 mm. at Agadez and Kidal, whereas in the savanna the mean is generally above 10 mm. for at least six months.

Figure 19 shows the mean rain per rainy day in a graphical form. The figure brings out clearly the varying length of the rainy season between the savanna and elsewhere, and also the similarity in the mean rain per rainy day characteristic of the rainy season in the savanna and the area to the south. This similarity is apparent from the central core of frequency (shown by the crowding of lines) within the rainy period both in the forest and in the savanna. The graphs also indicate the occasional instances of higher daily rainfall totals which, though few in number, nevertheless draw further attention to the rainfall variability factors already mentioned.

In view of the general similarity of values of the average rain per rainy day in the forest and savanna zones, an attempt was made to examine them more closely by using the statistical methods employed earlier.

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	0	0	0	1	3	3	7	9	5	0	0	0
Zinder	0	0	0	3	7	9	16	16	10	7	0	0
Sokoto	0	0	0	10	12	12	12	14	12	7	0	0
Kano	0	0	0	8	13	11	14	18	12	7	0	0
Kaduna	0	0	6	14	12	13	12	15	13	9	5	0
Minna	0	0	9	12	12	13	12	13	15	11	0	0
Ilorin	8	18	15	11	14	14	12	12	14	12	15	10
Enugu	9	13	13	18	16	15	10	12	16	14	27	13
Benin	20	11	15	16	14	16	14	12	13	14	15	7
Warri	11	10	13	17	15	16	17	16	18	13	11	12
CENTRAL ZONE												
Kidal	0	0	0	0	8	4	7	8	7	0	0	0
Mopti	0	0	0	6	8	8	13	14	10	7	0	0
Ouagadougou	0	0	6	6	11	11	15	17	12	9	0	0
Bobo-Dioulasso	0	4	9	12	14	13	15	17	13	9	6	0
Bouaké	12	9	14	18	15	13	9	9	14	13	10	12
Abidjan	11	10	12	12	19	23	45	5	5	10	12	9

Fig. 18. Matrix of Mean Rain (mm.) per Rainy Day
(Period 1945 to 1964)

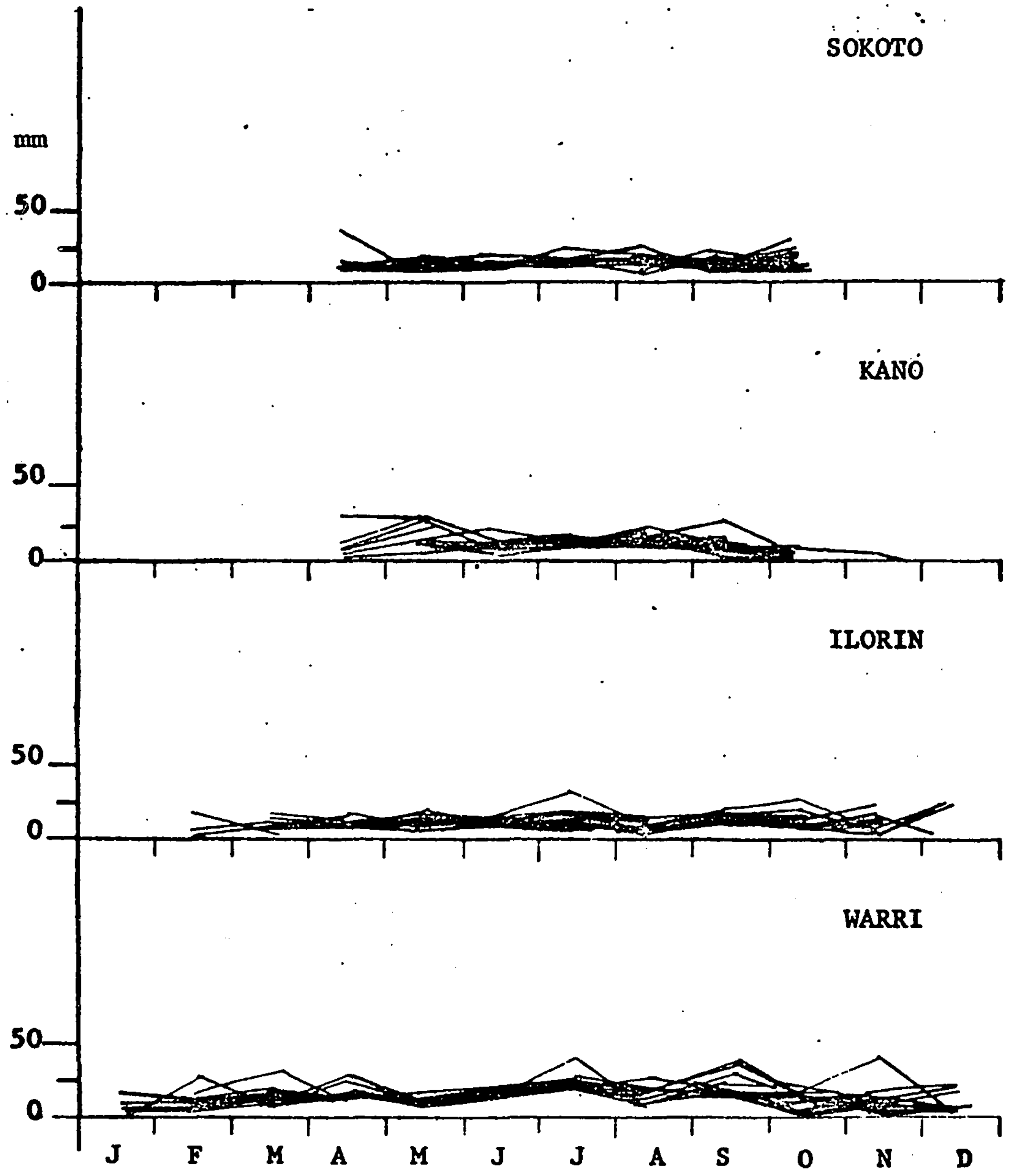


Fig. 19. Monthly Mean Rain per Rainy Day
at Four Stations: each year of the Period 1951 to 1960

The standard deviation and the coefficient of variability for a number of months at several stations were calculated. Those months, between May and October, for which the coefficient of variability was less than 30%, are given in Table V, together with the expected range at the 80% probability level. It will be noticed that at the forest and southern transition stations the range of rain per rainy day lies within the range of 11 to 19 mm. at Ilorin, and 13 to 18 mm. at Warri. Comparing these with the figures of the savanna stations one can see that they are comparable with figures such as those for Kano (11 to 19 mm. in July and 12 to 24 mm. in August) and for Ouagadougou (10 to 23 mm.). The lower levels of the scale of rainfall appears, indeed, to be almost identical in both the forest and savanna areas, but the upper limit of variation is higher in the savanna. Nevertheless, the general similarities between the two areas seem sufficient to strengthen the observations already made that, firstly, a key differentiating factor between the savanna and the forest lies in the contrasting lengths of the wet seasons rather than in any differences within them, and that, secondly, the well marked dry season of the savanna realm is absent in the forest.

TABLE V

RANGE OF PROBABILITY OF MEAN RAIN PER RAINY DAY IN

Station	Month	CV %	Mean
Sokoto	July	28.8	14
Kano	July	21.1	15
	Aug.	25.5	18
Ouagadougou	Aug.	28.6	16
Ilorin	June	22.4	15
	Sept.	28.3	15
Warri	June	18.9	16
	Oct.	27.5	14

All figures in mm.

TABLE V

RAINY DAY IN WET SEASON MONTHS AT FIVE STATIONS

Mean	Range at 0.8 Probability Level
14	9 - 20
15	11 - 19
18	12 - 24
16	10 - 23
15	11 - 19
15	11 - 21
16	13 - 18
14	9 - 19

igures in mm.

CHAPTER SIX

MONTHLY WATER BALANCE CHARACTERISTICS

So far the discussion has centered around precipitation as a major source of moisture supply for a given area. However, in the context of moisture conditions it is also important to examine how the supply of moisture is used up. This involves considering the "water balance", a concept which compares the amount of moisture arriving as precipitation with its return to the atmosphere in the form of vapour due to the combined processes of evaporation from the surface and transpiration by the plants. This combined process is known as "evapotranspiration" (Thornthwaite, 1948).

Evapotranspiration and water balance

Evapotranspiration is governed by factors both of the surface and of the weather or climate. Surface factors comprise the availability of water, the type of soil, and the nature of the plant covering. Climatic influences, on the other hand, are expressed in the heat, or energy, available to effect the necessary evaporation of moisture and in the ability of the atmosphere to accept the moisture being evaporated. The latter is known as the "sink strength" of the atmosphere and represents essentially the drying power of the air as expressed through atmospheric humidity and wind speed (Penman, 1948).

If surface conditions are non-restrictive, in the sense that water is plentiful and able to move readily through the soil so that plants can transpire freely, "potential evapotranspiration" will be achieved. This term is given to the evaporation that would occur from a large, wetted land surface where water supply is a non-limiting factor (Sellers, 1965, p. 89). It differs from actual evapotranspiration, which takes place under the actual conditions of a given place, in being essentially an expression only of the climatic factors which control the rate of evapotranspiration. That is to say, potential evapotranspiration is primarily an element of climate and is governed by the energy and atmospheric characteristics of a given place.

It follows from this definition of potential evapotranspiration that if the precipitation and potential evapotranspiration in a given area are compared, a climatic appraisal of the water balance will have been achieved. Many workers include soil characteristics in such a balance in view of the importance of water storage in the soil reservoir. However, this inevitably introduces a localising influence into the picture since it involves considering matters like soil composition, structure, and texture, as well as the type of vegetation present especially in respect to the depth of the rooting zone (Thornthwaite and Mather, 1957). The aim of the present thesis is to avoid such localising influences in order to try to evaluate moisture from a strictly climatic or atmospheric viewpoint. Consequently, the water balance in the following pages will be treated solely as a balance between precipitation and potential evapotranspiration, the latter expression being considered strictly as an indicator of the potential quantity of moisture which can be returned to the atmosphere in a given area.

Methods of calculating potential evapotranspiration

To enable the application of this idea in the present context, it is necessary to examine briefly how potential evapotranspiration can be evaluated. The kind of procedure adopted is typified by three widely accepted methods: that of Penman, that of Thornthwaite, and that of Budyko.

Penman's treatment of the calculation of potential evapotranspiration can be thought of as a "combination method" as it combines the energy process in evaporation with the power of the atmosphere to absorb the returned moisture. Net radiation is the primary force in the former respect and atmospheric humidity and wind conditions express the latter.

The mathematical calculation of potential evapotranspiration by the Penman method requires the availability of four elements: the duration of sunshine hours in the absence of radiation records, both temperature and vapour pressure from which to calculate the saturation deficit, and finally, the daily run of wind miles. The calculation is then effected by means of the formula

$$E_T = \left(\frac{\Delta}{\gamma} H_T + E_{at}\right) / \left(\frac{\Delta}{\gamma} + 1\right)$$

where the symbols have the following meaning (Penman, 1963):*

E_T = potential evapotranspiration in millimeters;

Δ = the slope of the saturation vapour pressure curve at mean air temperature (obtainable from tables);

γ = the constant of the wet and dry-bulb psychrometer equation;

H_T = $0.75\ R_I - R_B$, where R_I is global radiation derived from sunshine records and the radiation at the top of the atmosphere and R_B is back radiation derived from an empirical formula using air temperature, saturation deficit, and sunshine;

E_{at} = the sink strength of the atmosphere calculated from daily wind speed and the saturation deficit

* A full explanation of the formula is not needed here. Such an explanation can be found in numerous studies of which Penman (1963) offers the most recent explanation by the originator of the method. The original formula and the principles on which it is based are available in Penman (1948).

Penman's formula for calculating potential evapotranspiration has been widely accepted as a realistic and comprehensive approach (McCulloch, 1965). It is not easy to apply it widely on a regional scale, however, since it is not easy to obtain for a sufficient number of stations all the statistics needed to make then necessary calculations. This is particularly the case in West Africa.

Thornthwaite's method of calculating potential evapotranspiration is somewhat simpler than Penman's in that it requires only temperature statistics, which can then be readily used with the various tables prepared by Thornthwaite (Thornthwaite and Mather,1957). His method has, however, been criticised on the grounds that it overlooks the idea of the drying power of air (Garnier,1956). Other critical comments point out that temperature (and also humidity), is a result, and not a cause, of potential evapotranspiration rates and cannot, therefore, logically be used to evaluate it (Slatyer and McIlroy,1961). Nevertheless, the system is widely used because of its simplicity, especially in water balance studies on a regional scale. Two examples of its use in Africa are Carter,1954, and Howe,1953.

A third basic procedure for evaluating potential evapotranspiration is illustrated in Budyko's treatment of the problem. His idea is based on the assumption that over large areas, where advection is negligible, most of the net radiation is used up in the evapotranspiration process and, consequently, there is a direct relationship between net radiation and potential evapotranspiration. The latter can, therefore, be obtained by the simple step of dividing the net radiation by the latent heat of vapourisation to give an indication of the evaporative power of the air (Budyko,1956).

Budyko's idea has been followed up by Davies who developed a formula (with particular applicability to West Africa) in which he relates net radiation to the hours of sunshine by means of an empirical expression (Davies, 1969). He then proceeds to calculate "potential water loss" as he prefers to call it, from an equation of the form:

$$E_R = \frac{R_n}{L} = 0.017 \{ 0.617 \, Q_A \, (a - b \frac{n}{N}) - 24 \}$$

in which the symbols have the following meaning:

E_R = potential water loss in mm. per day;

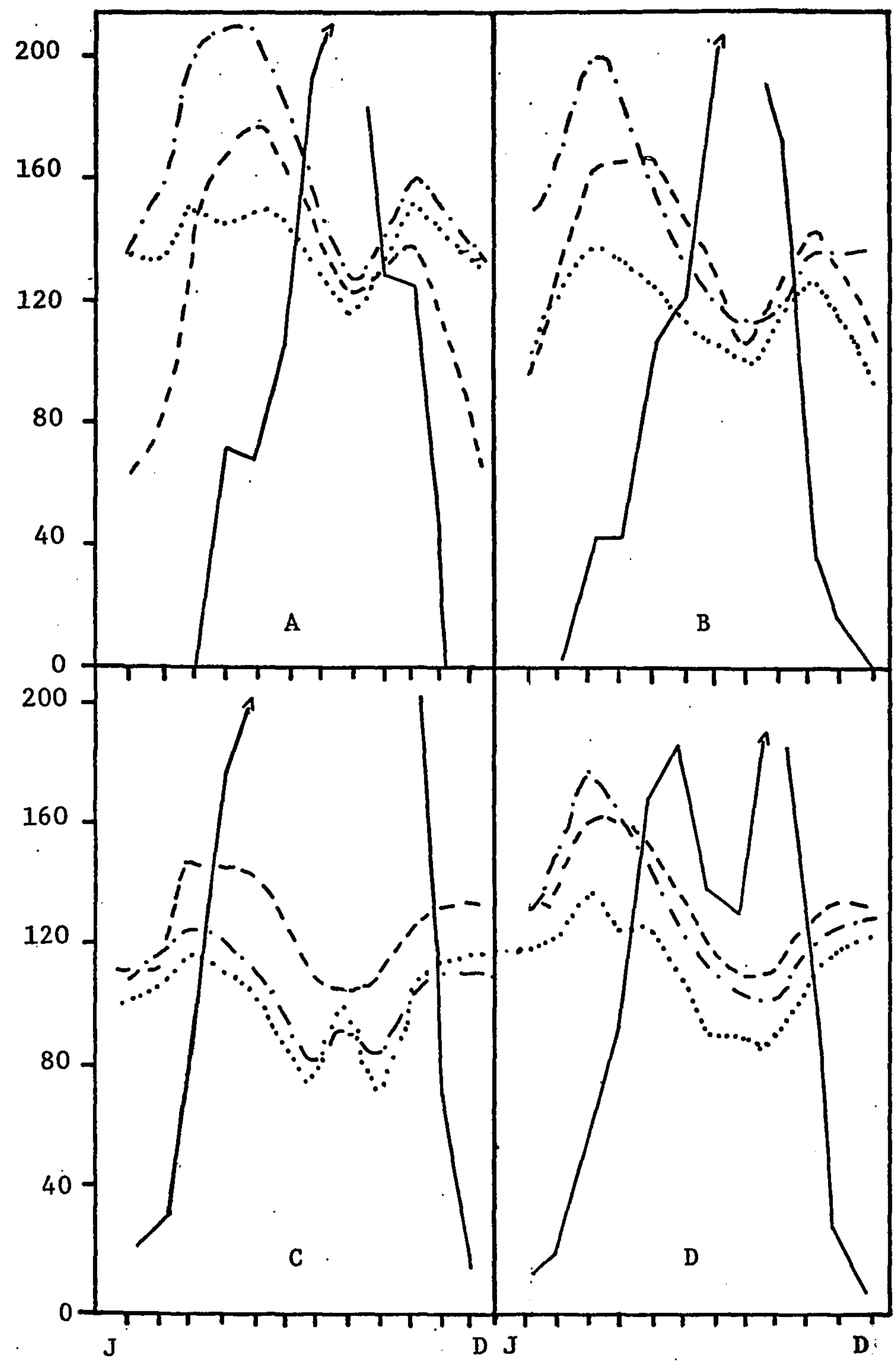
Q_A = the radiation at the top of the atmosphere;

n/N = the ratio between actual and possible daily sunshine hours.

Selection of appropriate method of calculating potential evapotranspiration

In order to help select the most suitable method for the purposes of this chapter, calculations of potential evapotranspiration using the methods of both Penman and Davies were made for several West African stations,* and figures for potential evapotranspiration by the Thornthwaite system were obtained for the same stations from published tables (Thornthwaite and Mather, 1957). The analyses were made to help select the most suitable method for the purposes of this chapter. Reference to the curves in Fig. 20 shows that although each method produced variable results in terms of actual values, the general shape of the curves is similar. The differences between the three methods were least during the wet season. Variations were larger in the early part of the year, when both temperature and humidity are also

* These calculations were carried out by a computer programme using, in the case of the Penman formula, basic constants given in Young, 1963. I am indebted to Professor B.J. Garnier for devising the programme.



Precipitation ——— Penman —.—.— Davies······ Thornthwaite - - -

A Kano B Bobo-Dioulasso C Benin D Ilorin

Fig. 20. Mean Monthly Precipitation and Potential Evapotranspiration at Four West African Stations

generally variable. When the precipitation curve was superimposed on the potential evapotranspiration curves it was found that the length of the "humid period", defined as the period when potential evapotranspiration is less than precipitation, hardly altered whichever method was used. This suggests that at the monthly level, the most accessible method would be a reasonable choice as it does not affect the essential characteristics of the water balance. Consequently, because information on potential evapotranspiration using Thornthwaite's method has already been published for a large number of stations over West Africa and temperature statistics are easy to come by to fill in necessary gaps, the Thornthwaite method of calculating potential evapotranspiration was used for the water balance studies in this chapter.

The second aspect of potential evapotranspiration which needs to be considered is its monthly variation from one year to another. Since the Thornthwaite method depends directly on mean temperatures, its variation from year to year will follow the variation in this element. This is small in West Africa, as the data of Table VI clearly show. The standard deviation for the temperature of any month rarely exceeds 2°F, while it is commonly under 1°F. Coefficient of variation values in the 2% or less range further emphasises the lack of change, whatever the month or location, from one year to another.

Thus, it is not surprising that when the Thornthwaite calculations for potential evapotranspiration were made for each year and plotted for several stations (Fig. 21), a similar lack of variability became apparent. A brief sample, over five years only, of the variability of potential evapotranspiration calculated by both the Penman and the Davies methods was also

TABLE VI

TEMPERATURE VARIABILITY*

PERIOD 1951-1960

	OUAGADOUGOU			KANO		
	Mean Temperature °F	SD	CV %	Mean Temperature °F	SD	CV %
J	77.7	1.7	2.1	70.4	1.5	2.1
F	81.8	2.2	2.6	75.0	2.6	3.5
M	87.3	1.5	1.7	82.7	1.6	1.9
A	89.9	1.5	1.7	87.0	1.3	1.5
M	88.3	1.6	1.8	85.3	3.4	4.1
J	83.6	1.2	1.5	82.0	2.3	2.8
J	80.4	0.7	0.9	78.7	1.4	1.8
A	78.7	0.6	0.8	77.3	1.2	1.6
S	79.9	0.7	0.9	78.3	0.8	1.1
O	83.8	1.2	1.5	80.3	1.1	1.4
N	82.7	1.6	1.9	76.6	1.7	2.3
D	77.7	1.6	2.0	71.2	2.7	3.8

	ILORIN			PORT HARCOURT		
	Mean Temperature °F	SD	CV %	Mean Temperature °F	SD	CV %
J	79.5	1.4	1.7	79.0	0.8	1.0
F	82.6	1.3	1.6	80.3	0.8	1.0
M	84.1	1.3	1.5	80.4	0.8	1.0
A	82.9	1.2	1.5	80.4	0.6	0.8
M	80.9	0.5	0.6	80.0	0.6	0.8
J	78.9	0.9	1.2	77.8	0.7	0.9
J	77.2	0.8	1.0	76.7	0.8	1.1
A	76.6	0.9	1.2	76.8	0.6	0.7
S	77.5	0.5	0.6	77.2	0.5	0.6
O	79.0	0.4	0.5	78.2	0.2	0.2
N	80.3	1.2	1.5	78.9	0.3	0.4
D	78.6	2.5	3.2	78.5	1.0	1.2

*Figures refer to mean monthly values

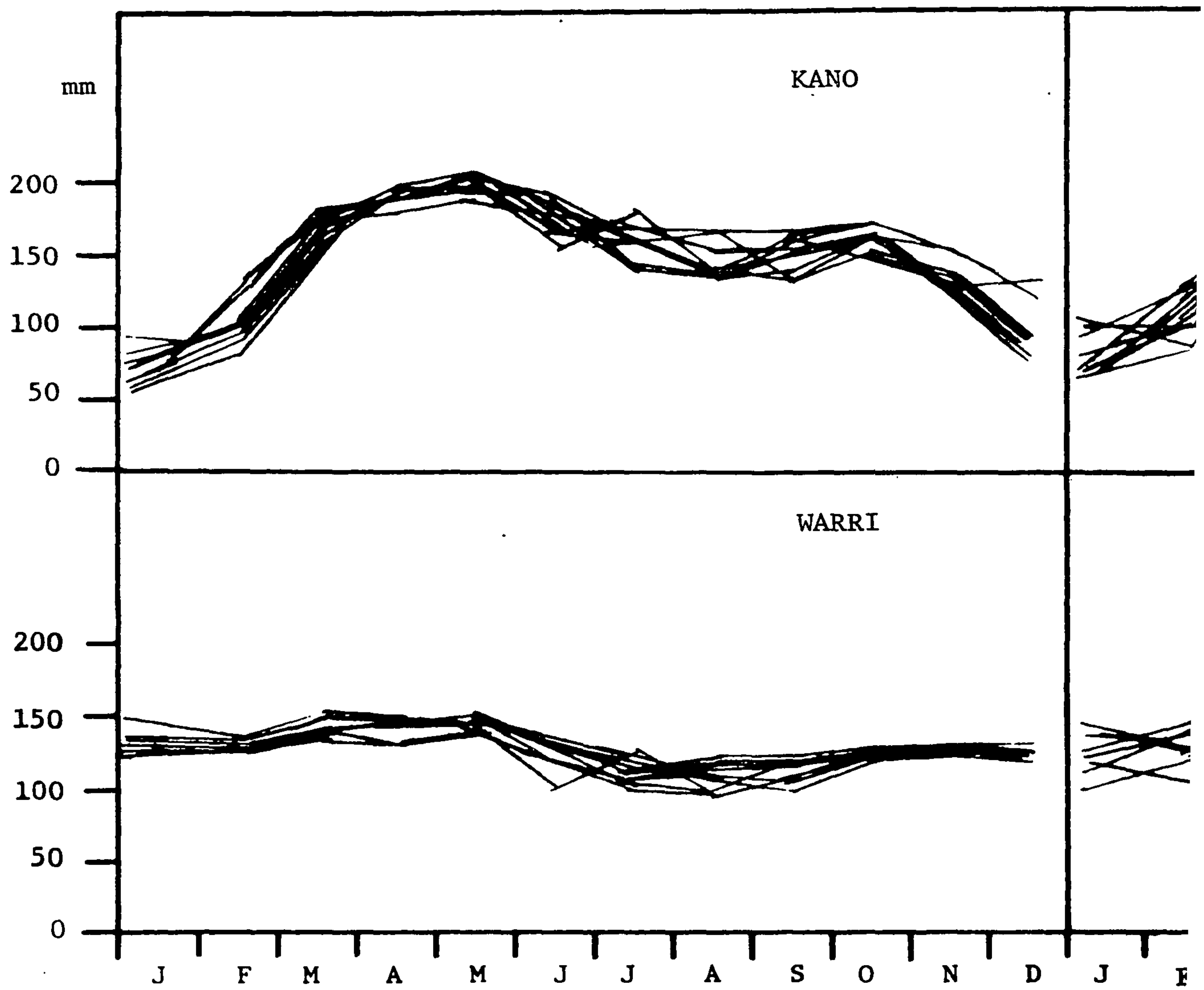
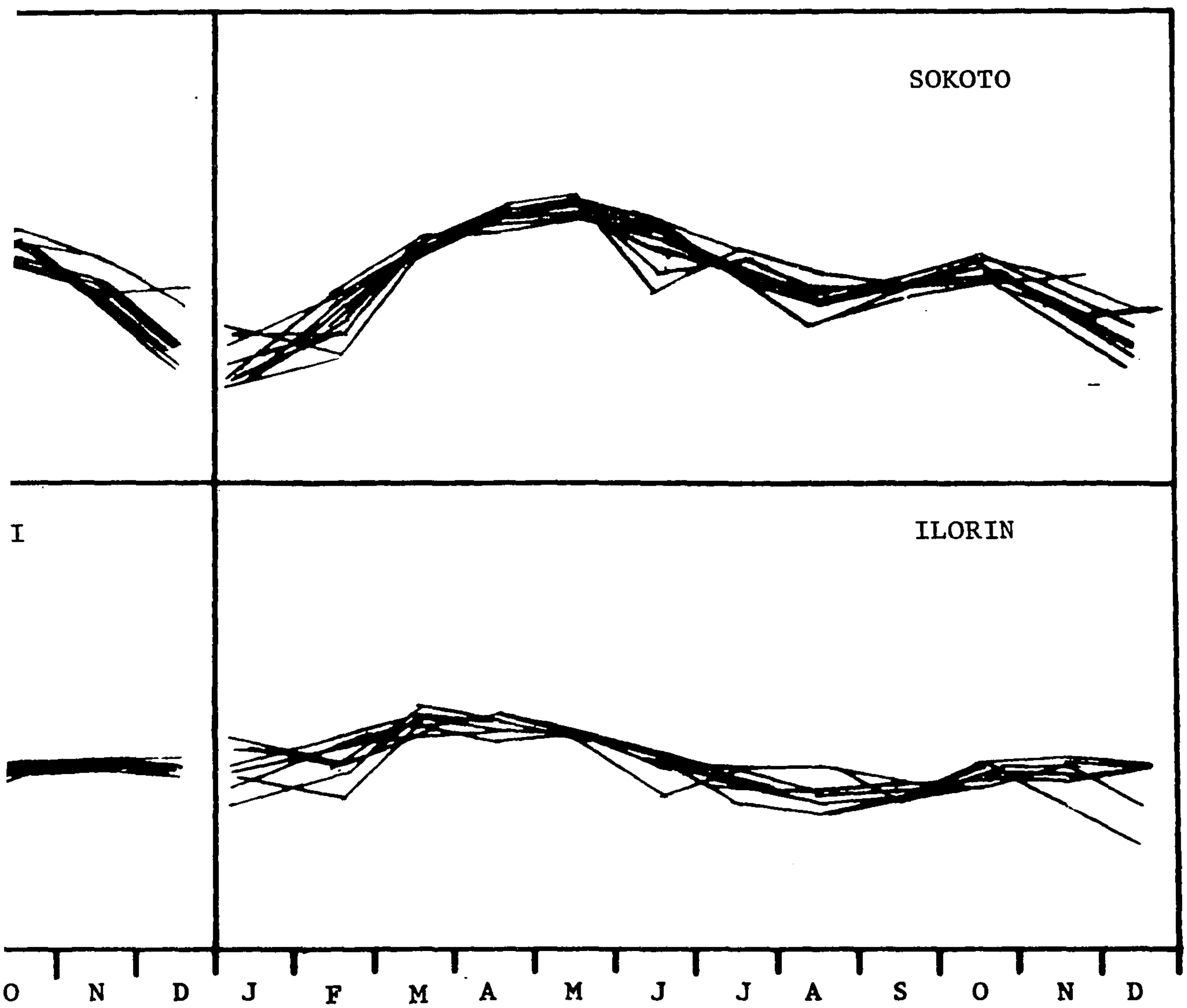


Fig. 21. Monthly Variation of Potential Evapot
(Period 1951



Potential Evapotranspiration at Four West African Stations
(Period 1951 to 1960)

made for Ibadan and compared with the potential evapotranspiration calculated by Thornthwaite's method over the same period. The results are shown in Fig. 22. Here again the variations from one year to another do not appear to be excessive, even though both the Penman and Davies methods of calculation use elements other than temperature. In the light of all this evidence, therefore, it seems reasonable that, for monthly analyses of potential evapotranspiration and the water balance, the Thornthwaite method of calculation can be employed and that the mean monthly values of potential evapotranspiration thus obtained can be used as the values for the water balance calculations of individual years.

Mean monthly water balance

The analysis of water balance follows the same procedures as in the previous case of mean monthly rainfall: there will be, firstly, an analysis based on mean monthly conditions, and secondly, an examination of the frequency of occurrences of the different monthly balance situations.

The matrix shown in Fig. 23 considers the relationship of precipitation to potential evapotranspiration at the stations used in the previous analysis of mean monthly rainfall. A simple comparison was made to show the number of months when potential evapotranspiration was equal to, or greater than, precipitation and those in which this was not the case. The outstanding feature of the matrix is the decrease from south to north in the number of months when precipitation exceeded potential evapotranspiration. The savanna seems to have a maximum of five months where precipitation is greater than potential evapotranspiration and a minimum of two months when this is so. In the forest, six months of precipitation greater than potential evapotranspiration are common except in the case of Abidjan when the little dry season

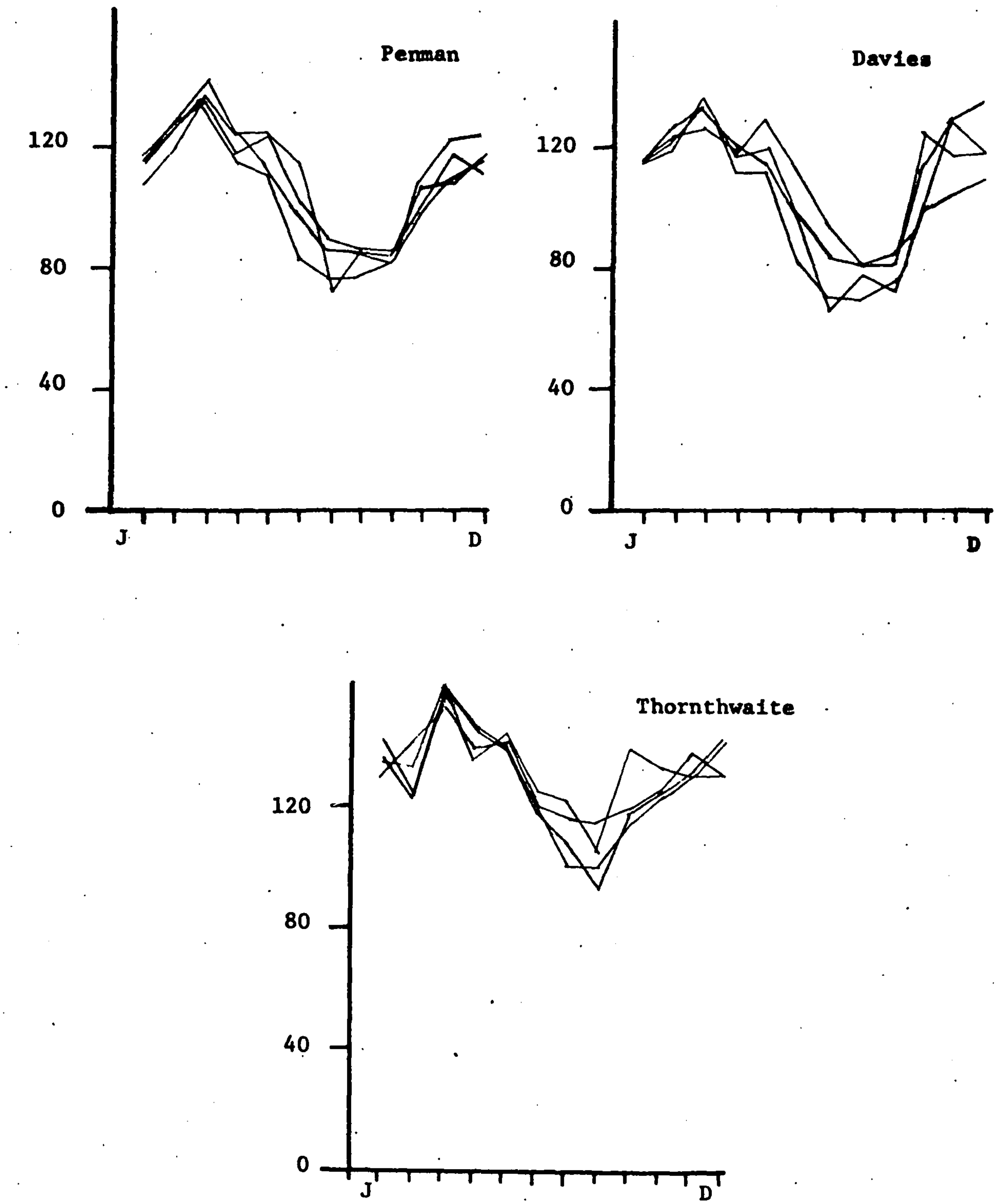


Fig. 22. Monthly Variability of Potential Evapotranspiration at Ibadan Calculated by Different Methods (Period 1958 to 1961)

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez												
Zinder								*				
Sokoto								*	*			
Kano							*	*	*			
Kaduna						*	*	*	*			
Minna						*	*	*	*	*		
Ilorin					*	*	*	*	*	*		
Ibadan					*	*	*		*	*		
Enugu					*	*	*	*	*	*		
Benin					*	*	*	*	*	*		
Warri					*	*	*	*	*	*		
Port Harcourt				*	*	*	*	*	*	*		
CENTRAL ZONE												
Kidal												
Timbuktu												
Niamey								*				
Ouagadougou							*	*	*			
Bobo-Dioulasso						*	*	*	*			
Natitingou						*	*	*	*			
Tamale							*	*	*			
Bouaké				*	*	*	*	*	*	*		
Kumasi				*	*	*	*		*	*		
Abidjan				*	*	*			*	*		
WESTERN ZONE												
Kidal												
Timbuktu												
Mopti								*				
Bamako							*	*	*			
Mamou					*	*	*	*	*			
Freetown					*	*	*	*	*	*		

* indicates precipitation exceeds potential evapotranspiration

Fig. 23. Matrix of the Relationship of Mean Monthly Precipitation and Potential Evapotranspiration

makes a break. But even here, from January to December in a calendar year, more than six months have a balance of precipitation greater than potential evapotranspiration. In the southern transition, the length of time when precipitation is greater than potential evapotranspiration is similar to that in the forest, but the actual number of months is generally less.

Frequency of occurrence of "wet" and "dry" months

A matrix expressing the percentage of years for each month over the periods analysed when precipitation was equal to, or greater than, potential evapotranspiration is shown in Fig. 24. This figure indicates in essence the frequency duration of wet months in the eastern and central test areas. Here again, the idea of strong seasonality in the savanna and the concentration of a wet season into a relatively short time period is a well established feature. Moreover, this short, wet season is again shown to be reliable in its occurrence. Isolines have been drawn on the matrix at the eight out of ten years level to emphasize this point. But if the savanna is characterized by a short, reliable wet season, it is also shown to be distinguished by a long and equally "reliable" dry season. From six to eight months, in which precipitation never exceeded potential evapotranspiration in the thirty to forty years analysed, clearly distinguish savanna stations like Minna, Ouagadougou, and Sokoto from transition and forest stations to the south, where a similar degree of dryness is normally confined to only two or three months of the year. Furthermore, the contrast between a high frequency of dry months and a high frequency of wet months is sharp in the savanna. The change-over is generally effected within two months at the beginning of the rains and only one month separates wet from dry at the end. The period of

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	0	0	0	0	0	0	0	0	0	0	0	0
Zinder	0	0	0	0	0	0	34	71	5	0	0	0
Sokoto	0	0	0	0	0	12	50	85	30	0	0	0
Kano	0	0	0	0	3	10	90	95	50	0	0	0
Kaduna	0	0	0	0	28	88	95	100	100	20	0	0
Minna	0	0	0	0	36	71	86	100	100	57	0	0
Ilorin	0	0	0	10	55	77	60	57	95	72	0	0
Enugu	0	0	13	42	90	95	32	64	100	97	5	0
Benin	0	7	28	36	86	100	93	79	100	100	14	0
Warri	0	10	40	93	93	100	98	83	100	100	35	5
CENTRAL ZONE												
Kidal	0	0	0	0	0	0	3	0	0	0	0	0
Mopti	0	0	0	0	0	0	36	70	8	0	0	0
Ouagadougou	0	0	0	0	13	16	71	100	52	0	0	0
Bobo-Dioulasso	0	0	0	0	20	31	87	95	82	3	0	0
Bouaké	0	3	9	43	40	46	31	54	86	40	0	3
Abidjan	0	4	23	31	92	100	62	8	12	73	77	15

Fig. 24. Matrix of Percentage Frequency
of Months When Precipitation Exceeds Potential Evapotranspiration
(For Periods see Appendix Two)

indeterminate conditions is by contrast longer in both the southern transition and the forest, especially in the period before the period of high reliability begins.*

Reference to conditions at individual stations seems to bear out quite precisely the general conclusions established by the foregoing survey of the different matrices. At the savanna stations illustrated in Chapter Four (see Fig. 11, p. 58), and at the two additional examples (Bamako and Ouagadougou) given in Fig. 25, there are distinctive and well marked dry periods of six months during which precipitation, when it occurred, was always less than potential evapotranspiration. On the other hand, there is always at least one month, and generally two, during which potential evapotranspiration is, with very rare exception, less than precipitation every year. In other words, the water balance at individual stations reflects clearly the rather long dry season and short, but reliable, wet season of the savanna region. It is also this reliability of wet season conditions which clearly distinguishes the region from the northern transition. The graphs for Agadez (Fig. 11, p. 58) and Mopti (Fig. 25) both show this. In each case, only two of the months with rainfall have precipitation values which exceed potential evapotranspiration, and in no case did this occur during the periods analysed for more than six years out of ten. By contrast, at a forest station like Warri (Fig. 11), one can expect precipitation to exceed potential evapotranspiration in most months of the year in

* An attempt was made to see if any different features would be seen in the characteristics revealed in Fig. 24 by making a matrix using precipitation figures that were greater than potential evapotranspiration by 25 mm. as a basis. Such a matrix, however, made no essential difference to what is already shown in Fig. 24, and so has not been included here.

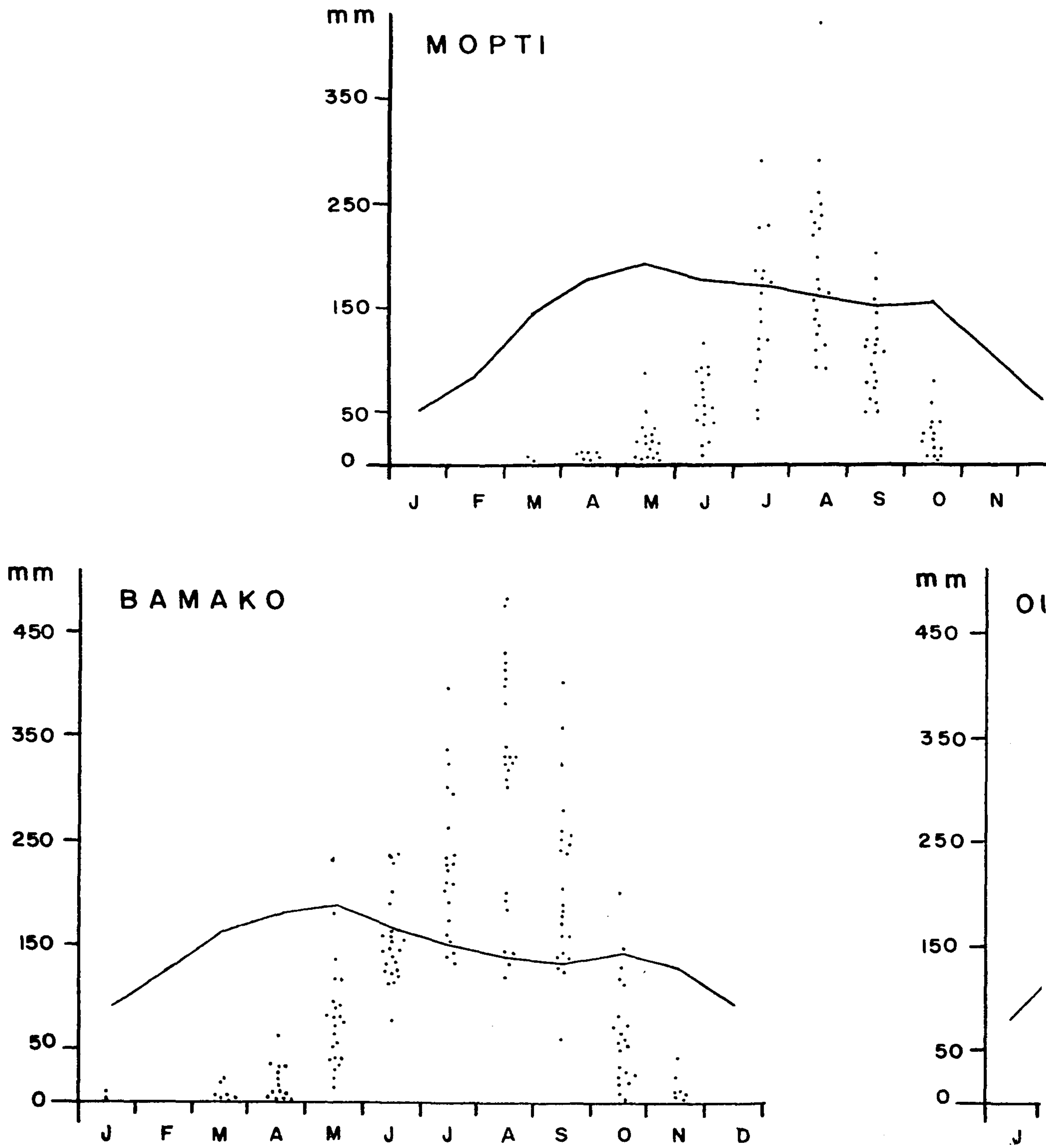
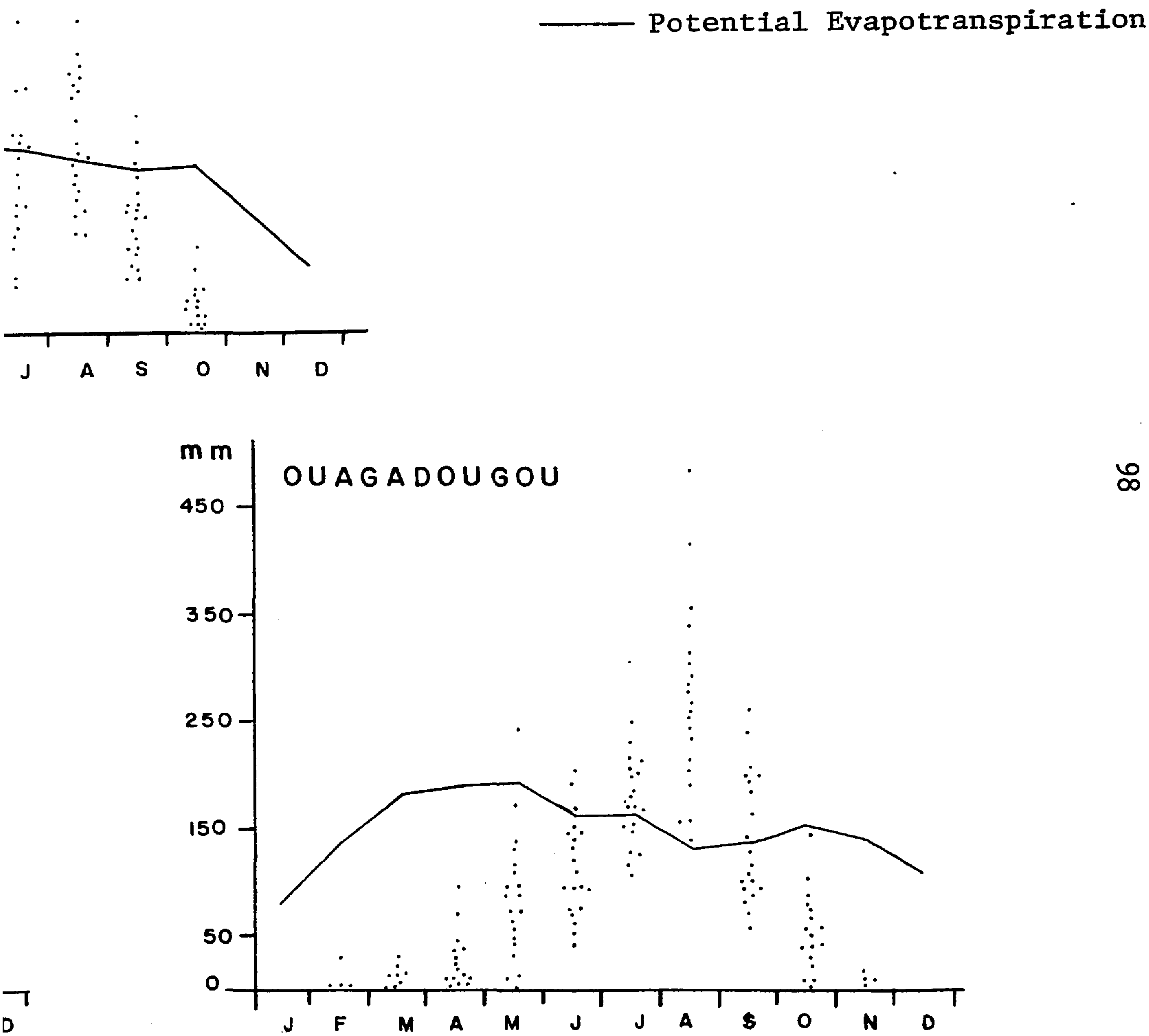


Fig. 25. Rainfall Variability and Potential Evapotran
(Period 1941 to 19



tential Evapotranspiration at Three West African Stations
(Period 1941 to 1960)

spite of the high variability of precipitation, and in no month is the lack of moisture extreme since rainfall, even in dry season months like January and December, often approaches to within two or three inches of the value of potential evapotranspiration. Ilorin (Fig. 11), on the other hand, lies somewhere between Warri and the savanna station, as would be expected of a southern transition location.

In conclusion then, it seems clear that the evidence of the relation of precipitation to potential evapotranspiration through the idea of the water balance supports the idea of the savanna having a definite dry season (resembling the desert) and a definite wet season (resembling the forest). Such a generalisation confirms the idea of Clements (1949) who recognises the savanna as an ecotone between the two great natural tropical environments of forest and desert.

10o

CHAPTER SEVEN

ATMOSPHERIC HUMIDITY

In considering precipitation and the water balance in the last two chapters, the emphasis has been placed on moisture in liquid form. This treatment of moisture means looking at it essentially as an element of the earth's surface and does not deal directly with moisture in the atmosphere, even though some reference to water vapour has entered into the discussion of potential evapotranspiration. In the present chapter, the point of view will be switched from moisture as liquid to moisture as vapour, by considering atmospheric humidity directly and for its own sake. It can, of course, be argued that the analysis of atmospheric humidity is not a direct moisture element in an ecological sense since vapour is not a natural source of humidity for plants. However, this thesis does not claim to be necessarily regarded as a study in "ecological climatology" although an ecological concept has been implicit in the context of wetness and dryness. But the argument already used to explain the omission of soil moisture can be invoked to justify the inclusion of atmospheric humidity: the study aims to evaluate moisture in a strictly climatic sense to see in what ways such an element can be regarded as distinctive of the savanna region.

Expression of atmospheric humidity

Atmospheric humidity, or the moisture conditions of the atmosphere, are commonly expressed by way of relative humidity, vapour pressure, and saturation deficit.

Relative humidity compares the amount of water vapour actually present in the air with the amount which will be saturated at the given air temperature. Thus, it is a proportional estimate of actual conditions in relation to the potential state of saturation. The vapour pressure, on the other hand, indicates the partial pressure which water vapour exerts in the atmosphere. It is thus indicative of the actual amount of water vapour present and is, therefore, a measure of the precipitable water available.

The third element of atmospheric humidity, the saturation deficit, is a direct measure of the difference in vapour pressure units, between the vapour pressure at which the water vapour will be saturated at a given temperature and the pressure being exerted by the water vapour which is actually present. As such, it provides a good indicator of the drying power of air and has been regarded by some as a factor of considerable ecological importance (Aubréville, 1949, pp. 52-55; Prescott, 1949; Phillips, 1959, p. 55). The contribution of surface condensation under conditions of high humidity should also not be forgotten (Aubréville, 1949, p. 71).

Mean monthly atmospheric humidity

Matrices expressing the mean monthly conditions of atmospheric humidity in the eastern and central cross-section zones being used in this study are displayed in Figs. 26, 27, and 28. The impression of the savanna obtained from a study of these figures is of a region in which there is a marked contrast between a period of high atmospheric moisture content and a period when the atmospheric moisture content is low. In general terms, the significant thresholds appear to be a vapour pressure in the region of 20 to 24 mb.,

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	6	6	7	7	15	17	23	25	20	12	9	7
Zinder	9	7	8	10	20	24	25	27	27	18	11	8
Sokoto	7	7	7	15	20	24	25	26	26	22	11	7
Kano	7	7	8	13	23	24	26	26	25	21	11	8
Kaduna	7	8	10	20	26	25	24	24	24	22	13	9
Minna	11	15	19	26	27	27	27	27	27	27	21	23
Ilorin	21	22	25	25	28	25	25	25	25	28	25	21
Enugu	23	24	27	29	29	27	26	24	27	27	27	23
Ibadan	26	26	29	29	29	28	27	26	27	28	28	27
Benin	27	27	29	30	30	28	25	25	28	29	29	27
Port Harcourt	27	28	28	30	29	29	27	27	28	28	29	28
CENTRAL ZONE												
Timbuktu	6	8	9	9	20	22	26	26	26	17	10	8
Niamey	7	7	7	13	22	25	26	27	27	23	12	8
Ouagadougou	9	9	11	17	25	25	26	26	27	26	17	10
Bobo-Dioulasso	8	11	15	22	25	26	26	26	26	26	20	12
Natitingou	10	13	21	25	27	27	26	26	26	26	19	11
Tamale	11	19	22	28	29	29	28	27	28	28	23	15
Bouaké	23	26	27	28	28	28	27	27	28	28	28	24
Kumasi	24	27	29	29	29	27	27	26	28	28	27	26
Abidjan	29	30	31	31	30	29	27	26	28	29	30	30

Fig. 26. Matrix of Mean Monthly Vapour Pressure (mb.)
(Period 1951 to 1964)

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	26	22	20	16	28	33	47	58	44	28	28	29
Zinder	34	21	19	20	40	52	66	76	69	43	30	29
Sokoto	21	21	17	29	41	55	67	75	71	53	30	24
Kano	27	25	22	30	52	62	75	81	75	57	34	30
Kaduna	25	25	29	51	71	78	82	85	80	71	45	32
Minna	32	37	43	59	70	80	83	85	83	79	59	41
Ilorin	59	58	60	66	72	75	79	81	80	84	70	63
Enugu	64	63	70	75	80	83	83	82	83	81	75	67
Ibadan	73	71	75	77	81	85	87	87	86	84	80	76
Benin	78	76	78	80	84	85	87	86	88	85	82	81
Port Harcourt	80	77	81	83	84	85	87	85	85	86	83	82
CENTRAL ZONE												
Timbuktu	23	24	22	19	25	41	56	66	58	37	26	29
Niamey	22	19	16	26	43	56	67	78	72	55	32	25
Ouagadougou	27	24	25	35	56	64	74	79	78	65	43	30
Bobo-Dioulasso	27	31	38	51	66	73	80	83	80	74	57	39
Natitingou	30	35	50	61	73	80	84	85	83	78	56	34
Tamale	28	45	50	66	75	81	84	85	85	80	60	40
Bouaké	66	77	81	83	85	84	87	88	88	86	84	83
Kumasi	76	77	81	83	85	84	87	88	88	86	84	83
Abidjan	84	84	84	82	85	88	86	88	89	87	84	85

Fig. 27. Matrix of Mean Monthly Relative Humidity (%)
(Period 1951 to 1964)

	J	F	M	A	M	J	J	A	S	O	N	D
EASTERN ZONE												
Agadez	17	22	29	38	38	34	25	18	26	30	23	18
Zinder	18	25	34	40	30	22	13	9	12	24	25	21
Sokoto	26	27	36	37	29	20	12	9	10	19	25	24
Kano	19	22	30	32	21	15	9	6	8	15	21	18
Kaduna	21	24	26	19	10	7	5	4	6	9	16	19
Minna	25	26	25	18	11	7	6	5	6	7	15	21
Ilorin	14	16	16	13	11	8	7	6	6	5	11	13
Enugu	13	14	11	10	7	6	5	5	6	6	9	12
Ibadan	10	11	10	8	7	5	4	4	4	5	7	8
Benin	8	9	8	7	6	5	4	4	4	5	6	6
Port Harcourt	7	8	7	6	6	5	4	5	5	5	6	6
CENTRAL ZONE												
Timbuktu	21	25	30	38	41	31	20	14	19	29	28	20
Niamey	24	29	38	38	29	20	13	8	11	19	26	23
Ouagadougou	24	28	33	32	20	14	9	7	8	14	22	23
Bobo-Dioulasso	23	24	25	21	13	10	7	5	7	9	15	19
Natitingou	25	25	21	16	10	7	5	5	5	7	15	23
Tamale	27	23	22	15	10	7	5	5	5	7	15	22
Bouaké	12	12	11	10	7	6	5	4	4	5	7	11
Kumasi	8	8	7	6	5	5	4	4	4	5	5	5
Abidjan	6	6	6	7	5	4	4	4	3	4	6	6

Fig. 28. Matrix of Mean Monthly Saturation Deficit (mb.)
(Period 1951 to 1964)

a relative humidity of 60% to 65%, and a saturation deficit of over 20 mb. and under 12 mb. Roughly speaking, half of the year, namely from May to October, lies on the high humidity side of these values in the southern part of the savanna and about four months fall in the same category for the northern part.

The crossing of these threshold values seems to take place rapidly. It usually occurs within the space of a month or even less judging from the frequent occasions when a month of low atmospheric humidity is next to a month of high value. The rapidity of the change seems more apparent at the end of the wet season than at the beginning. These contrasts can be readily seen from the matrices on which isolines have been placed to draw attention to both the significance of the thresholds suggested and the rapidity of the change-over at the beginning and end of the wet season.

The use of a vapour pressure of 20 mb., of a relative humidity of 60% to 65%, and of a saturation deficit of 12 mb. to govern the higher humidity limits of atmospheric humidity, also serves to distinguish the savanna clearly from the forest and generally from the southern transition. Mean monthly values on the drier side of these thresholds do not exist in the forest. For twelve months, mean monthly vapour pressures exceed 20 mb., and the same high degree of atmospheric humidity is indicated by the relative humidity and saturation deficit figures. This is likewise true of most months in the southern transition area where, however, the differentiation from the savanna is perhaps most clearly shown in the general absence of months on the drier side of the low humidity thresholds chosen. By contrast, most of the northern transition has at least ten months when there is a high saturation deficit generally exceeding 20 mb., while the relative humidity is below 60% and is, indeed, commonly below 30%. As far as vapour pressure is concerned, values below 12 mb. exist on the average for six months of the year, and values exceeding 20 mb. are confined to no more than three or four months.

The savanna, therefore, appears once more as a region where moisture conditions display a well marked contrast between a wet season comparable with the forest and a dry season similar to the desert or at least to northern transition conditions.

Atmospheric humidity at selected stations

Against this background of mean monthly conditions, it is useful to consider some specific examples. Figs. 29, 30, and 31 represent the year by year variation of monthly atmospheric humidity conditions at three savanna stations compared with some other station outside the savanna region. Thus, Kano, in the heart of the savanna, is compared with Benin, in the forest (Fig. 29); Minna, in the southern savanna, is compared with Ilorin, in the northern transition (Fig. 30); and Sokoto, in the savanna core, may be examined directly with Agadez, in the dry northern transition (Fig. 31).

A striking feature of each of the savanna stations is the well defined contrast between the wet and dry seasons, and in each of the three cases there is a remarkably short period of rapid change in conditions from those of low humidity in the dry season to higher humidities in the wet season. The conditions in the dry season within the savanna may be summarised by saying that vapour pressure is generally below 12 mb. and quite often it is under 8 mb., that the relative humidity is less than 40%, or even less than 35%, and that the saturation deficit is nearly always

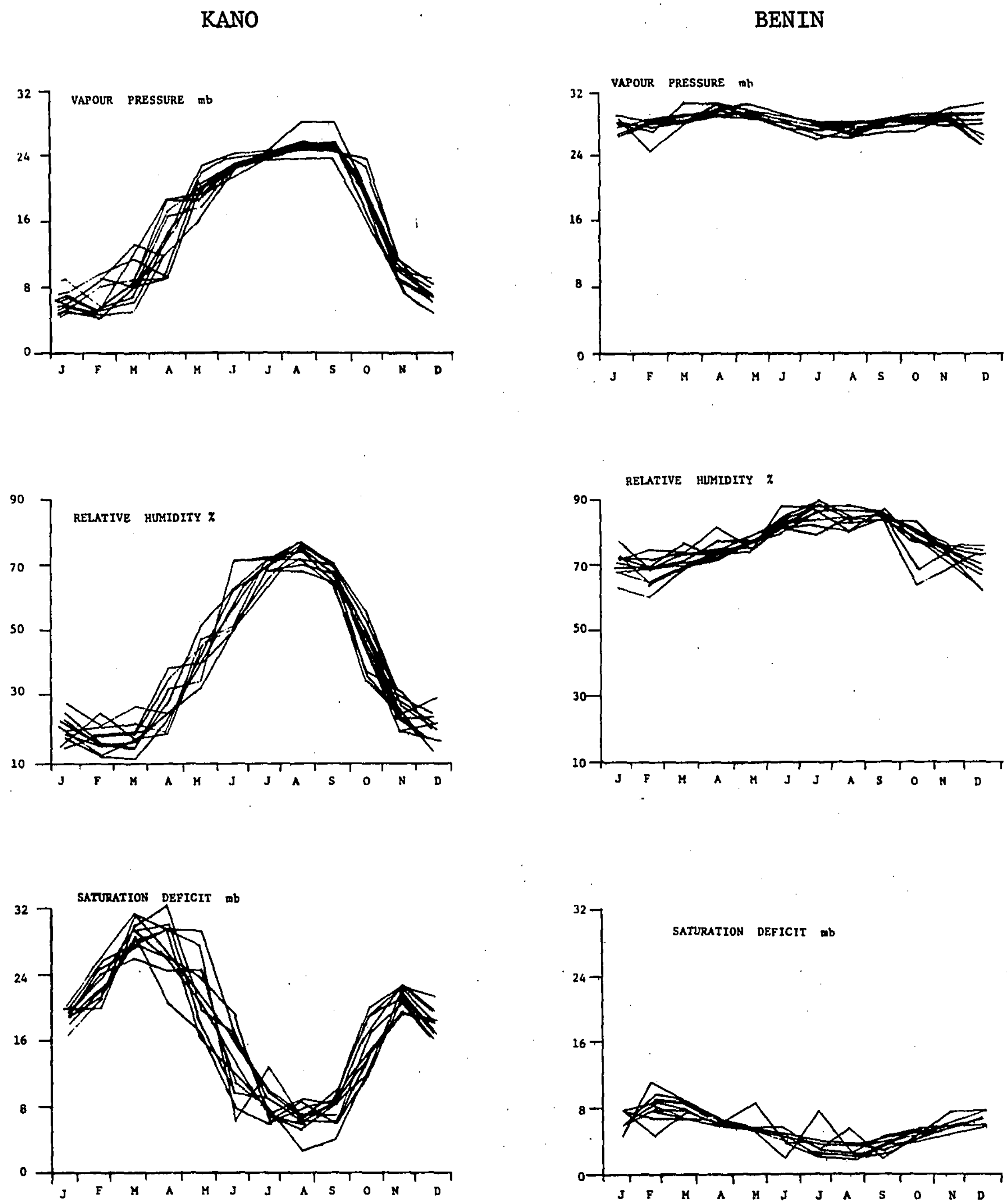


Fig. 29. Monthly Variability of Atmospheric Humidity Conditions at Kano and Benin (Period 1951 to 1960)

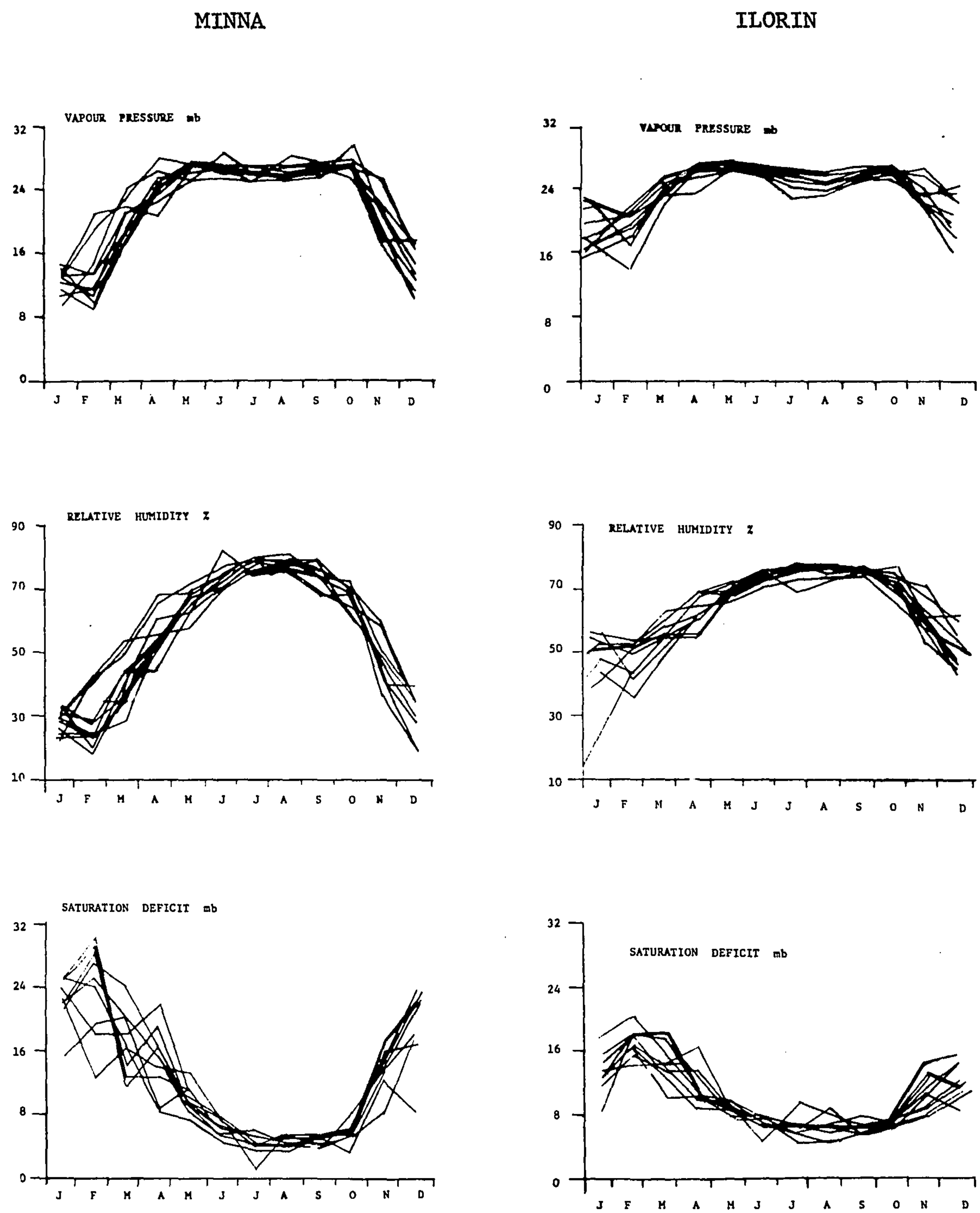


Fig. 30. Monthly Variability of Atmospheric Humidity Conditions at Minna and Ilorin (Period 1951 to 1964)

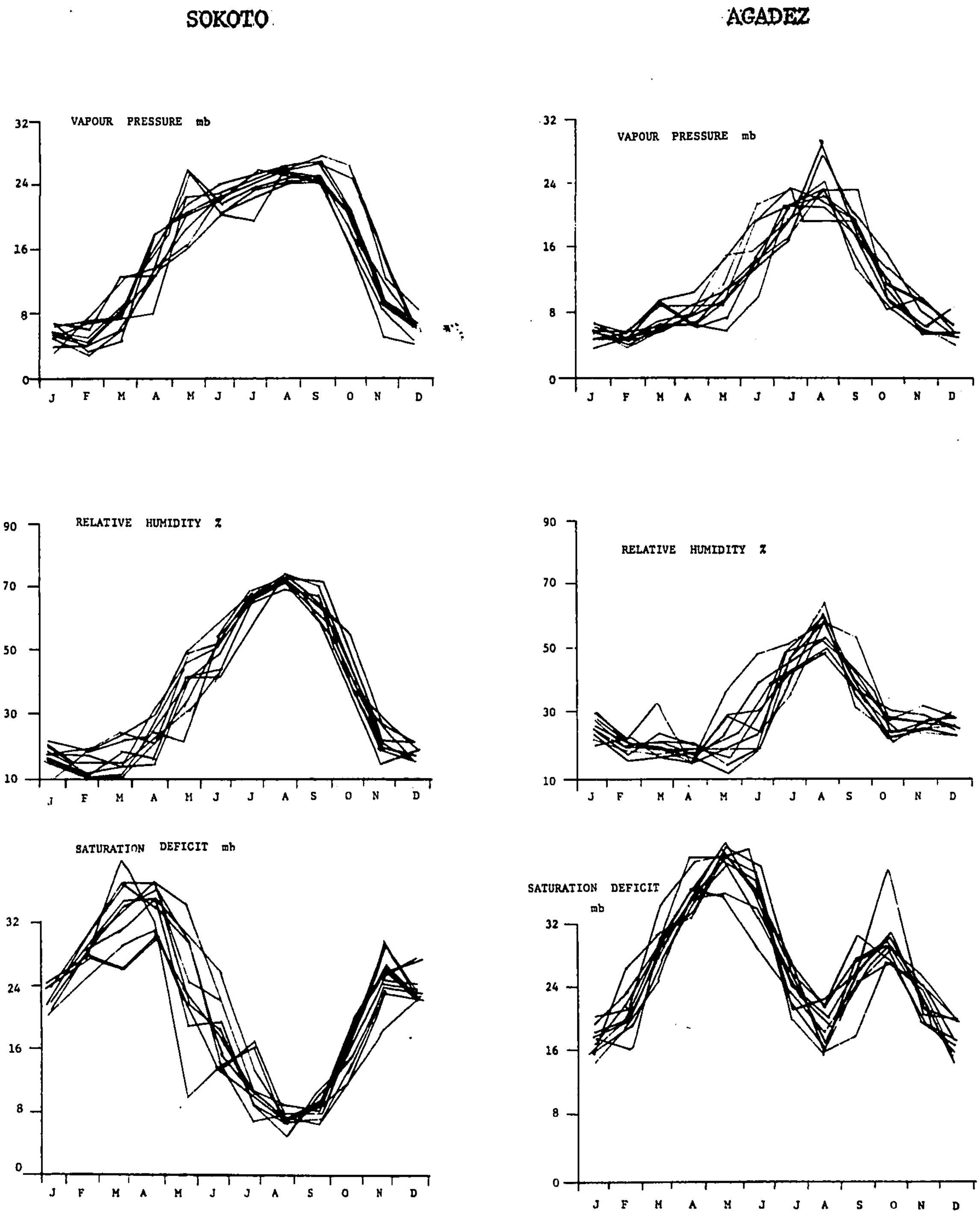


Fig. 31. Monthly Variability of Atmospheric Humidity Conditions at Sokoto and Agadez (Period 1951 to 1964)

greater than 20 mb. and indeed is often higher, being within the range of 24 mb. to 28 mb. In the wet season, on the other hand, the vapour pressure is more than 20 mb. or 24 mb., and the relative humidity is generally within the range of 60% to 70%. The saturation deficit, however, is reduced at this season to a level of 8 mb. to 12 mb.

The other noticeable aspect of the savanna lies in the fact that the period of high vapour pressure seems to maintain itself over a longer length of time than the corresponding period of relatively high rainfall discussed in an earlier chapter. At Kano, for example, the vapour pressure rises very rapidly from under 12 mb. in March to between 20 mb. and 24 mb. in May, and it is not until October that it starts to drop again, but it then drops very quickly to a level of around 8 mb. Similarly, at Minna the same pattern of increasing vapour pressure is seen at the end of February or at the beginning of March, after which the curve levels off until the end of the rainy period. The relative humidity indicates a very similar behaviour to that of the vapour pressure, but displays a greater degree of concentration during the rainy season as it is subject to the influence of temperature to which it responds readily. The saturation deficit, on the other hand, is at its lowest during the wet season and, like the relative humidity, the length of the period of low saturation deficit tends to be relatively limited in its duration since this element is sensitive to the rising temperatures at the end of the rains.

The conditions at the savanna stations stand in clear contrast to those at non-savanna stations. Looking at the vapour pressure situation in Benin and Kano, for example, we find that at Benin there is an outstanding uniformity in the atmospheric humidity. The vapour pressure remains in the region of 24 mb. to 30 mb. every month, which is higher than the maximum vapour pressure at Kano, and the relative humidity at Benin is likewise high, generally above 80% and rarely below 70%. The saturation deficit for most of the year is below 8 mb. and only occasionally, at the beginning of the year, does it vary between 8 mb. and 12 mb.

The results of this comparison suggest that even during the short wet season the savanna is atmospherically a little drier than the forest area. Approximately the same kind of situation is also seen between Ilorin and Minna, with Minna being slightly drier than Ilorin in the wet season. It is relevant to mention that in the dry season the vapour pressure and relative humidity at Ilorin are not as low as the savanna values, but they are lower than the conditions in the forest. There is a longer period at Ilorin than at Minna when the atmospheric humidity conditions conform with the more permanently damp conditions of the forest as illustrated by Benin; also, the dry season at Ilorin is less dry, in an atmospheric sense, than at either Minna or Kano. Comparable contrasts, indicating the greater atmospheric dryness in the northern transition compared with the savanna, can be seen in the graphs for Sokoto and Agadez.

Variation of atmospheric humidity

The examination of mean monthly atmospheric humidity values and the evidence from the year to year monthly variations at six individual stations, suggest that the following values may be significant for distinguishing savanna from non-savanna characteristics: a vapour pressure of 24 mb., 20 mb., and 12 mb.; a relative humidity of between 60% and 70% and under 40%; and a saturation deficit of 8 mb. to 12 mb. These values have been used as guides in selecting the reference levels in the series of matrices presented in Figs. 32, 33, and 34.*

The three matrices showing how frequently different atmospheric vapour pressure levels (Fig. 32) occur each month tell more or less the same story of the savanna being distinguished by its seasonal humidity contrasts. Of the three matrices, however, that for 20 mb. seems to show the more clear-cut regional contrasts. From it, the savanna stands out as an area where for four months the mean daily vapour pressure equals or exceeds 20 mb., and for five or six months this level is never attained. There is, moreover, a rapid change between these two frequency levels, the transfer from one to the other generally taking place within the space of a single month. The northern transition has fewer months with a 100% frequency of the higher vapour pressure level, and there are no months south of the savanna in which every year mean monthly vapour pressure values are below 20 mb.

A fairly clear-cut differentiation of the savanna, particularly in respect to the southern transition and the forest, is also shown on the matrix for 12 mb. In this matrix the savanna stations appear different from those to the south by having at least three months, and generally five or six, in which one can expect mean daily vapour pressure to be less than 12 mb., in contrast to the 100% frequency of this occurrence everywhere south of Minna. The matrix for 24 mb., however, shows a certain amount of regional irregularity. Even the forest zone is not distinguished by a 100% frequency for every month of the year at this high humidity level, and the general lack of systematic differentiation of the kind found in the 20 mb. matrix can be seen from the nature of the isolines.

* Only stations in the eastern sample zone have been considered in these matrices in view of difficulties in obtaining sufficiently complete records for all stations of the central zone.

Greater than 24 mb

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	0	0	0	0	0	0	0	79	14	0	0	0
Zinder	0	0	0	0	0	28	86	93	93	7	0	0
Sokoto	0	0	0	14	21	72	100	86	14	0	0	0
Kano	0	0	0	0	0	43	21	100	93	7	0	0
Kaduna	0	0	0	7	50	43	14	21	14	14	0	0
Minna	0	0	7	79	100	100	100	100	100	100	21	0
Ilorin	0	0	65	93	100	100	100	93	100	93	43	7
Enugu	0	29	86	100	100	100	100	93	100	64	71	36
Benin	100	93	100	100	100	100	100	100	100	100	100	100
Warri	93	100	100	100	100	100	100	100	100	100	100	100
Port Harcourt	93	100	100	100	100	100	100	100	100	100	100	93

Greater than 20 mb

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	0	0	0	0	0	7	79	100	21	0	0	0
Zinder	0	0	0	0	14	93	100	100	93	21	0	0
Sokoto	0	0	0	0	57	100	100	100	100	57	0	0
Kano	0	0	0	0	50	100	100	100	100	50	0	0
Kaduna	0	0	0	50	86	100	100	100	100	64	0	0
Minna	0	7	36	100	100	100	100	100	100	100	50	0
Ilorin	36	50	93	100	100	100	100	100	100	100	86	50
Enugu	57	71	100	100	100	100	100	100	100	100	100	86
Benin	100	100	100	100	100	100	100	100	100	100	100	100
Warri	100	100	100	100	100	100	100	100	100	100	100	100
Port Harcourt	100	100	100	100	100	100	100	100	100	100	100	100

Fig. 32. Matrix of Percentage Frequency
of Selected Levels of Monthly Vapour Pressures
(Period 1951 to 1964)

Under 12 mb

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	100	100	94	100	78	28	0	0	0	71	100	100
Zinder	100	100	93	50	0	0	0	0	0	0	79	100
Sokoto	100	100	93	29	0	0	0	0	0	0	79	100
Kano	100	100	93	29	0	0	0	0	0	0	93	100
Kaduna	100	100	50	0	0	0	0	0	0	0	57	100
Minna	21	50	0	0	0	0	0	0	0	0	0	21
Ilorin	0	0	0	0	0	0	0	0	0	0	0	0
Enugu	0	0	0	0	0	0	0	0	0	0	0	0
Benin	0	0	0	0	0	0	0	0	0	0	0	0
Warri	0	0	0	0	0	0	0	0	0	0	0	0
Port Harcourt	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 32 (continued)

Greater than 65%

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	0	0	0	0	0	0	0	7	0	0	0	0
Zinder	0	0	0	0	0	0	57	100	86	0	0	0
Sokoto	0	0	0	0	0	0	86	100	86	0	0	0
Kano	0	0	0	0	0	14	93	100	93	0	0	0
Kaduna	0	0	0	0	50	100	100	100	100	50	0	0
Minna	0	0	0	14	79	100	100	100	100	86	7	0
Ilorin	0	0	0	43	100	100	100	100	100	100	21	0
Enugu	0	0	14	79	100	100	100	100	100	100	57	14
Benin	93	86	100	100	100	100	100	100	100	100	100	86
Warri	100	100	100	100	100	100	100	100	100	100	100	100
Port Harcourt	100	100	100	100	100	100	100	100	100	100	100	100

Under 35%

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	100	100	100	100	100	86	0	0	86	100	100	100
Zinder	100	100	100	100	36	0	0	0	0	21	100	100
Sokoto	100	100	100	100	29	0	0	0	0	0	93	100
Kano	100	100	100	71	7	0	0	0	0	0	94	100
Kaduna	100	64	64	7	0	0	0	0	0	0	71	100
Minna	86	71	14	0	0	0	0	0	0	0	0	36
Ilorin	7	7	0	0	0	0	0	0	0	0	0	0
Enugu	0	0	0	0	0	0	0	0	0	0	0	0
Benin	0	0	0	0	0	0	0	0	0	0	0	0
Warri	0	0	0	0	0	0	0	0	0	0	0	0
Port Harcourt	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 33. Matrix of Percentage Frequency of Selected Levels of Monthly Relative Humidities (Period 1951 to 1964)

Greater than 12 mb

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	0	0	0	0	0	0	0	0	0	0	0	0
Zinder	0	0	0	0	0	0	21	100	29	0	0	0
Sokoto	0	0	0	0	0	0	71	100	86	0	0	0
Kano	0	0	0	0	0	29	86	100	93	0	0	0
Kaduna	0	0	0	7	57	100	100	100	100	64	0	0
Minna	0	0	0	14	86	100	100	100	100	100	29	7
Ilorin	14	0	7	50	100	100	100	100	100	93	57	14
Enugu	0	0	38	64	100	100	100	100	100	93	79	64
Benin	100	86	93	100	100	100	100	100	100	100	100	100
Warri	100	93	100	100	100	100	100	100	100	100	100	100
Port Harcourt	100	100	100	100	100	100	100	100	100	100	100	100

Under 8 mb

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	0	0	0	0	0	0	0	0	0	0	0	0
Zinder	0	0	0	0	0	0	0	14	0	0	0	0
Sokoto	0	0	0	0	0	0	7	57	21	0	0	0
Kano	0	0	0	0	0	7	43	79	36	0	0	0
Kaduna	0	0	0	0	7	50	93	100	86	7	10	0
Minna	0	0	0	0	7	100	93	100	100	93	0	0
Ilorin	0	0	0	7	93	93	86	93	86	14	0	0
Enugu	0	0	0	7	7	71	79	71	100	93	0	0
Benin	63	43	29	71	64	100	93	100	100	93	79	64
Warri	64	43	43	43	57	93	100	100	93	100	64	57
Port Harcourt	64	86	79	93	100	100	100	100	100	100	100	86

Fig. 34. Matrix of Percentage Frequency of Selected Levels of Monthly Saturation Deficits (Period 1951 to 1964)

Greater than 10 mb

	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	0	0	0	0	0	0	0	0	0	0	0	0
Zinder	0	0	0	0	0	0	0	93	14	0	0	0
Sokoto	0	0	0	0	0	7	21	100	71	0	0	0
Kano	0	0	0	0	0	14	79	100	93	0	0	0
Kaduna	0	0	0	0	57	93	100	100	100	36	0	0
Minna	0	0	0	14	50	100	100	100	100	93	14	0
Ilorin	7	0	0	21	79	100	100	100	100	93	29	0
Enugu	0	0	7	50	79	100	100	93	100	93	71	50
Benin	79	71	79	93	100	100	100	100	100	100	93	93
Warri	100	79	86	100	100	100	100	100	100	100	100	93
Port Harcourt	100	86	100	100	100	100	100	100	100	100	100	100

Fig. 34 (continued)

The same sort of clearly distinct pattern between savanna and non-savanna areas is also apparent when the relative humidity situation displayed in Fig. 33 is examined. Within the savanna, not less than one and not more than five months have a 100% probability of the mean daily relative humidity being more than 65%. Agadez, representative of the northern transition, has no months when these conditions are satisfied. In the forest zone, on the other hand, nearly all months have mean daily relative humidities exceeding 65%, while the southern transition has not less than six months at this level.

Examining the distribution of relative humidity at the lower limit of 35%, we see that the chances of occurrence at or below this level increase northwards. For eight months of the year, Agadez has a 100% frequency of a mean daily relative humidity of less than 35% whereas the savanna has one to six months with the same situation. Needless to say such low relative humidity figures are never attained in the forest regions.

Of the three matrices depicting saturation deficit (Fig. 34), that for a frequency of mean daily values below 8 mb. each month seems to represent too great a state of atmospheric dryness to offer a satisfactory basis for observing systematic regional contrasts. The information shown seems, indeed, to be a better indicator of how the forest differs from elsewhere, rather than of how the savanna region may be regarded as distinctive. The matrices for saturation deficit of 10 mb. and 12 mb., however, both help to identify the savanna from its surroundings. The picture presented is very much the same in each case: the savanna is shown as having from one to four months with a 100% frequency on the humid side, the limit value chosen for each matrix, a 100% frequency of three to seven months on the drier side of the limit in the case of the 12 mb. matrix, and from four to eight months in the same direction in the case of the 10 mb. matrix. Of the two, perhaps that for the frequency of a mean daily saturation deficit of below 10 mb. offers the more satisfactory picture in that it distinguishes Sokoto from Zinder in the north in terms of the July figure and shows up better the beginning and end of year dryness at Minna in comparison with Ilorin. These are, however, minor details in an overall pattern of differentiation which again draws attention to the marked seasonality of the savanna area by comparison with the non-savanna regions.

Relation of savanna to humid tropical conditions

It is interesting to notice how the levels chosen in the analyses of these different humidity matrices relate to Garnier's definition of humid tropical conditions (Garnier, 1961). This definition was reached after examining air mass characteristics and relevant climatic data, and it resulted in a humid tropical month being considered as one in which the mean relative humidity is at least 65%, the mean vapour pressure 20 mb. or greater, and the mean temperature not below 68°F.

In West Africa mean monthly or daily temperatures are rarely as low as 68°F. Figures in the vicinity of 75°F or 80°F are more characteristic. At these temperatures, and at the relative humidity figure cited by Garnier, the vapour pressure is 19.3 mb. and 22.8 mb. respectively, and the saturation deficit is 10.1 mb. and 12.2 mb. respectively. These latter values are not unlike the vapour pressure and saturation deficit thresholds held in this thesis to be significant for distinguishing the savanna region, while a relative humidity of 65% has already been suggested as a suitable differentiating level. It would appear, therefore, that a further basis on which to differentiate the savanna region might be in terms of the frequency of occurrence of humid tropical months as defined by Garnier.

Fig. 35 shows the results of such an analysis. It indicates that the savanna is characterised by at least one to four months where a 100% frequency of humid tropical months prevails and that the northern limit is given when there is no 100% certainty of this occurring even in one month. Towards the south, a period of five months with a 100% certainty of humid tropicality marks the southern limit of the savanna. In other words, the savanna experiences regularly at least one and not more than four humid tropical months. There is, moreover, a 100% reliability of five months not being humid tropical months in the savanna. This combination serves to clearly distinguish the area from its neighbours.

In summarising the atmospheric humidity conditions it may be said that they serve to distinguish savanna characteristics with considerable clarity. The sharp contrast between high and low atmospheric humidity is clearly apparent and emphasises the rapid change in atmospheric conditions between one part of the year and another. The impression gained is one of the atmosphere acting as a fundamental background in which seasonal contrasts are readily apparent but in which the variations within a given season are less strong than in the case of the variation of rainfall from year to year. Thus, the seasonal moisture contrasts of the savanna region become highlighted, and their differentiation from other regions becomes clear-cut in atmospheric humidity terms.

It may be, therefore, that the key to a precise recognition of moisture conditions in the savanna as different from non-savanna regions lies in regarding atmospheric moisture as a fundamental condition against which to examine the fluctuations and seasonal differences of precipitation and water balance characteristics.

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	J	F	M	A	M	J	J	A	S	O	N	D
Agadez	0	0	0	0	0	0	0	7	0	0	0	0
Zinder	0	0	0	0	0	0	57	100	79	0	0	0
Sokoto	0	0	0	0	0	0	86	100	86	0	0	0
Kano	0	0	0	0	0	14	93	100	93	0	0	0
Kaduna	0	0	0	0	57	100	100	100	100	50	0	0
Minna	0	0	0	14	79	100	100	100	100	86	7	0
Ilorin	0	0	0	43	100	100	100	100	100	86	29	0
Enugu	0	0	14	79	100	100	100	100	100	100	86	29
Benin	93	86	100	100	100	100	100	100	100	100	100	86
Warri	100	100	100	100	100	100	100	100	100	100	100	100
Port Harcourt	100	100	100	100	100	100	100	100	100	100	100	100

Fig. 35. Matrix of Percentage Frequency
of Humid Tropical Months
(Period 1951 to 1964)

CHAPTER EIGHT

DAILY MOISTURE CONDITIONS

The conditions surveyed in the previous chapter suggest that the savanna might be regarded as a region in which the atmospheric situation is predominantly dry, but into which a wedge of humid air, with precipitation generating forces, penetrates for a greater or shorter length of time depending on location. In general within the savanna, at least two months are influenced by such forces, and any shorter duration of them tends to coincide with the northern transition region. By contrast, the forest has a fundamentally humid atmosphere, in which precipitation generating forces are potentially present for twelve months, and in which they are normally apparent for at least ten. For brief periods there may be incursions of dry air from the north, but these do not produce more than transitory changes in the hot and humid atmosphere.

Analysis at the monthly level has implied that during the time the precipitation generating forces are active in the savanna, there is a general similarity between the moisture, particularly rainfall, conditions in the savanna and those of the area to the south. It now seems worthwhile to make a more detailed investigation of this apparent similarity by examining it on a day to day, rather than on a monthly, basis.

Daily moisture data

Climatological data at this level of detail are not usually readily available, and for the present purpose it has been necessary to limit the investigation to Nigeria, using both published and unpublished material obtained from the Nigerian Meteorological Service. These sources have enabled a day to day investigation of precipitation, atmospheric humidity, and the water balance to be undertaken.

Complete statistics for this purpose, using calculations of potential evapotranspiration by both the Penman and Davies formulae, were available for a number of stations over Nigeria for the years 1955 and 1956. Additional daily statistics of sunshine were obtained from the record of daily sunshine hours for 1951 to 1960 published by the Nigerian Meteorological Service. Since 1959, the same service has published daily precipitation figures in its monthly rainfall summaries, and these were available for the years 1959, 1960, and 1961.

In summary, therefore, the statistics available for daily analysis comprised rainfall statistics for five years, sunshine hours for ten years of which only four years (1957 to 1960) were in fact used, and atmospheric humidity, temperature and wind statistics for two years. Although the analysis has been of necessity confined to Nigeria, it has been shown all through this thesis that on the basis of environmental patterns, a cross-section across this territory is in fact representative of much of West Africa. The treatment of these daily statistics can, therefore, at least be considered illustrative of the savanna and non-savanna areas even if no claim for regional generalisations can validly be made.

Daily rainfall analysis

Attention has been focused on the four rainy months of June, July, August, and September, and as a basis for study the days have been classified into: days with more than 25 mm. of rain, days with 12 mm. to 25 mm. of rain, days with rainfall less than 12 mm., and days without rain. Some attention was also paid to days with a trace of rain. It was found, however, that this classification made little contribution to the features of the differentiating elements and, consequently, such days were classed as days without rain. Table VII shows an analysis of these categories from the viewpoint of the amount of rain each one brought and the corresponding frequency of rain days. In examining the table it should be remembered that it is not necessarily appropriate to compare the same months in both regions, due to the delay caused in the beginning of the rainy months by the northward progression of rain belts, and the influence of the "little dry" season in southern Nigeria.

The table suggests a general similarity between the wet season in the savanna and that of the region to the south. Although there tends to be a not unexpected decrease in the total quantity of rain as one goes northward, the relative totals brought by falls of different categories and the balance of rainy days are very much the same. Thus, in general one can say that between 50% and 60% of the total rain comes in falls of over 25 mm., representing between 20% and 25% of the total days of rain at both savanna and non-savanna stations in comparable months. Likewise, some 50% to 60% of rainy days tend to be in the under-12 mm. category, which between them produce 25% or less of the total rain. There tends to be more rain at Benin, the sole forest station in the table, than at the two savanna stations, but this is to be expected. One feature of this rainfall difference, however, is that the biggest contrasts seem to be in respect to rainfalls exceeding 25 mm.; the totals of the lower categories are not so very different. The overall result of considering daily rainfall by categories, however, is to draw attention to

TABLE VII

DAILY PRECIPITATION CHARAC

	BENIN					ENUGU					ILOR			
	1	2	3	4	5	1	2	3	4	5	1	2	3	
June														
25mm.+	161	4	40	55	22	111	3	37	46	17	138	3	46	
12-25mm.	87	5	17	30	28	72	4	18	30	22	52	4	13	
less 12mm.	47	9	5	15	50	56	11	5	24	61	30	12	3	
Total	295	18	16	100	100	239	18	13	100	100	220	19	12	1
July														
25mm.+	283	5	57	69	25	142	3	47	56	17	113	3	38	
12-25mm.	54	3	18	13	14	64	4	16	25	22	47	3	18	
less 12mm.	73	14	5	18	61	48	11	4	19	61	9	7	1	
Total	410	22	19	100	100	254	18	14	100	100	169	13	13	1
August														
25mm.+	114	3	38	60	20	77	2	39	60	16	29	1	29	
12-25mm.	47	3	16	25	20	20	1	20	15	8	55	3	18	
less 12mm.	28	9	3	15	60	32	9	3	25	76	21	5	4	
Total	189	15	13	100	100	129	12	11	100	100	105	9	12	1
Sept.														
25mm.+	227	5	45	58	23	162	4	41	60	17	154	3	51	
12-25mm.	92	5	18	24	23	53	3	18	20	13	74	4	19	
less 12mm.	71	12	7	18	54	53	16	3	20	70	47	12	4	
Total	390	22	18	100	100	268	23	12	100	100	275	19	14	[illegible]

Key to Columns: (1) Total Rainfall in
(2) Number of days of
(3) Mean Rain per Rai

TABLE VII

TATION CHARACTERISTICS

ILORIN					KANO					SOKOTO				
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
138	3	46	63	16	29	1	29	28	9	47	1	47	55	8
52	4	13	23	21	31	2	15	30	18	23	1	23	27	8
30	12	3	14	63	43	8	5	42	73	15	5	3	18	84
220	19	12	100	100	103	11	9	100	100	85	7	12	100	100
113	3	38	67	23	123	3	41	50	18	115	3	38	58	21
47	3	18	28	23	83	4	21	34	23	53	3	18	27	21
9	7	1	5	54	38	10	4	16	59	30	8	4	15	58
169	13	13	100	100	244	17	14	100	100	198	14	14	100	100
29	1	29	28	11	186	5	37	54	28	119	3	40	52	23
55	3	18	52	33	89	5	18	26	28	65	3	22	28	23
21	5	4	20	56	68	8	9	20	44	45	13	3	20	54
105	9	12	100	100	343	18	19	100	100	229	19	12	100	100
154	3	51	56	16	67	2	33	52	15	51	1	51	41	10
74	4	19	27	21	28	2	14	22	15	47	3	16	38	30
47	12	4	15	63	34	9	4	26	70	25	6	4	21	60
275	19	14	100	100	129	13	10	100	100	123	10	12	100	100

l Rainfall in mm. (4) % of Total Rainfall
er of days of Rain (5) % of Total Rainy Days
Rain per Rainy Day

the similarity between the savanna stations and those to the south: both display interesting characteristics illustrating the arrival and daily partitioning of rainfall in a tropical context. From the viewpoint of distinguishing the moisture characteristics of the savanna, however, the table merely tends to confirm indications, already provided by earlier chapters, of the similarity of wet season conditions between the savanna and non-savanna realms.

Daily atmospheric humidity and water balance

This impression of similarity begins to break down when attention is turned to the tables depicting atmospheric humidity on the one hand (Table VIII), and that indicating potential evapotranspiration on the other (Table IX). In the former table (Table VIII), the savanna stations remain generally similar to Enugu and Ilorin in the southern transition, but can be seen as clearly different from Benin. At the latter station, atmospheric humidity is high from whatever angle we regard it and whatever the category of rainfall. Only in September is there an indication of lower humidity values, especially in the 12 mm. to 25 mm. rainfall class. By contrast, Kano and Sokoto display drier atmospheric conditions, which are expressed in all humidity categories but are particularly noticeable in terms of saturation deficit which, like those at Ilorin and Enugu as well, are commonly double those at Benin for both non-rainy days and all classes of days with rain.

But if the savanna stations unite with those of the southern transition in their atmospheric humidity contrasts with Benin, they display unique features when potential evapotranspiration is examined (Table IX). This element was calculated by both the Penman and Davies formulae. Both methods

TABLE VIII

ATMOSPHERIC HUMIDITY

DURING DAYS OF DIFFERENT DAILY RAIN

	BENIN 1	BENIN 2	BENIN 3	ENUGU 1	ENUGU 2	ENUGU 3	ILORIN 1	ILORIN 2	ILORIN 3
June									
25mm.+	29.5	89	3.3	26.5	74	6.9	27.2	68	[illegible]
12-25mm.	28.7	84	4.5	26.7	77	6.1	27.2	76	[illegible]
less 12mm.	28.1	85	4.1	26.7	80	5.5	26.8	76	[illegible]
all rain days	28.6	84	4.6	26.5	76	6.3	27.0	76	[illegible]
no rain days	28.4	85	4.4	25.8	72	7.0	26.2	73	[illegible]
July									
25mm.+	27.5	89	3.1	25.4	72	7.4	26.3	80	[illegible]
12-25mm.	27.9	90	2.7	26.0	70	7.8	25.7	83	[illegible]
less 12mm.	28.0	91	2.6	25.6	73	7.2	25.7	80	[illegible]
all rain days	27.5	89	3.1	25.6	73	7.2	25.7	81	[illegible]
no rain days	26.0	91	2.3	24.6	67	8.2	25.3	79	[illegible]
August									
25mm.+	27.1	87	3.5	25.5	76	6.2	25.2	81	[illegible]
12-25mm.	27.0	90	2.7	26.1	77	6.1	25.0	88	[illegible]
less 12mm.	27.5	94	1.6	25.3	70	7.5	24.5	72	[illegible]
all rain days	27.3	89	2.9	25.5	71	7.3	25.0	73	[illegible]
no rain days	26.2	85	4.0	23.9	63	8.9	23.9	79	[illegible]
Sept.									
25mm.+	28.3	81	5.5	28.1	67	9.4	25.4	77	[illegible]
12-25mm.	28.0	68	8.9	26.7	71	7.7	26.6	83	[illegible]
less 12mm.	28.5	85	4.3	24.8	72	6.9	26.0	84	[illegible]
all rain days	28.3	79	6.1	25.9	73	6.9	26.0	82	[illegible]
no rain days	28.7	80	5.7	26.3	72	7.5	25.8	76	[illegible]

Key to Columns: (1) Mean Daily Vapour Pre
(3) Mean Daily Saturatio

TABLE VIII

MOSPHERIC HUMIDITY

FFERENT DAILY RAINFALL CATEGORIES

NUGU		ILORIN			KANO			SOKOTO		
2	3	1	2	3	1	2	3	1	2	3
74	6.9	27.2	68	8.8	23.9	62	14.6	23.6	60	16.0
77	6.1	27.2	76	6.6	22.6	59	15.4	23.0	52	20.9
80	5.5	26.8	76	6.4	23.0	67	11.4	22.4	53	20.0
76	6.3	27.0	76	6.4	23.8	79	6.3	22.5	53	19.9
72	7.0	26.2	73	7.0	21.5	71	8.6	22.1	53	19.6
72	7.4	26.3	80	5.4	25.6	77	7.6	22.1	54	18.9
70	7.8	25.7	83	5.4	24.0	73	9.2	22.2	53	19.7
73	7.2	25.7	80	6.5	24.5	77	7.2	24.2	73	9.0
73	7.2	25.7	81	4.2	25.0	78	7.2	23.5	65	12.6
67	8.2	25.3	79	6.9	24.2	73	9.0	23.2	57	17.3
76	6.2	25.2	81	5.9	25.2	77	7.6	24.9	67	12.5
77	6.1	25.0	88	8.3	25.3	84	4.9	25.5	77	7.7
70	7.5	24.5	72	5.7	25.0	82	5.6	25.0	79	6.7
71	7.3	25.0	73	5.2	25.2	79	6.5	24.9	75	8.3
63	8.9	23.9	79	6.3	24.2	78	6.9	25.1	71	10.1
67	9.4	25.4	77	7.4	25.2	79	6.2	24.2	71	9.6
71	7.7	26.6	83	5.6	24.3	75	8.1	24.7	70	10.3
72	6.9	26.0	84	5.1	24.5	79	5.4	25.2	78	7.0
73	6.9	26.0	82	5.7	24.6	79	5.3	25.2	76	8.0
72	7.5	25.8	76	8.0	24.4	72	9.4	24.8	61	15.7

an Daily Vapour Pressure (mb.), (2) Mean Daily Relative Humidity (%),
an Daily Saturation Deficit (mb.)

TABLE IX

DAILY POTENTIAL EVAPOTRANSPI

DURING PERIODS OF DIFFERENT DAILY RAI

	BENIN			ENUGU			ILORIN		
	1	2	3	1	2	3	1	2	3
June									
25mm+	40	2.9	2.9	37	2.8	2.3	46	4.9	4.
12-25mm.	17	2.7	2.6	18	2.5	1.9	13	4.1	4.
less 12mm.	5	2.8	2.8	5	3.1	3.0	3	3.5	3.
all rain days	16	2.8	2.7	13	2.9	2.6	12	4.0	3.
no rain days		3.2	3.4		3.6	3.5		4.1	4.
July									
25mm.+	57	2.0	1.7	47	3.0	2.5	38	3.1	2.
12-25mm.	18	2.2	2.0	16	2.9	2.3	18	2.9	2.
less 12mm.	15	2.1	2.0	4	2.8	2.3	1	3.3	2.
all rain days	19	2.2	2.0	14	2.9	2.3	13	3.1	2.
no rain days		3.1	3.7		3.6	3.4		3.7	3.
August									
25mm.+	38	2.7	2.6	39	2.9	2.5	29	4.2	4.
12-25mm.	16	1.8	1.5	20	2.8	2.3	18	2.5	2.
less 12mm.	3	2.2	2.3	3	3.0	2.4	4	2.7	2.
all rain days	13	2.4	2.4	11	2.9	2.4	12	2.9	2.
no rain days		2.7	2.6		3.3	2.7		3.1	2.
Sept.									
25mm.+	45	1.9	1.7	41	3.5	2.7	51	3.5	3
12-25mm.	18	2.5	2.4	18	3.5	3.1	19	3.1	2
less 12mm.	7	2.6	2.4	3	3.0	2.6	4	3.1	2
all rain days	18	2.5	2.2	12	3.1	2.7	14	3.2	2
no rain days		3.4	3.4		3.9	3.8		3.7	3

Key to Columns: (1) Mean Rain per Rainy Day
Penman Formula, (3) Pot

TABLE IX

AL EVAPOTRANSPIRATION

'ERENT DAILY RAINFALL CATEGORIES

	ILORIN			KANO			SOKOTO		
3	1	2	3	1	2	3	1	2	3
2.3	46	4.9	4.8	29	4.8	4.0	47	5.9	5.0
1.9	13	4.1	4.0	15	5.5	5.1	23	6.0	4.4
3.0	3	3.5	3.2	5	4.6	4.3	3	6.9	5.2
2.6	12	4.0	3.7	9	4.0	4.3	12	6.7	5.1
3.5		4.1	4.0		4.3	4.5		6.8	5.2
2.5	38	3.1	2.7	41	4.7	4.9	38	6.2	3.9
2.3	18	2.9	2.5	21	4.7	4.8	18	6.6	4.9
2.3	1	3.3	2.7	4	3.3	2.8	4	4.2	4.1
2.3	13	3.1	2.7	14	3.9	3.7	14	4.9	4.3
3.4		3.7	3.5		4.9	5.1		6.2	4.7
2.5	29	4.2	4.4	37	4.4	4.4	40	4.6	3.4
2.3	18	2.5	2.3	18	3.0	2.8	22	4.2	3.9
2.4	4	2.7	2.2	9	3.2	2.9	3	3.8	3.5
2.4	12	2.9	2.5	19	3.9	4.1	12	4.0	3.6
2.7		3.1	2.7		3.8	3.7		4.7	4.0
2.7	51	3.5	3.1	33	3.8	3.7	51	4.7	4.5
3.1	19	3.1	2.7	14	5.5	4.2	16	5.2	4.5
2.6	4	3.1	2.9	4	4.0	4.1	4	3.6	3.3
2.7	14	3.2	2.9	10	3.8	3.7	12	4.1	3.8
3.8		3.7	3.2		4.9	4.8		5.4	4.8

.n per Rainy Day, (2) Potential Evapotranspiration using 'ormula, (3) Potential Evapotranspiration using Davies Formula show that when the evaporating energy forces are added to atmospheric humidity, the savanna stations become portrayed as distinctly different from both Benin and the southern transition stations. One can say that at Kano and Sokoto, whatever the class of rainfall day, potential evapotranspiration generally equals or exceeds 3.0 mm. a day, whereas elsewhere the common figure for rainy days during the principal rainfall months is lower. This contrast carries over into days without rain as well, though perhaps not quite so strongly. Thus, at Kano the mean potential evapotranspiration for all rainy days is close to 4.0 mm. in both July and August, the corresponding figures at Benin for July and September lie between 2.0 mm. and 2.5 mm., while at Ilorin for the same two months they are about 3.0 mm. On the other hand, the mean potential evapotranspiration for rainless days at Kano in July is 5.0 mm. and in August is 3.8 mm., which compares with corresponding figures in the region of 3.5 mm. at Benin and similar ones at Enugu and Ilorin.

There is, however, another notable feature characteristic of Kano and Sokoto which is not repeated at the other stations shown in Table IX: the comparatively high potential evapotranspiration for rainy days having more than 25 mm. In both July and August this is over 4.0 mm., except at Sokoto under the Davies formula. Moreover, the value of potential evapotranspiration in this rainfall class commonly equals or exceeds that of non-rainy days and is, indeed, also higher than nearly all the other rainy day classes of either month. Such a feature is found only at Ilorin in June and August among the analyses for the other stations. It has already been shown that at all stations most of the rain, commonly more than 50%, comes on days with more than 25 mm. In other words, at the savanna stations, more than half the rainfall tends to be associated with the highest rates of potential evapotranspiration during a wet season month, and these rates are one and a half to two times those of the higher rainfall days elsewhere. Perhaps this single fact indicates the most notable way in which savanna moisture conditions differ from those of the area to the south.

The moisture character of individual days

Further substance to these distinguishing elements of the savanna is given by examining conditions on individual days. An extensive sample of these could not be undertaken owing to the limited data available. However, it proved possible to obtain photo or microfilm copies of a number of autographic charts of temperature, relative humidity, and precipitation for several stations. From these a selection was made to illustrate the conditions of individual days for the different categories grouped in the preceding tables. It was not possible to calculate potential evapotranspiration for these days since the necessary data of sunshine or radiation required in any acceptable formula for detailed work were not available. In any case, these formulae are intended for periods somewhat longer than a day. Nevertheless, by calculating saturation deficit from the available data, an idea of the drying power of the air can be obtained, and the contrasts that exist between the savanna and the non-savanna may be further illustrated. The results of such analyses are shown in the accompanying figures.

Fig. 36 is one in which days with more than 25 mm. of rainfall are compared. In it the hourly curve of saturation deficit at Minna for the twenty-four hours beginning at 9 a.m. on July 30, 1960, during which 97 mm. of rain fell between 10 a.m. and 12.30 p.m., is compared with two twenty-four hour periods at Benin. During one of these - September 15-16, 1955 -

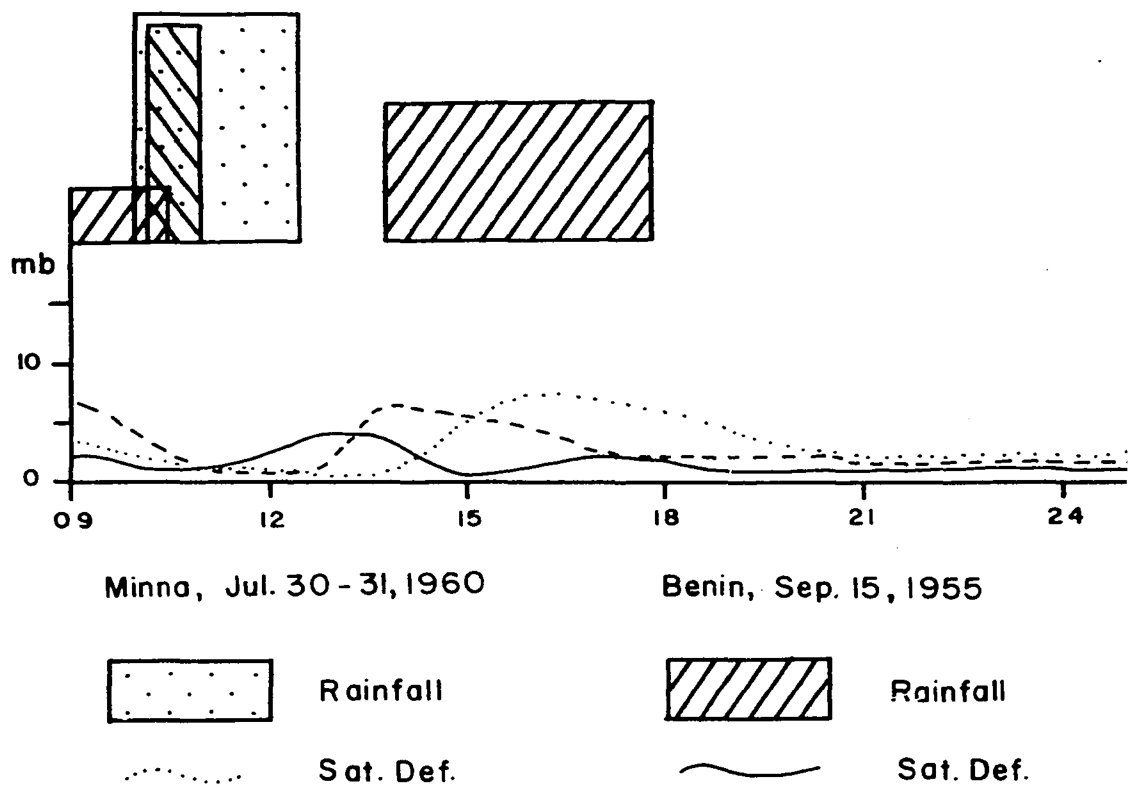
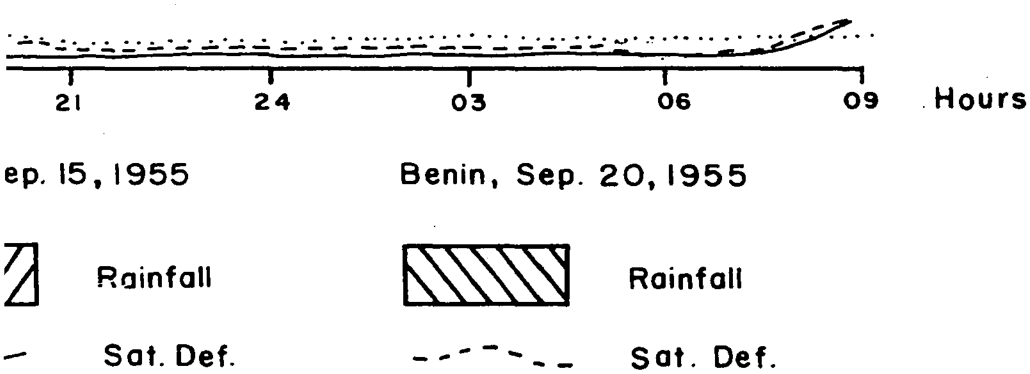


Fig. 36. Saturation Deficit and Rain

Rainfall proportional to area shad



ɘficit and Rainfall for Minna and Benin
al to area shaded. Key area = 25 mm.

105 mm. of rain fell, 14 mm. between 9 a.m. and 10.30 a.m. and 91 mm. between 1.45 p.m. and 5.50 p.m., and on the other day - September 20-21, 1955 - 30 mm. of rain fell in the morning. The differences between the two stations is clearly seen from the graph. The recovery to a high saturation deficit after the rainfall had stopped at Minna is rapid, and the value reached at Minna is higher than that shown either day at Benin. Moreover, the duration of relatively high saturation deficit is longer at Minna through the day than at Benin. Following the day's rain, the saturation deficit during the night at Minna is some 2 mb. or 3 mb. higher than that of Benin. It is noteworthy also that at Benin the higher saturation deficit was associated with the day which had the lower rainfall of the two days shown.

The next figure (Fig. 37) compares a day at Ikeja (near Lagos), which is in the southern transition but very close to the forest, with one at Kano. At each station, and on the same date, 14 mm. of rain fell in the early afternoon. This offers a particularly direct comparison from which the higher saturation deficit at Kano can be clearly seen. There is similarity in the nocturnal situation, but the next morning, although there was no rain at either place, the saturation deficit at Ikeja remained low, whereas the value of this element at Kano rose rapidly shortly after sunrise. This particular example seems an especially apt illustration of the general conclusions towards which the analyses in this chapter seem to be leading: that the rainy season in the savanna is, in fact, different from the forest area despite the apparent similarity in rainfall figures. An example of days with less than 12 mm. is presented in a third figure (Fig. 38). Here Ilorin is compared with Maiduguri, a station in the northern savanna close to the northern transition. Once again the greater saturation deficit at the savanna station compared with that of the non-savanna station can be clearly seen.

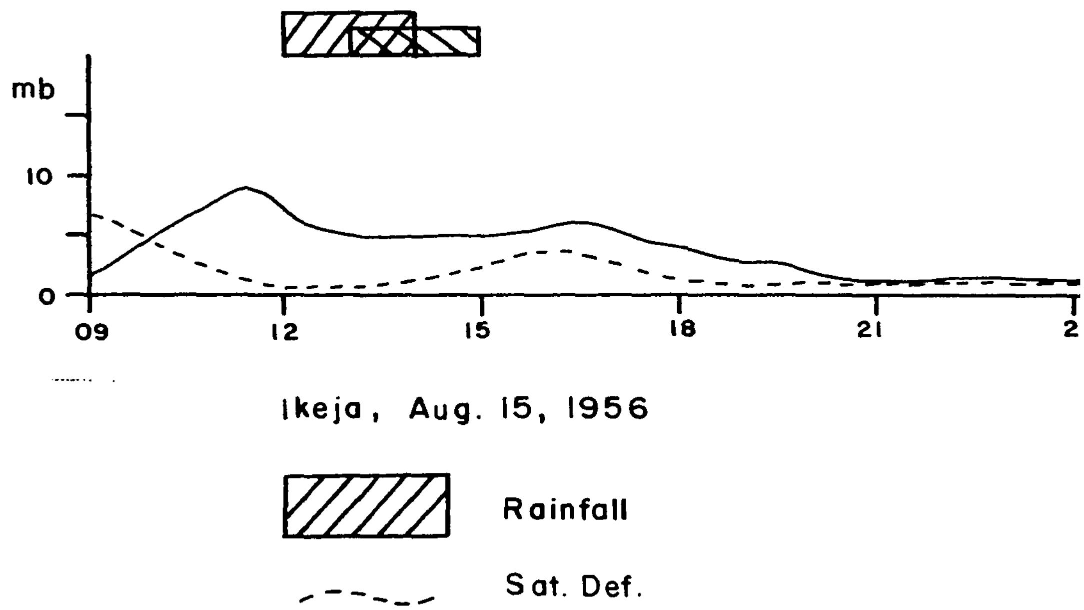
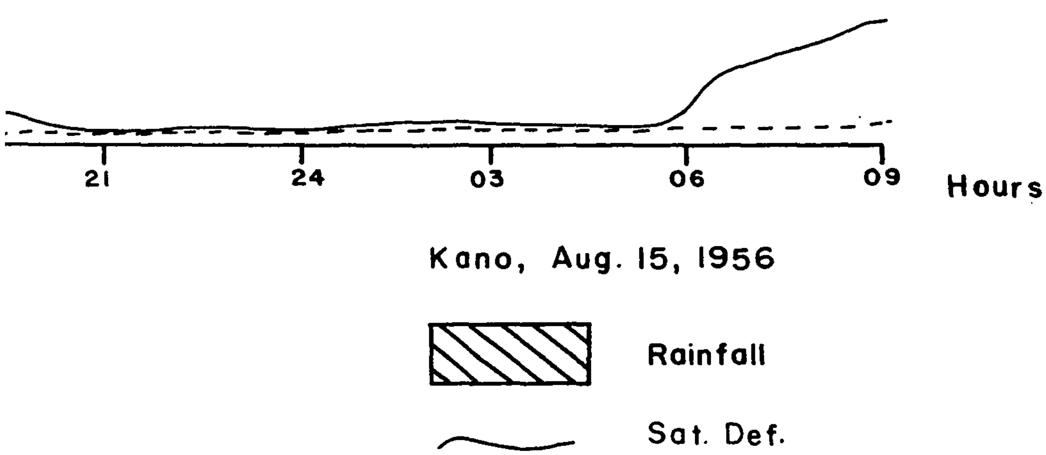


Fig. 37. Saturation Deficit and Rai
Rainfall proportional to area shad



ɘficit and Rainfall for Ikeja and Kano
L to area shaded. Key area = 25 mm.

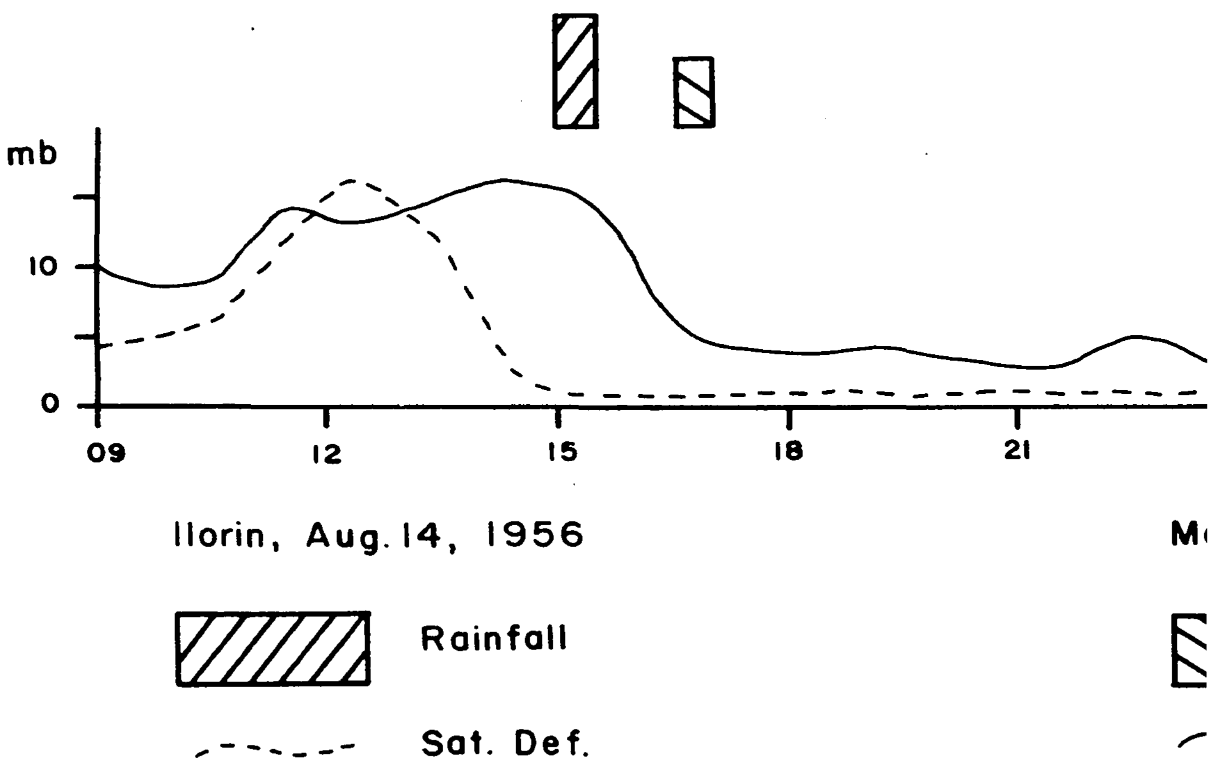
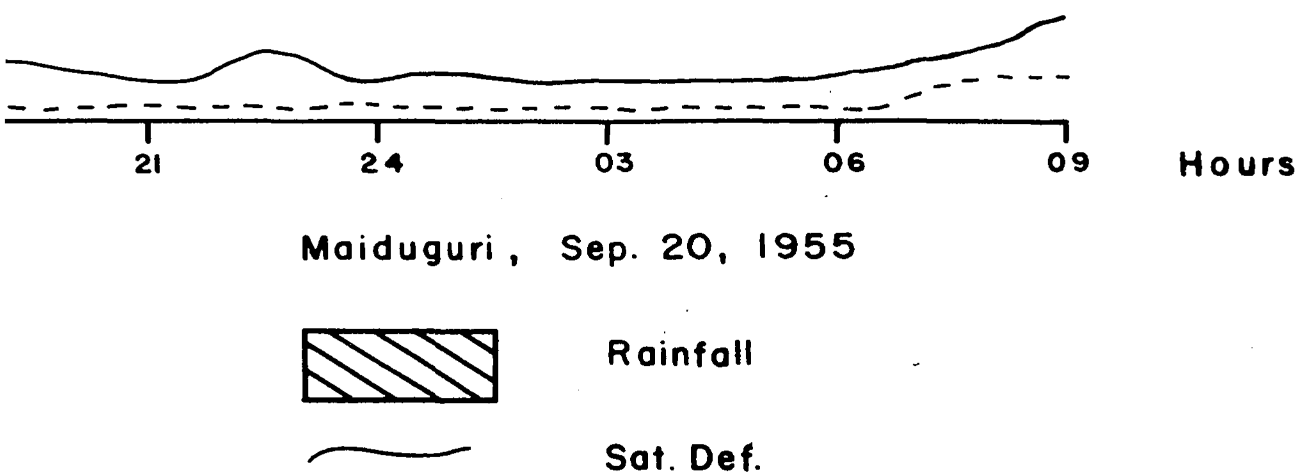


Fig. 38. Saturation Deficit and Rainfa
Rainfall proportional to area shac



:icit and Rainfall for Ilorin and Maiduguri
ıal to area shaded. Key area = 25 mm.

A final figure (Fig. 39) illustrates conditions on rainless days. The graphs are self-explanatory in the way they portray the systematic decrease southwards in the values of the saturation deficit both during the day and during the night. Yet in spite of this difference, the "rainy season" situations are comparable in each case in that each of the dates shown for the stations were immediately preceded and followed by days with appreciable rainfall. At Maiduguri, for example, July 26 and 27 were two days sandwiched between days with more than 35 mm. of rain in each case: July 29, 1960, at Benin had been preceded by a fall of 25 mm., and the rainless day at Minna lay between a day of 5 mm. and one of 20 mm.

Basic climatology of daily moisture conditions

It would appear that the evidence of this chapter implies the need to take another look at the idea that the rainy season in the savanna is like that of the rainy season in the forest. This may be true of the arrival of moisture as precipitation but does not seem correct in terms of the total moisture picture. To investigate the matter further it is necessary to return to the viewpoint of Chapter Three, where the basic climatology of West Africa is discussed.

It was there shown that the savanna region is largely dominated by weather zone C as far as the rainy season is concerned, and that at other times the area is dominated mainly by weather zone A. Thus, the rainfall which comes in the savanna is that which is characteristic of zone C. Moreover, it is predominantly the northern half of zone C which covers the savanna for most of the time, whereas the region to the south is in the southern part of this zone or else in zone D during the rainy season.

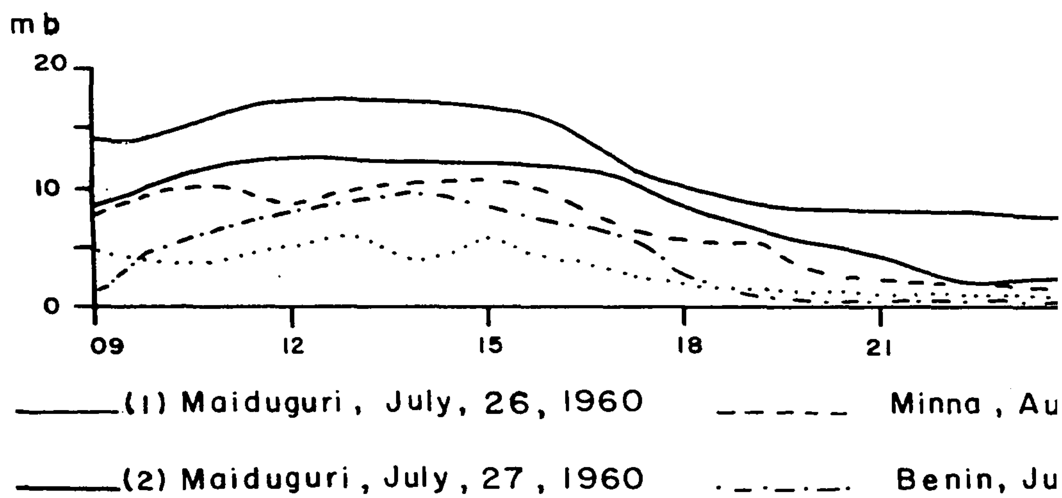
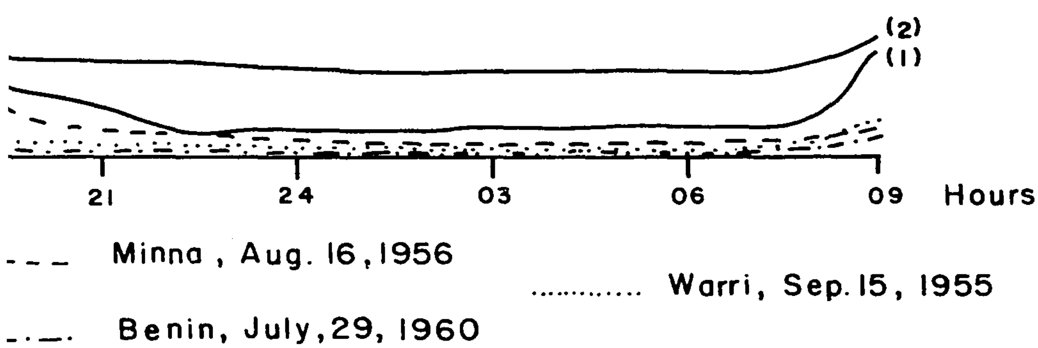


Fig. 39. Saturation Deficit of Five Rai



: of Five Rainless Days at Different Stations

Zone C is pre-eminently the weather zone of West Africa where disturbance lines are active and the greater part of the rain in this region is brought about by these phenomena. The diagrams of Fig. 40, taken from Eldridge's account of the disturbance lines of West Africa (Eldridge, 1957), show that at Navrongo, a station in the savanna, the proportion of rainfall brought by disturbance lines is much greater than at Axim, a station in the forest. These disturbance lines constitute a well marked phenomenon of the West African climate (Eldridge, 1957; Hamilton and Archbold, 1944; Garnier, 1967). They consist essentially of a line of thunderstorms which moves from a generally east to a generally west direction at a speed of 25 to 30 miles per hour. The rainfall along them is localised. It is short in duration, but heavy, and characteristically 70% to 80% of the total rainfall comes in the first 10% to 15% of the time of the fall (Garnier, 1953). After the passage of the disturbance line there is a relatively rapid return to the atmospheric condition which characterises the region. There may be an hour or two of cloudiness, but this is not always so. Another feature of the disturbance line is that very often its southern part is mingled with a large area of widespread rain, brought by scattered thunderstorm activity within a region of generally overcast skies and high humidity (Eldridge, 1957).

These factors concerning the character of the disturbance lines are extremely important for a proper understanding of moisture conditions in the savanna, as opposed to those of the other regions in West Africa. Because the savanna region is predominantly the area covered by zone C and especially by its northern part, its rainfall is particularly closely associated with that part of the disturbance lines where thunderstorm activity predominates

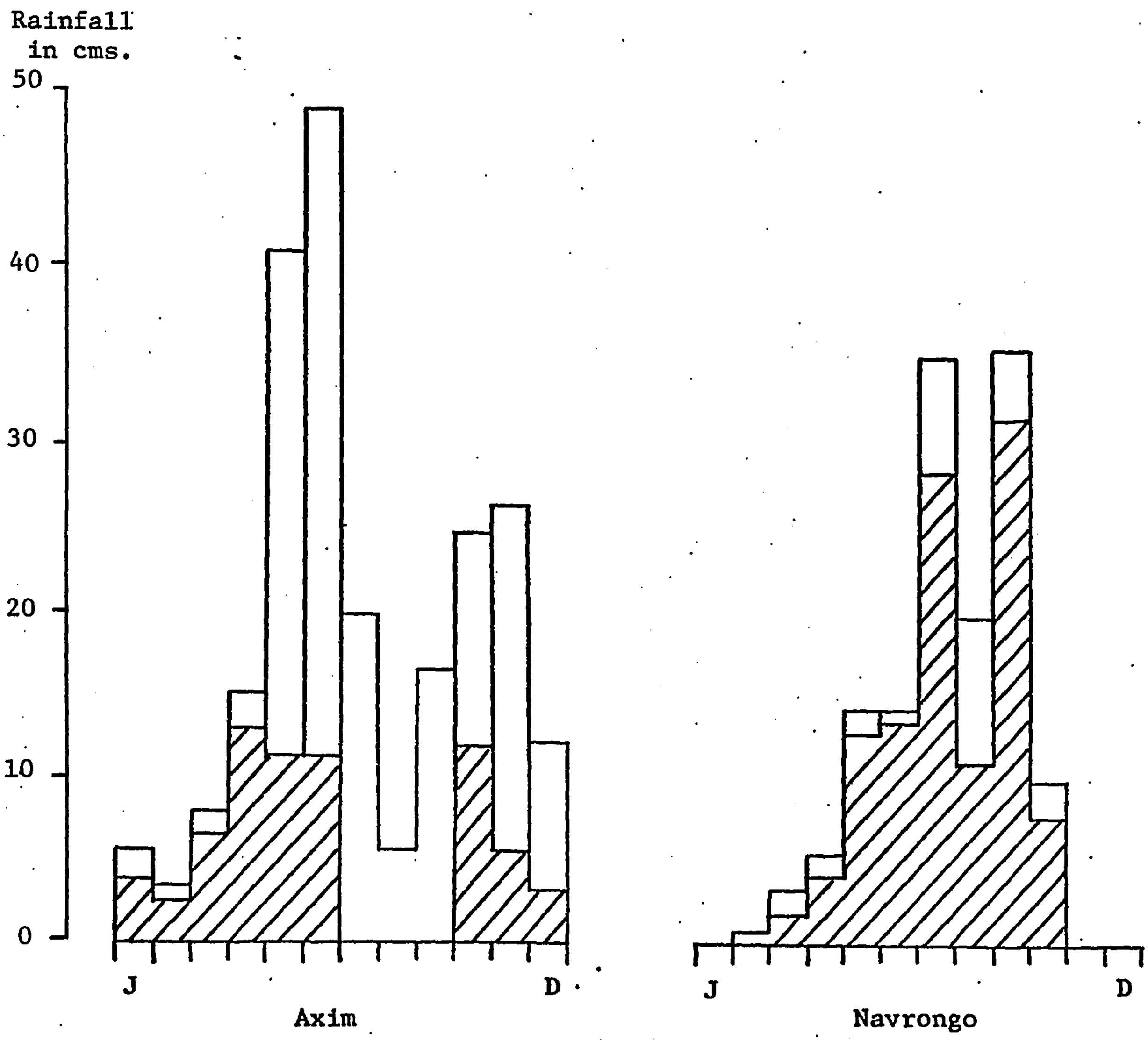


Fig. 40. Proportion of Rain Brought by Disturbance Lines at Navrongo and Axim
(redrawn from Eldridge 1957)

but passes quickly. By contrast, the area to the south of the savanna is one in which, during the rainy season, high humidity and extensive periods of cloudiness prevail. This situation results partly from the predominance of the humid air moving in from Atlantic sources. It is also closely connected with the disturbed region of rain and cloudiness at the southern ends of the disturbance lines.

To recognise the different relationship of the disturbance lines to the savanna region as compared with the non-savanna area, is fundamental to any understanding of moisture conditions in the two regions. An indication of their relationships is given in Figs. 41 and 42, both adapted from Garnier, 1967.

Fig. 41 indicates the position of all the disturbance lines, irrespective of date and time, which, according to the West African synoptic charts prepared at three hourly intervals at Ikeja airport, Lagos, traversed West Africa from July 26th to 30th, 1960, inclusive. Fig. 42 represents the distribution of rain over Nigeria for one individual day - July 30, 1960 - and the passage of the disturbance line associated with it. On both figures the boundaries of the savanna core region have been marked. This region seems located squarely within the zone of passage of the disturbance lines. In particular, the southern ends of these lines of atmospheric instability coincide closely with the southern boundary of the savanna area.

Distinctive element of savanna daily condition

It seems, therefore, that the rainy season in the savanna must in fact be regarded as somewhat different from that of the region to the south of it, despite the apparent similarity given to it by the rainfall figures. This

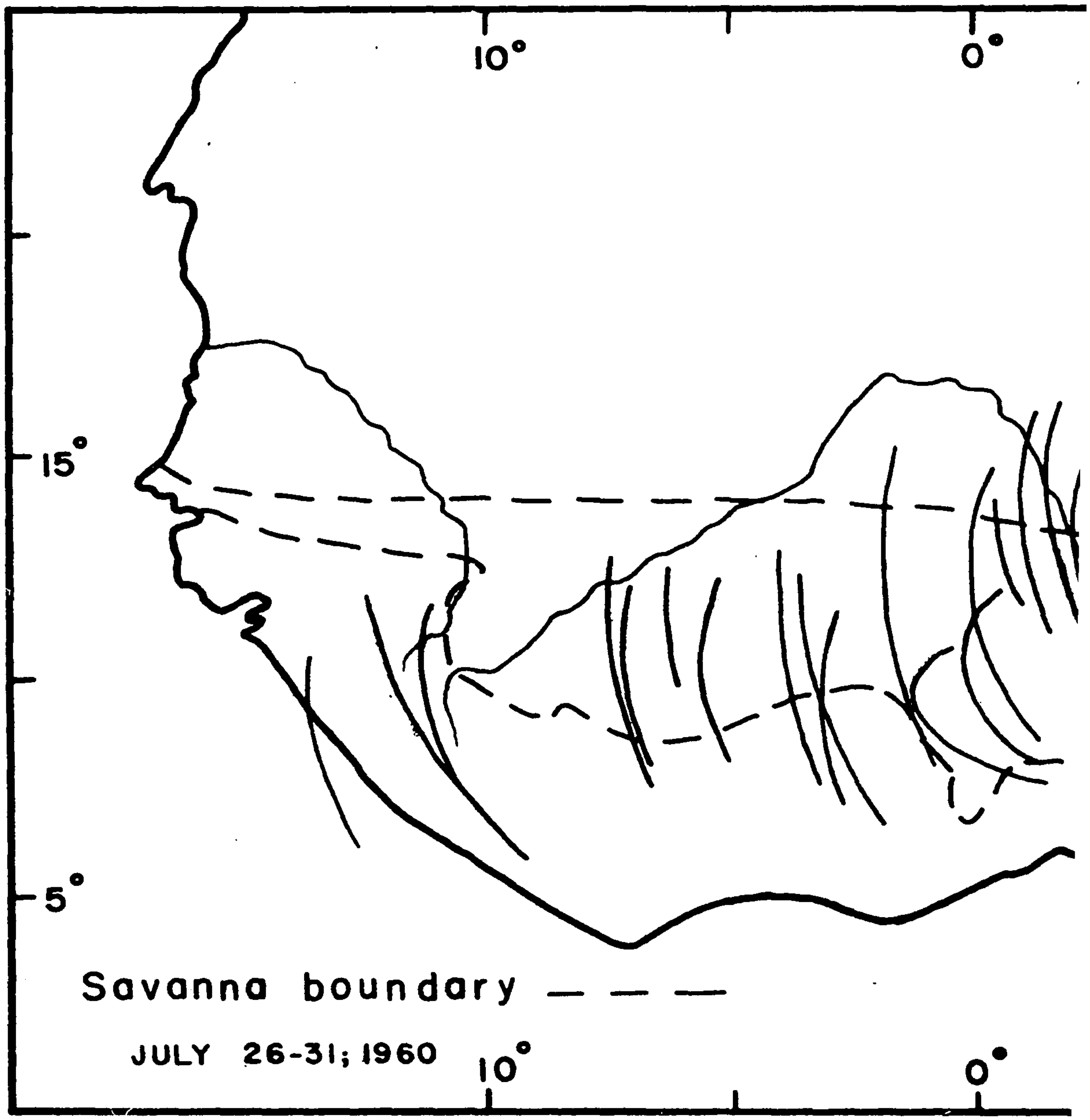
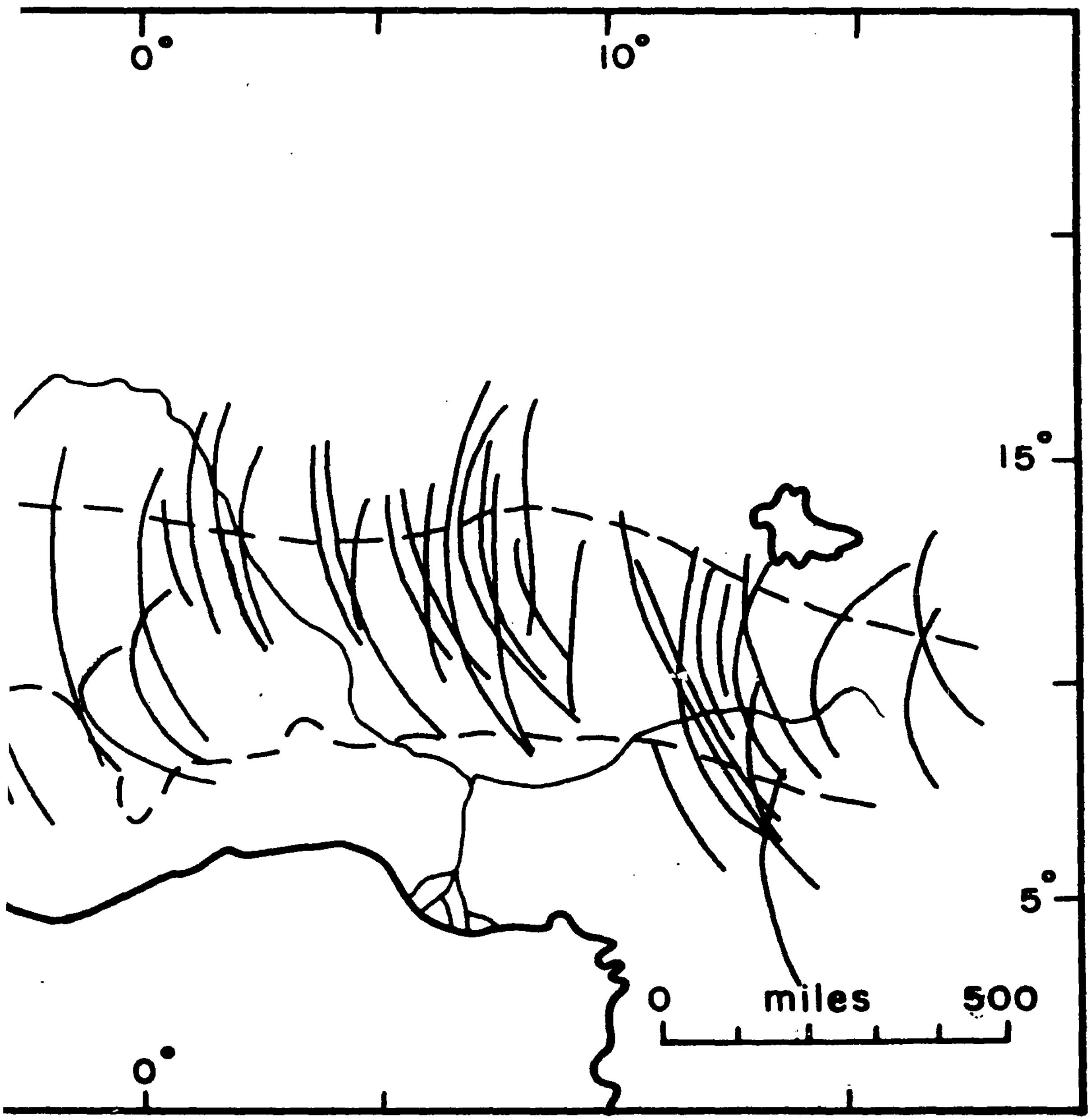
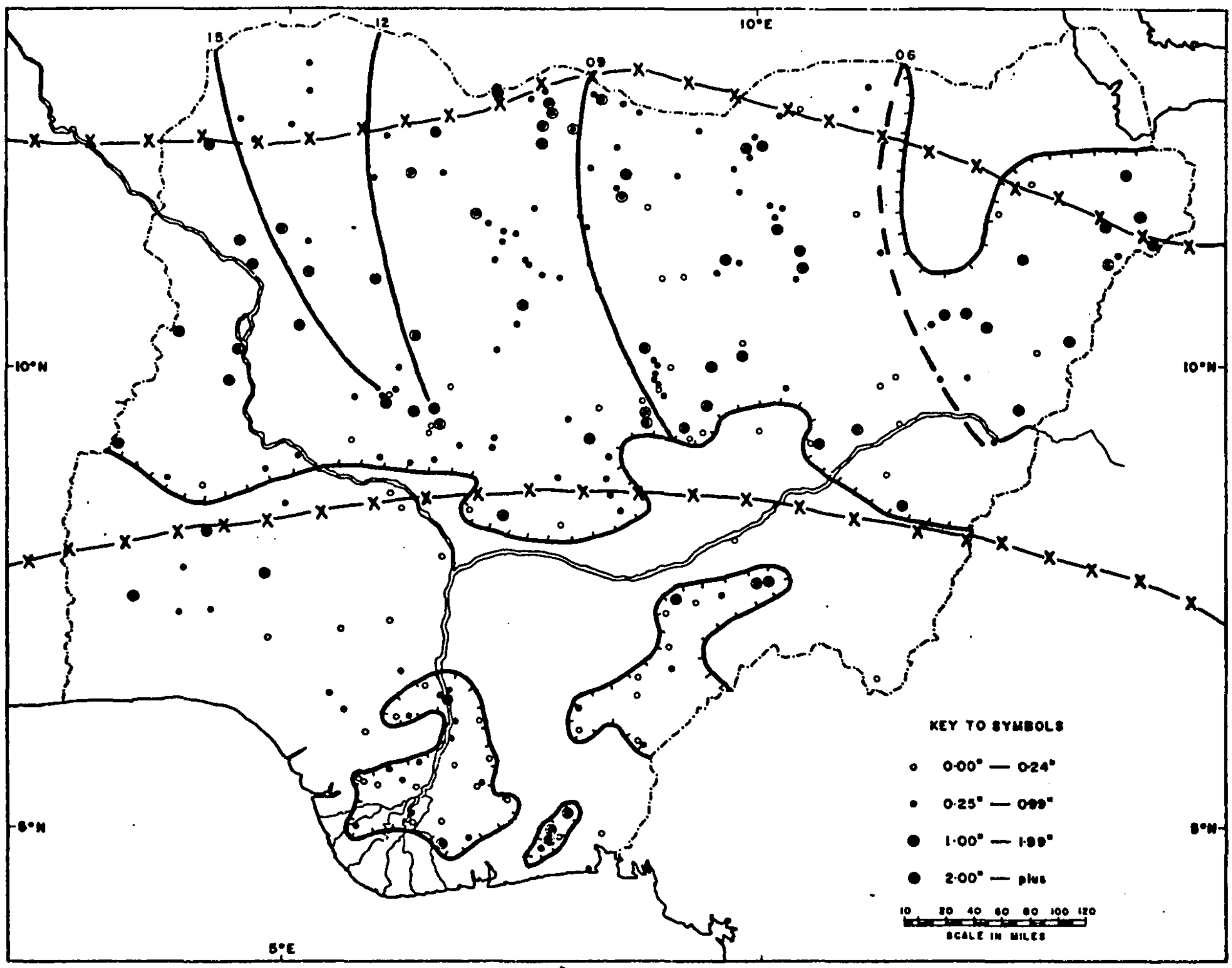


Fig. 41. Relation of Savanna Boundary to the Passa

Disturbance Lines are shown by solid lines.



to the Passage of Disturbance Lines across West Africa
olid lines. (Based on Garnier 1967)



— x — x — x — Savanna Boundary

(Disturbance Lines

Fig. 42. Rainfall, Disturbance Lines and the Savanna Boundary in Nigeria, July 30, 1960 (based on Garnier, 1967)

difference is clearly a consequence of different potential evapotranspiration rates, which are themselves a reflection of differences in the actual nature and duration of the rainfall and associated synoptic systems. This difference in the character of the savanna may be quite significant ecologically. Potential evapotranspiration is often held to be a good indicator of growth rate. Under conditions of high potential evapotranspiration, when water is non-limiting, the rate of plant growth may well be strong. There is clearly no question of a water shortage during the short and reliable savanna wet season. The statistics given in Table IX, for example, show that the water balance for each rainfall category is always positive. Thus it is possible to think that the relatively high potential evapotranspiration of the savanna, particularly on days which bring the majority of the rain, provides a strong stimulus to plant growth. This is perhaps a major factor in maintaining the vegetation character of the area. To expand this idea, which would require information on transpiration and growth rates, lies outside the scope of the present inquiry. It is nevertheless an interesting thought that if the rainy season of the savanna were, in fact, like that of the forest, with its higher humidities and lower potential evapotranspiration, the savanna vegetation might not be so well maintained, and that the region preserves its present character because of wet season differences rather than because of wet season similarities with its southern neighbour.

CHAPTER NINE

CONCLUSION

The aim of this thesis has been to try to contribute towards an understanding of the savanna ecosystem by treating moisture in a strictly climatic sense. A survey of works which considered the character and causes of the savanna indicated that although most people recognised moisture as a vital factor in the savanna ecosystem (either directly or indirectly), it was difficult to think of the influence of climate as a controlling factor, especially in view of the sharpness of the forest/savanna boundary. Hence, non-climatic factors have been invoked as causal factors in relation to the presence and maintenance of the savannas.

However, it seems reasonable to say that the relative importance of climatic and non-climatic factors in the distribution and character of the savannas cannot be properly judged without first inquiring into the nature of moisture as a climatic element, to see whether or not there is in fact any noticeable difference between the moisture characteristics of the savanna and non-savanna regions. In the present thesis, therefore, an attempt has been made to offer a study providing information relevant for such a judgement.

To enable an investigation of this kind to be undertaken, it was decided first to establish an "agreed" savanna core region, and then to examine its moisture characteristics. West Africa was selected for this investigation both because of the availability of necessary data and because of the unique location of the West African savannas, between the forest to the south and the desert to the north. In addition, the area has been well studied by many workers, from different viewpoints, so that a reliable composite picture of an "agreed" savanna area could be readily obtained.

This "agreed" savanna region was used as a test zone in which moisture conditions were analysed in different ways and compared with the results of similar analyses in the neighbouring areas, namely the southern transition and forest to the south and the northern transition to the north of the savanna. The greater part of the analysis was made at the monthly level and included aspects of precipitation, water balance and atmospheric humidity. The results of these studies tended to confirm the findings of the majority of workers, who have looked at the climate of the savanna in monthly terms. The repetition, in all aspects of monthly moisture investigations, of the fact that the savanna experiences a seasonal contrast between a reliably "wet" and a reliably "dry" season, made the moisture conditions of the savanna appear to resemble the forest conditions in the wet season and the desert conditions in the dry season. It follows, therefore, that at this level the distinguishing elements of moisture characteristics of the savanna have been revealed in terms of the length of the dry and wet seasons, and also in terms of seasonal contrasts, rather than in any noteworthy particularities of a "savanna" wet season or a "savanna" dry season as such.

At the second level of investigation however, namely the daily characteristics of rainfall and moisture, the apparent similarity of moisture conditions between the savanna and the forest during the wet season has been shown to break down. This was particularly noticeable when the factors of atmospheric humidity and potential evapotranspiration were introduced. Whereas the arrival of moisture as rainfall in the savanna was shown as comparable in many ways to that of the forest even at the daily level,the area was revealed as being different in the total moisture picture because of the greater drying power of the air and higher potential evapotranspiration. The difference was shown to be particularly marked on days of higher (over 25 mm.) rainfall, which are also the days producing most of the rain both in the savanna and in the forest. This tendency was confirmed by an examination of hour by hour conditions on selected days for a limited number of stations.

Thus, the major conclusion reached in this thesis suggests that there are, in fact, significant ways in which the savannas of West Africa are distinguished in terms of moisture conditions, in a climatic sense, from their neighbours. The full extent and nature of these distinguishing features, however, can only be adequately appreciated by analysing daily statistics and relating the results to the basic physical processes of the area's climatology. The generalisations necessary in studies at the monthly level tend to mask the realities of the diurnal situation. Investigation at the monthly level suggests that the moisture conditions of the savanna are distinguished primarily by seasonal contrast and length of wet season. This thesis, however, has shown that there is more to the matter than this. The wet season of the West African savanna is different from that of the forest not solely in terms of its length: it is different also because, in the savanna, rainfall arrives predominantly in association with disturbance lines, and because the predominating background to such arrival is a dry atmosphere and plentiful sunshine, expressed in high rates of potential evapotranspiration. These circumstances combine to provide a sharp cut-off in time between the rainy and non-rainy periods, however short, and a clear-cut spatial distribution of the area affected, owing to the localised and well marked area traversed by the disturbance lines. All this provides a major contrast with the forest areas where widespread rainfall over an indeterminate area is associated with a high atmospheric humidity, considerable cloud, and low potential evapotranspiration rates. Perhaps, therefore, the sharpness of the forest/savanna boundary in West Africa does not entirely rule out a fundamentally climatically derived cause. Moreover, the day to day situation in the savanna also has important potential implications for growth rates and vegetation characteristics in the region, two possible consequences of the moisture factor which merit a more thorough investigation than has been possible here. A study of daily conditions and frequencies certainly provides a basis for distinguishing moisture characteristics in the area in a way which appears not yet to have been widely used in studies of the savanna ecosystem.

In the light of the above discussion it seems undoubtedly reasonable to think that climate, as expressed in moisture conditions, is a factor that "predisposes the vegetation to the development of savanna rather than forest" as Hills has suggested (Hills, 1965(b), p. 2). Indeed, to limit climate to "predisposition" rather than to being a "causal factor" (Hills, 1965(a), 1965(b)) provides perhaps too modest a role for this element in the savanna ecosystem. It must be emphasised, however, that this study has been limited to West Africa and that, therefore, any conclusions drawn from it are not necessarily applicable to all savanna areas in other parts of the world. It is hoped, nevertheless, that the thesis may have offered both evidence and a way of looking at moisture conditions in the savanna which could help to elucidate further some of the differing viewpoints on the savanna and its distribution which were briefly reviewed in the opening chapters.

APPENDIX ONE

DATA SOURCES

A. Published Material

British West African Meteorological Services:

(i) Annual Summary of Observations 1949 - 1959.
(ii) Statistics Illustrating the Climate of Sierra Leone, 1951.

Ghana Meteorological Services:

(i) Annual Summary of Observations 1954 - 1959.
(ii) Monthly Weather Report 1953 - 1959.
(iii) Monthly Summary of Rainfall 1956 - 1960.

Ministère de la France d'Outre-Mer:

(i) Annales des Services Météorologiques de la France d'Outre-Mer. 1[er] Vol. 1955, 1956, 1957.

Nigerian Meteorological Services:

(i) Meteorological Notes No. 2. Preliminary Note on the Rainfall of Nigeria.
(ii) Monthly Rainfall Summaries 1953 - 1965.
(iii) Monthly Weather Report 1948 - 1963.
(iv) Daily Hours of Bright Sunshine 1951 - 1960.
(v) Annual Summary of Observations 1948 - 1960.

Service Météorologique de l'A.O.F.:

(i) Pluviométrie 1929 - 1940 : (a) Côte d'Ivoire
(b) Soudan
(c) Dahomey
(d) Niger
(e) Sénégal
(f) Haute-Volta.
(ii) Résumé Mensuel des Observations 1954 - 1958.

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(ii) World Weather Records 1951 - 1960 Vol. 5. Africa.

Welter, L.:

"Memento du Service Mêtêorologique, N° 7 A, Moyennes". Haut Commissariat de l'Afrique Française Service Mêtêorologique, 1941.

B. Unpublished Material*

(i) Manuscript data of daily rainfall, sun, wind, and atmospheric humidity for 1955 and 1956 for 13 stations in Nigeria.

(ii) Daily Synoptic Charts prepared by the Nigerian Meteorological Services for 1958, 1959, and 1960.

(iii) Photocopies and microfilm copies of autographic rain gauge, temperature and humidity charts for 26 stations in Nigeria for selected dates.

(iv) Manuscript data of daily position of Surface Discontinuity in 1958 and 1959. Supplied by Ghana Meteorological Services.

* This material was made available through the courtesy of Professor B.J. Garnier who had obtained it from the respective Meteorological Services.

APPENDIX TWO

THE PERIOD OF RECORD FOR THE DIFFERENT STATIONS USED

Note: This appendix lists stations in alphabetical order, irrespective of vegetation zones, and indicates for each station the type of data used and the period of such data at the monthly level. In the case of potential evapotranspiration, using Thornthwaite figures (Thornthwaite, 1962), only the length of record is given since the period is not indicated in the reference volume. No listing for daily or hourly analyses is given here since the relevant periods are explained in the text.

ABIDJAN:

Mean Monthly Rainfall	1932 - 1949; 1951 - 1958.
Mean Monthly Potential Evapotranspiration	5 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1932 - 1949; 1951 - 1958.

AGADEZ:

Mean Monthly Rainfall	1922 - 1949; 1951 - 1958.
Mean Monthly Potential Evapotranspiration	1951 - 1960*.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1922 - 1949; 1951 - 1958.
Monthly Variability of Water Balance	1922 - 1949; 1951 - 1958.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

BAMAKO:

Mean Monthly Rainfall	1920 - 1949; 1951 - 1960.
Mean Monthly Potential Evapotranspiration	8 years.

BENIN:

Mean Monthly Rainfall	1949 - 1962.
Mean Monthly Potential Evapotranspiration	46 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1949 - 1962.
Monthly Variability of Water Balance	1949 - 1962.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

* Not available in Thornthwaite. Calculated from temperature data using Thornthwaite's method.

BOBO-DIOULASSO:

Mean Monthly Rainfall	1921 - 1949; 1951 - 1960.
Mean Monthly Potential Evapotranspiration	7 years.
Monthly Variability of Precipitation	1921 - 1949; 1951 - 1960.
Monthly Variability of Water Balance	1921 - 1949; 1951 - 1960.

BOUAKE:

Mean Monthly Rainfall	1923 - 1949; 1951 - 1958.
Mean Monthly Potential Evapotranspiration	14 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1923 - 1949; 1951 - 1958.
Monthly Variability of Water Balance	1923 - 1949; 1951 - 1958.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

ENUGU:

Mean Monthly Rainfall	1923 - 1960.
Mean Monthly Potential Evapotranspiration	35 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1923 - 1960.
Monthly Variability of Water Balance	1923 - 1960.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

FREETOWN:

Mean Monthly Rainfall	1931 - 1960.
Mean Monthly Potential Evapotranspiration	10 years.

IBADAN:

Mean Monthly Rainfall	1923 - 1960.
Mean Monthly Potential Evapotranspiration	48 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.

ILORIN:

Mean Monthly Rainfall	1921 - 1960.
Mean Monthly Potential Evapotranspiration	37 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1921 - 1960.
Monthly Variability of Water Balance	1921 - 1960.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

KADUNA:

Mean Monthly Rainfall	1921 - 1960.
Mean Monthly Potential Evapotranspiration	35 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1921 - 1960.
Monthly Variability of Water Balance	1921 - 1960.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

KANO:

Mean Monthly Rainfall	1921 - 1960.
Mean Monthly Potential Evapotranspiration	48 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1921 - 1960.
Monthly Variability of Water Balance	1921 - 1960.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

KIDAL:

Mean Monthly Rainfall	1923 - 1949; 1953 - 1960.
Mean Monthly Potential Evapotranspiration	5 years.
Monthly Variability of Precipitation	1923 - 1949; 1953 - 1960.
Monthly Variability of Water Balance	1923 - 1949; 1953 - 1960.

KUMASI:

Mean Monthly Atmospheric Humidity	1951 - 1964.

MAMOU:

Mean Monthly Rainfall	1941 - 1960.
Mean Monthly Potential Evapotranspiration	5 years.

MINNA:

Mean Monthly Rainfall	1949 - 1962.
Mean Monthly Potential Evapotranspiration	37 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1949 - 1962.
Monthly Variability of Water Balance	1949 - 1962.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

MOPTI:

Mean Monthly Rainfall	1922 - 1949; 1951 - 1960.
Mean Monthly Potential Evapotranspiration	6 years.
Monthly Variability of Precipitation	1922 - 1949; 1951 - 1960.
Monthly Variability of Water Balance	1922 - 1949; 1951 - 1960.

NATITINGOU:

Mean Monthly Rainfall	1925 - 1949; 1951 - 1960.
Mean Monthly Potential Evapotranspiration	9 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.

NIAMEY:

Mean Monthly Atmospheric Humidity	1951 - 1964.

OUAGADOUGOU:

Mean Monthly Rainfall	1929 - 1949; 1951 - 1960.
Mean Monthly Potential Evapotranspiration	7 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1929 - 1949; 1951 - 1960.
Monthly Variability of Water Balance	1929 - 1949; 1951 - 1960.

PORT HARCOURT:

Mean Monthly Atmospheric Humidity	1951 - 1964.

SOKOTO:

Mean Monthly Rainfall	1921 - 1960.
Mean Monthly Potential Evapotranspiration	37 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1921 - 1960.
Monthly Variability of Water Balance	1921 - 1960.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

TAMALE:

Mean Monthly Atmospheric Humidity	1951 - 1964.

TIMBUKTU:

Mean Monthly Rainfall	1951 - 1960.
Mean Monthly Potential Evapotranspiration	17 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1951 - 1960.
Monthly Variability of Water Balance	1951 - 1960.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

WARRI:

Mean Monthly Rainfall	1921 - 1960.
Mean Monthly Potential Evapotranspiration	46 years.
Monthly Variability of Precipitation	1921 - 1960.
Monthly Variability of Water Balance	1921 - 1960.

ZINDER:

Mean Monthly Rainfall	1922 - 1949; 1951 - 1958.
Mean Monthly Potential Evapotranspiration	18 years.
Mean Monthly Atmospheric Humidity	1951 - 1964.
Monthly Variability of Precipitation	1922 - 1949; 1951 - 1958.
Monthly Variability of Water Balance	1922 - 1949; 1951 - 1958.
Monthly Variability of Atmospheric Humidity	1951 - 1964.

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