CONSORTIUM FOR INTERNATIONAL
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END OF TOUR REPORT
AGRICULTURAL ENGINEERING

By

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EOT 86-4

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1.0 Assignment

The specific tasks to be completed during my March 4 - 10, 1986 trip to Sri Lanka were as follows:

1. Consult with Professor Don Senanayake about the progress of the project.
2. Visit the Tea Research station at Hantana.
3. Conduct the following three seminars:
   a. Using Meterological Data
   b. Agrometeorological Studies
   c. Measuring the Environment

2.0 Recommendations for Upgrading Meterological Studies

There is a need for two Agrometerological courses to acquaint the postgraduate students with the atmospheric role in the wide field of agriculture. Each course consists of 45 hours of lectures and could be taught sequentially or concurrently. Following is an outline of the two courses:

Course One: Agrometeorology

Topic:	Number of hours
Introduction - historical	1
Environmental factors - axioms of research	2
Weather and climate controls	2
Climatic patterns and classification	2
Regional climates	2
Climate, soil and vegetation	2
Types of agrometeorological studies	1
Radiation patterns and their effects on plants	4
Temperature and its effect on plants	4
Water budget - gain and loss	2
Soil conditions	1

Drought	1
Plant response to moisture	2
Air flow and its effect on plants	2
Small scale climates	2
Atmospheric modification	3
Climatic variability	3
Agrometeorological surveys	2

Study to be directed specifically to the problems of Sri Lanka:

Climate and crops Climate and domestic animals Climate and insects Climate and diseases	7

Course Two: Obtaining and Analyzing Agrometeorology Data

Obtaining:	Number of hours
Making relevant meteorological observations	6
Limitations of the measurements	2
Instrument problems	2
Processing and storing data	2
Remote sensing techniques	2
Empirical and physical estimates	3
Analyzing:	
General principles	3
Frequency distribution of the data	4
Spatial distributions of the data	3
Time series	3

Single variables - patterns of the climatic elements	3
Multiple variables - interrelationships among climatic elements	3
Indices	2
Preparing an agrometeorological survey	3
Crop models	4

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3.0 Recommendations for Library Materials on Agricultural Meteorology

While surveying the libraries at the Postgraduate Institute and the University, I was struck by the almost complete lack of material in the field of agricultural meteorology. With this in mind, I am enclosing a list of suggested publications to be obtained for student use. These are divided into five sections as follows:

1. Books
2. Technical publications and monographs
3. Journals
4. Relevant journal articles
5. Conference proceedings and bibliographies

Bibliography appears in Appendix 1.

4.0 Proposed Agroclimatology Survey

Sri Lanka offers an ideal and rare opportunity for the making of a detailed agroclimatology survey of the type given in W.M.O. publication No. 210. In detail the Sri Lanka survey would differ considerably from that given in the W.M.O. survey of the Sahelian region of West Africa. It seems advisable to develop the survey under the supervision of the Postgraduate Institute of Agriculture in conjunction with the Sri Lankan Department of Agriculture. Such a survey would be of great benefit in the decision-making process and for economic planning.

Details needed in such a survey would have to be determined by a committee of specialists from Sri Lanka, together with the services of a consultant. However, the outline in Appendix 2 is submitted in order to suggest the type of material to be covered.

See Appendix 3 for a copy of the contents of the W.M.O. survey.

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5.0 Proposed Agrometeorological Station

It is desirable that Sri Lanka set up an agrometeorological station in order to accomplish the completion of the survey. This recommendation assumes that funds will be limited and that the station would be used for educational and not research purposes. If more funding was available, a list of more sophisticated equipment can be prepared.

The following equipment is required:

1. Instrument shelter (can be made locally) to house:
   a. maximum and minimum thermometers
   b. wet and dry bulb thermometers
   c. hair hygrograph
2. Soil thermometers - a minimum of three, at 10cm, 20cm, but ideally two others at 5cm and 50 cm
3. Anemometers - run-of-wind (notes miles of wind) at two heights, 2m and 10m with attached wind vane
4. Solar Radiation
   a. a pyranograph for global radiation
   b. a Campbell-Stokes sunshine recorder
   c. a photometer with filter for visible spectrum
5. Evaporimeter
   a. two types, ideally 2' and 3' diameter style (can be made locally)
   b. lysimeter of floating type (can be made locally)
6. Soil moisture
   a. gravimetric apparatus
   b. tensiometers
   c. neutron probe (if funds available)

APPENDIX 1

APPENDIX I
CONFERENCE PROCEEDINGS AND BIBLIOGRAPHIES

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*Note - Many of these are difficult to obtain; we could supply photocopies at cost plus mailing if required.

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APPENDIX 2

Agrometeorological Survey Contents

Meteorology of area

Agriculture of area

Precipitation

temporal	annual - probability calculations monthly - probability calculations pentad - patterns 24 hour amounts - distribution daily variation
spatial	mean monthly mean pentad between station patterns - monthly, pentad between station patterns - daily

Evapotranspiration
- empirical estimates

Soil Moisture
- water budget techniques, using various time intervals

Atmospheric humidity
- temporal patterns of dewpoint
- spatial patterns of saturation deficit

Air flow
- seasonal patterns
- mesoscale patterns
- variation with height

Radiation/sunshine
- analysis of observations
- theoretical calculations

Discussion of requirements of main crops

- climatic aspects
- phenologic aspects

Future Needs and Studies

APPENDIX 3

W.M.O. Publication No. 210

THE WMO

The World Meteorological Organization (WMO) is a specialized agency of the United Nations of which 125 States and Territories are Members.

It was created :

— to facilitate international co-operation in the establishment of networks of stations and centres to provide meteorological services and observations,
— to promote the establishment and maintenance of systems for the rapid exchange of meteorological information,
— to promote standardization of meteorological observations and ensure the uniform publication of observations and statistics,
— to further the application of meteorology to aviation, shipping, agriculture, and other human activities,
— to encourage research and training in meteorology.

The machinery of the Organization consists of the following bodies.

The *World Meteorological Congress*, the supreme body of the Organization, brings together the delegates of all Members once every four years to determine general policies for the fulfilment of the purposes of the Organization, to adopt Technical Regulations relating to international meteorological practice and to determine the WMO programme.

The *Executive Committee* is composed of 21 directors of national meteorological services and meets at least once a year to conduct the activities of the Organization and to implement the decisions taken by its Members in Congress, to study and make recommendations on matters affecting international meteorology and the operation of meteorological services.

The six *Regional Associations* (Africa, Asia, South America, North and Central America, South-West Pacific and Europe), which are composed of Member Governments, co-ordinate meteorological activity within their respective regions and examine from the regional point of view all questions referred to them.

The eight *Technical Commissions* composed of experts designated by Members are responsible for studying the special technical branches related to meteorological observation, analysis, forecasting and research as well as to the applications of meteorology. Technical Commissions have been established for synoptic meteorology, climatology, instruments and methods of observation, aerology, aeronautical meteorology, agricultural meteorology, hydrometeorology and maritime meteorology.

The *Secretariat*, located at Geneva, Switzerland, is composed of an international scientific, technical and administrative staff under the direction of the Secretary-General. It undertakes technical studies, is responsible for the numerous technical assistance and other technical co-operation projects in meteorology throughout the world aimed at contributing to economic development of the countries concerned. It also publishes specialized technical notes, guides, manuals and reports and in general acts as the link between the meteorological services of the world. The Secretariat works in close collaboration with the United Nations and other specialized agencies.

WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 86

AN AGROCLIMATOLOGY SURVEY OF A SEMIARID AREA IN AFRICA SOUTH OF THE SAHARA

by
J. Cochemé and P. Franquin

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FOREWORD

Early in 1960, representatives of three specialized agencies of the United Nations met to organize an inter-agency project in agroclimatology. The agencies were the Food and Agriculture Organization (FAO), the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the World Meteorological Organization (WMO). The project was a study of agroclimatology in semiarid and arid zones of the Near East. WMO Technical Note No. 56 (WMO - No. 141.TP.66) is a report of that project.

In 1962, the same three agencies agreed to make a similar study in a tropical area in Africa south of the Sahara, with a semiarid climate of summer rains. The present Technical Note constitutes the general report of this second study.

It is my pleasure to take this opportunity to thank the authors, Mr. J. Cochemé and Mr. P. Franquin, for their efforts. In their introduction, the authors acknowledge the valuable assistance of a number of individuals and agencies to whom I also extend grateful appreciation. Finally, I wish to thank the Directors-General of FAO and UNESCO for their continued collaboration in this series of most useful studies.

D. A. Davies

(D. A. Davies)
Secretary-General

SUMMARY

An area with a semiarid climate of summer rains in Africa south of the Sahara is delineated and its soils and vegetation briefly described. A simple model of the atmospheric circulation illustrates the origins of its tropical climate with a long dry northern winter and summer rains. Annual crops are cultivated extensively during the rains with graded systems of cultivation adapted to an increase from north to south of the single annual growing season which is never long enough to permit consecutive cultivation of main crops.

The seasonal pattern of rainfall shows a maximum in August. Its variabilities and intensities are somewhat above world average values and, on an annual basis, rainfall per day of rain is about 14 mm throughout the area. Mean annual rainfall increases from 250 mm in the north to 1100 mm in the south, whilst potential evapotranspiration decreases from 2200 mm to 1400 mm. By comparing the seasonal variation of these two quantities the duration of availability-of-water periods is estimated. The mean annual "humid" period, during which rainfall exceeds potential evapotranspiration, increases from nil in the north to 140 days in the south, and the "moist plus storage" period, correspondint to the season during which annual crops can be grown, increases similarly from 55 to 200 days. The supply of solar energy is sustained throughout the year, but in summer it is not very much higher than in temperate countries. During the growing season of summer rains, air dryness, temperatures and rates of evaporation are reduced to amounts less likely to impose severe stress on annual crops than those prevailing immediately before and after the rains. The night temperatures, however, tend to remain high and reduce dry matter production.

The cereals sorghum and millet, which are subsistence crops in the area, need, for maximum production, close matching of the growth cycle length of varieties to the local length of availability-of-water periods. Another adaptation to local climate is the timing of heading to coincide with the end of the humid period; this timing is also regulated by photoperiodism, especially with late varieties which are short day. Such adaptations have been achieved by traditional agriculture, but careful consideration is required when introducing new varieties. Groundnut and cotton, both cash crops which flower axially, also require matching of growth cycle length and of the timing of useful flowering to the duration of the availability-of-water periods. Whilst millet, sorghum and groundnut show a wide spectrum of varieties able to cover most of the area, the cotton form grown there at present is an ecotype of fairly narrow range. Closer analysis of its agroclimatic needs and tolerances was therefore possible. Restitution of fertility to the soils is by long fallows which also provide pastures. Various measures to intensify pastures and fodder production in the area are technically possible and all involve careful consideration of the climatic needs and tolerances of the varieties of grasses and legumes involved.

Comparisons of yield with climatic factors of rainfall and availability of water periods showed that, where there was a marked relation, the regression tended to be curvilinear, with yield dropping off whenever values of the climatic variables exceeded an optimum range, as well as when they fell short of it. Information on yields and the timing of biological events needed for comparisons of agronomic and climatic variables is even scarcer than meteorological information. The type of data required is described in the report.

SUMMARY

A consideration of the information gathered by the survey and its scale suggest that, once agroclimatic characterization of places from which sufficient data are available has been worked out, great caution must be exercised in extrapolating this information to delineate agroclimatic sub-regions for agricultural planning and development. Regions with climates similar to that of the area surveyed are found on both sides of the Equator and in all continents, but none are as wide. Outside Africa, the most important homologous areas are in the northwest of the Indian sub-continent and in the north of Australia. Follow-up action recommended includes the periodical publication of agroclimatic information enlarged and reviewed up to date and the holding of a technical meeting jointly by the international agencies concerned and agronomists and meteorologists from the survey area, in addition to the initiation of more detailed studies of smaller areas and the building of energy and water-balance models more specific to selected crops and localities.

RESUME

La présente Note indique les limites de la zone semi-aride et décrit brièvement ses sols et sa végétation. Un modèle simple de la circulation atmosphérique illustre les origines de son climat tropical caractérisé par un long hiver sec et des pluies d'été. Les plantes annuelles sont cultivées de façon extensive pendant la saison des pluies à l'aide de systèmes progressifs de culture adaptés à un accroissement, du nord au sud, de l'unique saison végétative annuelle, qui n'est jamais suffisamment longue pour permettre la culture consécutive des principales plantes agricoles.

Le régime saisonnier des pluies a un maximum en août. Ses fluctuations et intensités sont légèrement supérieures aux valeurs moyennes mondiales et, calculée sur une période d'une année, la quantité de pluie quotidienne est d'environ 14 mm dans toute la région. La pluie annuelle moyenne augmente de 250 mm, dans le nord, à 1100 mm, dans le sud, tandis que l'évapotranspiration potentielle décroît de 2200 mm à 1400 mm. En comparant les variations saisonnières de ces deux quantités, on peut évaluer la durée des périodes "d'eau disponible". La période "humide" annuelle moyenne, au cours de laquelle la pluie dépasse l'évapotranspiration potentielle, augmente de zéro, au nord, à 140 jours, au sud, et la période d'excédent hydrique ("moist plus storage" period), qui correspond à la saison au cours de laquelle on peut faire pousser les cultures annuelles, augmente de façon analogue de 55 à 200 jours. L'apport d'énergie solaire reste le même toute l'année, mais en été il n'est que légèrement supérieur à celui des pays à climat tempéré. Durant la saison des pluies d'été propice à la croissance, la sécheresse de l'air, les températures et les taux d'évaporation sont réduits à des quantités qui risquent moins d'endommager les récoltes annuelles que celles qui sont observées immédiatement avant et après les pluies. Toutefois, les températures nocturnes tendent à rester élevées et à freiner l'élaboration de matières sèches.

Pour pouvoir obtenir une production maximale de sorgho et de millet, qui sont les cultures de subsistance de cette région, il faut que la durée du cycle de croissance de ces variétés coïncide étroitement avec la durée locale des périodes "d'eau disponible". Il faut également s'adapter au climat local en faisant coïncider l'épiaison avec la fin de la période humide; cette synchronisation est également commandée par le photopériodisme, particulièrement en ce qui concerne les variétés tardives, qui sont des plantes à jours courts. L'agriculture traditionnelle a permis de réaliser ces adaptations, mais de grandes précautions doivent être observées lorsque l'on introduit de nouvelles variétés. Pour l'arachide et le coton, qui sont tous deux des cultures commerciales fleurissant de façon axiale, il faut également accorder la longueur du cycle de croissance et la synchronisation de la floraison utile avec la durée des périodes "d'eau disponible". Tandis que le millet, le sorgho et l'arachide présentent une large gamme de variétés pouvant couvrir la plus grande partie de cette région, la variété de coton qui y est actuellement cultivée est un écotype dont l'aire d'extension est assez limitée. C'est pourquoi il a été possible d'effectuer une analyse plus approfondie de ses besoins et de ses tolérances agroclimatiques. Les sols peuvent être refertilisés par de longues jachères qui servent également de pâturage. Il est techniquement possible d'appliquer divers procédés destinés à intensifier la production des pâturages et des fourrages dans la région, mais il faut dans tous les cas étudier avec soin les besoins et les tolérances climatiques des variétés de graminées et de légumineuses en cause.

En comparant les rendements avec des facteurs climatiques tels que la pluie et les périodes "d'eau disponible", on a constaté que, lorsqu'il y avait une corrélation nette entre lesdits facteurs, la régression tendait à être curvilinéaire avec une baisse de rendement chaque fois que les valeurs des variables climatiques dépassaient un intervalle optimal

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et lorsqu'elles n'atteignaient pas la limite inférieure dudit intervalle. Les renseignements relatifs aux rendements et à la synchronisation des événements biologiques sont encore plus rares que les renseignements météorologiques. Le présent rapport décrit le type de données dont on a besoin en la matière.

Si l'on examine les renseignements rassemblés par cette enquête, on constate que, dès que l'on a pu établir une caractérisation agroclimatique des lieux où l'on peut obtenir un nombre suffisant de données, il faut procéder avec beaucoup de prudence à l'extrapolation de ces informations pour déterminer les sous-régions agroclimatiques à des fins de planification et de développement agricole. On trouve des régions dont le climat est analogue à celui de la région étudiée, de part et d'autre de l'équateur et sur tous les continents, mais aucune n'est aussi vaste. En dehors de l'Afrique, les régions homologues les plus importantes se situent au nord-ouest du sous-continent indien et dans le nord de l'Australie. Outre la mise en route d'études plus approfondies, portant sur des régions plus limitées, et l'élaboration de modèles du bilan énergétique et hydrique spécialement pour les récoltes et les localités choisies, la Note recommande notamment de publier périodiquement des renseignements agroclimatiques plus complets et mis à jour, et d'organiser une réunion technique à laquelle participeraient les institutions internationales compétentes, ainsi que les agronomes et les météorologistes de la région considérée.

РЕЗЮМЕ

В отчете дается общая характеристика полузасушливой зоны с ее почвенными и растительными условиями. Упрощенная модель атмосферной циркуляции об'ясняет существование в этой зоне тропического климата, для которого характерна продолжительная сухая зима с северными ветрами и летние дожди. Ежегодное произрастание культур осуществляется в основном за счет дождей, так что интенсивность произрастания сельскохозяйственных культур возрастает с севера на юг; в этой зоне на протяжении года имеется только один вегетационный период, который никогда не бывает достаточным для выращивания одного урожая основных сельскохозяйственных культур.

Наибольшее количество осадков в году выпадает в августе. Колебания сумм осадков и интенсивности их отличаются от средних значений по земному шару; а для всего года в среднем количество осадков, выпадающее в день с дождем составляет около 14 мм для всей территории в целом. Средние ежегодные суммы осадков увеличиваются от 250 мм на севере до 1100 мм на юге, а потенциальная величина эвапотранспирации уменьшается от 2200 мм до 1400 мм. На основании сравнения сезонных колебаний этих двух величин, определяется продолжительность периодов, когда растения могут получать влагу. В среднем "влажный" период, во время которого количество осадков превышает величину потенциальной эвапотранспирации, увеличивается от 0 на севере до 140 дней на юге, а период "влагообеспеченности" соответствующий времени года, когда наблюдается вегетация культур, аналогично увеличивается от 55 до 200 дней. Приток солнечной радиации почти постоянен на протяжении всего года, но летом он не намного больше, чем в странах с умеренным климатом. Во время вегетационного сезона с летними дождями сухость воздуха, температура и степень испарения уменьшаются до величин, которые оказывают более благоприятное влияние на сельскохозяйственные культуры, чем те метеорологические условия, которые наблюдаются до и после выпадения дождей. Однако ночью температура остается высокой, что приводит к снижению выхода сухой массы.

Для получения наивысших урожаев таких злаков, как сорго и просо, являющихся основными сельскохозяйственными культурами в этой зоне, требуется, чтобы колебания продолжительности периода вегетации соответствовали величине периодов, когда растения могут получать воду в местных условиях. Другим примером приспособления к местному климату является то, что время колошения злаков приходится на конец влажного периода; выбор времени вегетации также определяется фотопериодизмом, в особенности для поздних культур короткого дня. Такое приспособление к местным климатическим условиям достигнуто путем разработки традиционных методов ведения сельского хозяйства, а выращивание новых культур требует большой осторожности. Земляной орех (арахис) и хлопок - культуры, которые характеризуются осевым расположением цветов, также требуют совпадения периода вегетации и наиболее благоприятного времени их цветения с тем периодом, когда растения могут получать влагу. В то время, как на большей части территории выращиваются различные сорта проса, сорго и арахиса, сорта хлопка выращиваемые здесь в настоящее время, представляют собой экологический тип, который насчитывает небольшое количество сортов. В связи с этим можно было бы провести анализ агроклиматических условий и сельскохозяйственных характеристик этой культуры. Восстановление плодородия почвы осуществляется применением многолетних паров, которые используются под пастбища.

РЕЗЮМЕ

Технически возможно принять меры для увеличения степени использования пастбищ и роста производства получаемых с них кормов для скота, но при этом необходимо тщательное изучение агроклиматических характеристик различных видов трав и бобовых, выращиваемых здесь.

Сопоставление величин получаемого урожая с такими климатическими факторами, как количество осадков и продолжительность периодов влагообеспеченности показали, что там, где можно вывести определенное соотношение между ними, мы получаем уравнение регрессии, которое подчиняется криволинейным законам, т.е.величина урожая уменьшается в тех случаях, когда климатические переменные превышают оптимальные величины, а также, когда они меньше этих величин. Количество данных о зависимости между величиной урожая и продолжительностью различных биологических периодов, которые нужны для сравнения агрономических и климатических переменных еще меньше, чем количество метеорологических данных. В данном отчете описывается, какие данные нужны для этой цели.

Рассмотрение информации, собранной во время исследования и диапазон ее говорит о том, что после определения агроклиматических характеристик участков этой зоны, по которым имеется достаточное количество данных, необходимо с большой осторожностью подходить к экстраполяции этих данных для определения агроклиматических характеристик подрайонов в целях планирования и развития сельского хозяйства. Районы с климатом, аналогичным климату рассматриваемой зоны, располагаются по обе стороны от экватора на всех континентах, но не простираются так широко, как в Африке. После Африки, наиболее важные зоны находятся на северо-западе Индийского полуострова и в северной части Австралии.

В связи с этим рекомендуется принять меры по периодической публикации агроклиматической информации расширенного характера, которая пополнена новейшими данными, а также созвать совместную техническую конференцию с участием международных организаций, занимающихся этими вопросами, и специалистов по метеорологии, работающих в странах обследуемой зоны; кроме того, необходимо приступить к более тщательному исследованию еще меньших районов зоны и составлению моделей величин получаемой энергии и водного баланса, которые более характерны для определенных видов культур и районов.

RESUMEN

En este informe se delimita la zona semiárida y se describe brevemente su suelo y su vegetación. Por medio de un modelo sencillo de la circulación atmosférica se explica el origen del clima tropical de esta zona, caracterizado por la existencia de un largo y seco invierno y lluvias estivales. Durante la época de las lluvias se practican extensos cultivos anuales según sistemas escalonados, adaptados a una progresión de norte a sur de la única estación anual de cultivo, que nunca tiene la duración suficiente para permitir que se haga una serie consecutiva de cosechas de primera importancia.

La pluviometría de la zona registra su punto máximo en el mes de agosto. Sus variaciones y su intensidad son algo superiores al promedio mundial y, un año con otro, las precipitaciones por día de lluvia son de unos 14 mm en toda la zona. Las precipitaciones medias anuales aumentan de 250 mm en el norte a 1.100 mm en el sur, y la evapotranspiración potencial anual disminuye de 2.200 mm a 1.400 mm en los mismos lugares. Los períodos en que se dispone de agua pueden calcularse comparando las variaciones estacionales de esas dos cantidades. El período medio anual llamado "húmedo", durante el cual las precipitaciones exceden de la evapotranspiración potencial, aumenta de 0 en el norte a 140 días en el sur, y el período de "humedad almacenada", que corresponde a la estación de crecimiento de las cosechas anuales, aumenta igualmente de 55 a 200 días. La energía solar se mantiene constante durante el año, pero en verano no es muy superior a la de los países templados. Durante la estación de crecimiento en que se producen las lluvias estivales, la sequedad de la atmósfera, las temperaturas y los porcentajes de evaporación se reducen de tal modo que someten a los cultivos anuales a influencias menos severas que las ejercidas antes y después de las lluvias. Sin embargo, las temperaturas nocturnas tienden a mantenerse elevadas, con lo que se reduce la producción de secano.

El sorgo y el mijo —alimentos fundamentales en la zona— precisan, para dar un rendimiento máximo, que la duración de las variaciones del ciclo de crecimiento se adapte a la de los períodos en que se dispone de agua en la región. Otra adaptación al clima local consiste en hacer que el momento de la granazón coincida con el final del período húmedo. El tiempo de granazón se regula también mediante la periodicidad lumínica, especialmente con las variedades tardías que granan cuando los días ya son cortos. Tales adaptaciones se han logrado siguiendo los métodos tradicionales de la agricultura, pero es indispensable estudiar cuidadosamente la introducción de nuevas variedades. El cacahuete y el algodón —cultivos comerciales ambos que florecen axialmente— también requieren la sincronización de la duración del ciclo de desarrollo y de la época de florecimiento útil con la duración de los períodos en que se dispone de agua. Mientras que el mijo, el sorgo y el cacahuete tienen una gama muy amplia de variedades que permite cubrir la mayor parte de la zona, el algodón que se cultiva allí actualmente constituye un tipo ecológico que tiene pocas variedades, y por lo tanto ha sido posible realizar un análisis más estricto de sus necesidades y tolerancias agroclimáticas. La restitución de la fertilidad a los suelos se realiza por medio de barbechos prolongados que también sirven para pastos. Hay varias medidas técnicamente posibles para intensificar los pastos y la producción de forrajes en la zona y todas requieren un estudio detenido de las necesidades y tolerancias climáticas de las variedades de hierbas y arbustos correspondientes.

Las comparaciones de la producción obtenidas con los factores climáticos de las precipitaciones acuosas y con los períodos de disponibilidad de agua indicaron que, cuando había una relación marcada, la regresión tendía a ser curvilínea, reduciéndose la producción cuando los valores de las variables climáticas excedían del punto óptimo de la gama,

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lo mismo que cuando no alcanzaban el punto inferior de la misma. La información sobre el rendimiento de las cosechas y las épocas de los cambios biológicos necesarias para comparar las variables agronómicas y climáticas todavía es más escasa que la información meteorológica. En el informe se describen los tipos de datos requeridos.

El examen de la información reunida por medio de la encuesta y el de su escala sugiere que, una vez se han determinado las características agroclimáticas de los lugares respecto a los cuales se dispone de datos suficientes, deben tomarse grandes precauciones en la extrapolación de esta información, con el objeto de delimitar las subregiones agroclimáticas para la planificación y desarrollo agrícolas. En ambos lados del Ecuador y en todos los continentes existen regiones con climas similares al de la zona estudiada pero no hay ninguna tan extensa. Fuera de Africa, las zonas homólogas más importantes se hallan en el noroeste de la India y en el norte de Australia. Entre las medidas que se recomienda seguir está la de la publicación periódica de información agroclimática ampliada y revisada, para que esté al día, y la celebración de una reunión técnica mixta con los organismos internacionales interesados y con agrónomos y meteorólogos de la zona que se estudia, además de la iniciación de estudios más detallados de zonas más pequeñas y la construcción de modelos de distribución de la energía y del balance hidrológico más específicos, con el fin de seleccionar los cultivos y las localidades.

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INTRODUCTION

The FAO/UNESCO/WMO Agroclimatology Project originated from the desire of FAO and WMO to investigate the basic climatic potentials of agriculture in those parts of the world where an intensification of agricultural practices and an extension of cultivated lands showed most promise of an increase in agricultural production. It was soon realized that this co-operation between the two organizations could profitably be related to the Arid Zone and similar programmes of UNESCO.

In April 1960, an inter-agency study group representing the three organizations met in Rome to discuss the scope of an initial survey, and to decide upon a region for it. The region chosen consisted of the arid and semiarid zones of Jordan, Lebanon, Syria, Iraq and Iran with dry summers and winter rains. An agronomist from FAO (G. Perrin de Brichambaut) and a meteorologist selected by WMO (C.C. Wallén) were appointed to make the survey from FAO headquarters in Rome. They published a technical report* and a shorter, general report.**

In October 1962, the study group met again, and selected for the second survey a tropical area in Africa south of the Sahara, with a semiarid climate of summer rains. This area, bounded to the west by the Atlantic Ocean and to the east by the frontier of Chad with the Sudan, consists of parts of the following countries: Senegal, Mauritania, Mali, Upper Volta, Ghana, Togo, Dahomey, Niger, Nigeria, Cameroon and Chad. (Its northern and southern boundaries are not sharply defined.) An agronomist, P. Franquin, and a meteorologist, J. Cochemé, were recruited at the end of 1963 to make the second survey, FAO being once more the executing agency of this inter-agency project.

The Institut des Recherches Agronomiques Tropicales (IRAT) was commissioned to collect agronomic information from the area surveyed; it delegated Mr. L. Castaing to do this work.

Again a technical and a general report were prepared, the latter being this publication.

Contributions to the Technical Report were also made by three pedologists from the Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), B. Dabin, R. Fauck and J. Pias, and by an FAO expert botanist in Senegal, A. F. Naegelé.

The necessary information could not have been collected without the help of the national and agricultural services of the countries of the Area. Much assistance was also given by research stations, amongst which will be mentioned the Centre de Recherches Agronomiques at Bambey in Senegal and the Regional Research Station in Samaru in Northern Nigeria.

The meteorological sections of the Agence pour la Sécurité de la Navigation Aérienne (ASECNA) in Senegal and other French-speaking countries of the Area provided very useful climatic data and, besides IRAT and ORSTOM, several similar technical agencies in these countries were of assistance.

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* Technical report on a study of agroclimatology in semiarid and arid zones of the Near East. Rome, FAO: 23061/2, 1962.

** A study of agroclimatology in semiarid and arid zones of the Near East. Geneva, WMO: Technical Note No. 56, WMO - No. 141.TP.66, 1963.

INTRODUCTION

Le Projet d'agroclimatologie FAO/UNESCO/OMM est dû au désir de la FAO et de l'OMM d'étudier les conditions climatiques de base de l'agriculture dans les parties du globe où, en intensifiant les méthodes de culture et en étendant la superficie des terres cultivées, on est le plus en droit d'espérer un accroissement de la production agricole. On s'est rapidement rendu compte que cette coopération entre les deux organisations pourrait avantageusement se rattacher au Programme de recherches sur la zone aride et à d'autres projets analogues de l'UNESCO.

En avril 1960, un groupe d'étude mixte représentant les trois organisations s'est réuni à Rome afin de définir la portée de l'étude initiale et de choisir la région qui devait en faire l'objet. La région choisie comprenait des zones arides et semi-arides de Jordanie, du Liban, de Syrie, d'Irak et d'Iran ayant des étés secs et des pluies en hiver. Un agronome de la FAO (G. Perrin de Brichambaut) et un météorologiste désigné par l'OMM (C.C. Wallén) furent chargés de procéder à cette enquête au siège de la FAO à Rome. Ils ont publié un rapport technique* et un rapport général, plus bref**.

En octobre 1962, le groupe d'étude s'est de nouveau réuni et a choisi pour la seconde enquête une région tropicale d'Afrique, située au sud du Sahara et ayant un climat semi-aride à pluies d'été. Cette région, limitée à l'ouest par l'océan Atlantique et à l'est par la frontière séparant le Tchad du Soudan, comprend des parties des pays suivants: Sénégal, Mauritanie, Mali, Haute-Volta, Ghana, Togo, Dahomey, Niger, Nigéria, Cameroun et Tchad (ses limites septentrionales et méridionales ne sont pas nettement définies). Un agronome, P. Franquin, et un météorologiste, J. Cochemé, furent désignés à la fin de 1963 pour effectuer la seconde enquête, la FAO étant une fois de plus l'agent exécutif de ce projet interinstitutions.

L'Institut des Recherches Agronomiques Tropicales (IRAT) a été chargé de rassembler les données agronomiques de la région considérée et a confié ce travail à M. L. Castaing.

Deux nouveaux rapports, l'un technique et l'autre général, ont été préparés, ce dernier constituant la présente publication.

Trois pédologues de l'Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) -- B. Dabin, R. Fauck, et J. Pias -- et un spécialiste de la botanique envoyé par la FAO au Sénégal, A.F. Naegelé, ont également contribué à l'élaboration du Rapport technique.

Les renseignements nécessaires à cette étude n'auraient pas pu être rassemblés sans l'aide des services météorologiques et agricoles des pays de la région. Des stations de recherches, parmi lesquelles il y a lieu de mentionner le Centre de Recherches Agronomiques de Bambey (Sénégal) et la Regional Research Station de Samaru (Nigéria du Nord), ont elles aussi largement prêté leur concours à cette étude.

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* Rapport technique sur une étude d'agroclimatologie dans les zones arides et semi-arides du Proche-Orient, Rome, FAO : 23061/2, 1962.

** Une étude d'agroclimatologie dans les zones arides et semi-arides du Proche-Orient, Genève, OMM : Note technique N° 56, OMM - N° 141.TP.66, 1963.

Les sections météorologiques de l'Agence pour la Sécurité de la Navigation Aérienne (ASECNA) au Sénégal et dans d'autres pays d'expression française de la région ont fourni des données climatiques très précieuses. Outre l'IRAT et l'ORSTOM, plusieurs organismes techniques analogues de ces pays ont également été d'une grande aide.

ВВЕДЕНИЕ

Совместный проект ФАО, ЮНЕСКО и ВМО по агроклиматологии был разработан ФАО и ВМО с целью изучения основных потенциальных возможностей сельского хозяйства и климатических условиях тех стран, где интенсификация сельского хозяйства и расширение посевных площадей может дать наилучшие результаты с точки зрения роста сельскохозяйственной продукции. В дальнейшем было установлено, что этот проект, разработанный совместно этими двумя организациями, целесообразно увязать с программой исследований в засушливых районах и другими аналогичными программами ЮНЕСКО.

В апреле 1960 года в Риме состоялось совещание группы представителей этих трех организаций с целью обсудить программу первоначального обследования и определить район, в котором должен быть проведен проект. Был избран район засушливых и полузасушливых земель в Иордании, Ливане, Сирии, Ираке, для которых характерны засушливое лето и зима с большим количеством осадков. Специалисту по агрономии, представителю ФАО (Ж. Перрену де Бришамбо) и метеорологу, назначенному ВМО (К.К. Валлену), было поручено провести соответствующее исследование, работая в штаб-квартире ФАО в Риме. Они подготовили технический доклад* и более короткий общий доклад**.

В октябре 1962 года состоялась вторая сессия исследовательской группы, на которой в качестве района для проведения второго исследования была намечена тропическая зона в Африке к югу от Сахары, для которой характерен полузасушливый климат с дождями в летний период. Эта зона, простирающаяся на западе до Атлантического океана, а на востоке до границы между Чадом и Суданом, включает в себя отдельные районы следующих стран: Сенегала, Мавритании, Мали, Верхней Вольты, Ганы, Того, Дагомеи, Нигерии, Камеруна и Чада (северные и южные границы зоны не имеют четких очертаний).

В конце 1963 года для проведения второго исследования были привлечены специалист по агрономии П.Франкен и метеоролог Ж.Кошеме; ответственность за осуществление этого проекта вновь взяла на себя ФАО.

Сбор информации по состоянию сельского хозяйства в обслуживаемой зоне был поручен Научно-исследовательскому институту по проблемам сельского хозяйства в тропиках, который выделил для этой цели своего сотрудника Л.Кастэна.

На этот раз вновь были подготовлены технический и общий доклады; общий доклад воспроизводится в настоящем документе.

* Технический доклад о результатах агроклиматологических исследований в полузасушливых и засушливых районах Ближнего Востока. Рим, ФАО, 23061/2,1962г.

** Агроклиматологические исследования в полузасушливых и засушливых районах. Женева, ВМО, Техническая записка № 56, ВМО-№ 141, ТР. 66, 1963 г.

В составлении технического доклада участвовали три специалиста по почвоведению из Научно-технического управления заморских территорий Б.Дабэн, Р.Фок и Ж.Гиа, а также эксперт ФАО в Сенегале, специалист по ботанике А.Ф.Ваэгеле.

Вся необходимая информация не могла не быть собрана без помощи национальных служб и сельскохозяйственных учреждений стран, расположенных в этой зоне. Большая помощь была оказана также научно-исследовательским учреждениями, среди которых следует отметить Научно-исследовательский агрономический центр в Бамбее (Сенегал) и Региональную научно-исследовательскую станцию в Самару (Северная Нигерия).

Весьма полезные климатологические данные были представлены метеорологическими отделами Агенства по безопасности аэронавигации (ASECNA) в Сенегале и других франко-говорящих странах обследуемой зоны. Помимо Научно-исследовательского института по проблемам сельского хозяйства в тропиках (IRAT) и Научно-технического управления заморских территорий (ORSTOM), большую помощь оказали также некоторые другие аналогичные учреждения.

INTRODUCCION

El proyecto FAO/UNESCO/OMM de agroclimatología tuvo su origen en el deseo de la FAO y de la OMM de investigar las condiciones climáticas básicas para la agricultura en las partes del mundo donde hay mayores posibilidades de incrementar la producción agrícola por medio de la intensificación de los cultivos y la ampliación de las tierras cultivadas. Pronto se llegó a la conclusión de que esta colaboración entre ambas organizaciones podría vincularse provechosamente a los programas de la UNESCO sobre zonas áridas y cuestiones análogas.

En abril de 1960, un grupo de estudio mixto compuesto de representantes de las tres organizaciones se reunió en Roma para examinar el alcance que debía darse al estudio inicial de esta cuestión y escoger la región en que debería efectuarse. Por fin fueron elegidas las zonas áridas y semiáridas de Jordania, Líbano, Siria, Irak, Irán, caracterizadas por veranos secos e inviernos lluviosos. Un agrónomo de la FAO (G. Perrin de Brichambaut) y un meteorólogo escogido por la OMM (C.C. Wallén) fueron designados para efectuar la encuesta en la sede de la FAO en Roma. Publicaron un informe técnico* y un informe general, más breve**.

En octubre de 1962, volvió a reunirse el grupo de estudio y seleccionó para su segunda encuesta una zona tropical de Africa situada al sur del Sahara caracterizada por un clima semiárido de lluvias estivales. Esta zona, que limita al oeste con el Océano Atlántico y al este con la frontera del Tchad y el Sudán, abarca partes de los siguientes países: Senegal, Mauritania, Malí, Alto Volta, Ghana, Togo, Dahomey, Níger, Nigeria, Camerún y Tchad. (Ni al Norte ni al Sur está esa zona delimitada con precisión).

A fines de 1963, se contrató a un agrónomo, P. Franquin, y a un meteorólogo, J. Cochemé, para realizar la segunda encuesta; una vez más, la FAO se encargó de la ejecución del proyecto.

Se encomendó al Instituto de Investigaciones Agronómicas Tropicales (IRAT) que reuniera información de carácter agrícola de la región objeto de estudio y se designó al señor L. Castaing para realizar ese trabajo.

También en este caso se preparó un informe técnico y un informe de carácter general. La presente publicación constituye el informe de carácter general que acabamos de mencionar.

Contribuyeron también a la redacción del informe técnico tres edafólogos de la Oficina de Investigaciones Científicas y Tecnológicas de Ultramar (ORSTOM) : el Sr. B. Dabin, el Sr. R. Fauck y el Sr. J. Pias y un experto en botánica de la FAO destacado en el Senegal, el Sr. A.F. Naegelé.

* Informe técnico sobre un estudio de agroclimatología en las zonas áridas y semiáridas del Cercano Oriente. Roma, FAO : 23061/2, 1962.

** Un estudio de agroclimatología en las zonas áridas y semiáridas del Cercano Oriente. Ginebra, OMM : Nota Técnica N° 56, OMM - N° 141.TP.66, 1963.

Hubiera sido imposible reunir la información necesaria sin la ayuda de los servicios agrícolas nacionales de los países de la región. También se recibió mucha ayuda de los centros de investigación, entre los que merecen mención: el Centro de Investigaciones Agronómicas de Bambey, Senegal y el Centro de Investigaciones Regionales de Samaru en Nigeria del Norte.

Las secciones meteorológicas del Organismo para la Seguridad de la Navegación Aérea (ASECNA) situadas en Senegal y otros países de habla francesa de la región, comunicaron datos climatológicos muy útiles y además del IRAT y de la ORSTOM otros diversos organismos técnicos de varios países prestaron su valiosa ayuda.

P A R T I

THE BACKGROUND

AIMS AND METHODS OF SURVEY

1. NATURE

This survey is basically an inventory of the climatic resources of an area, these resources being looked upon as potentials for agricultural development.

2. GENERAL METHODS

In order to be able to make such an inventory of resources, it had to be decided which climatic factors were the most relevant; it was then necessary to obtain as detailed a picture as possible of the distribution of these factors over the area, and at all times of the year, and, even more important, of the likelihood of a particular pattern of climate being repeated in a particular place in future years. At the same time, the individual climatic needs and tolerances of the main crops of the area had to be studied, in order to decide how they could best fit into this detailed picture, when and where they could most profitably be grown, and what new areas could be exploited.

3. USES

Any plan for increasing agricultural production can benefit from such a survey: whether the plan involves intensifying existing cultivations, extending them, introducing new crops or techniques (such as mechanization), or improving protection against pests and parasites -- whatever the plan may be, the influence of climate cannot be ignored.

4. USEFULNESS IN TIMES OF CHANGE

Traditional cultivation has learned by trial and error how to cope with limited materials and existing conditions. It is when some radical step forward is contemplated, and capital is to be invested in new agricultural schemes, that tradition can no longer be relied upon, and reliable climatological data can save years of trial and expensive error.

5. PRESENTATION OF INFORMATION

It is not intended, as a result of this study, to evolve a new system of agro-climatic classification nor is it intended to subdivide the survey area into a rigid system of agro-climatic regions within which certain crops should be grown. To push conclusions as far as this would, if anything, reduce the usefulness of this type of survey. (This point will be discussed again at the end of the report.)

6. EXPLORATORY NATURE OF THE SURVEY

The study is not only a survey of an area, but a survey of methods -- of the best ways of producing serviceable agroclimatic information. It is therefore to a large extent explorative and tentative in its approach.

7. SCALE

The scale of the study must necessarily be broad, since the Area is vast, and time limited. However, a number of more detailed studies of various items were carried out, in the hope that they might serve as pilot studies for local investigations on a scale appropriate to direct local application.

8. LIMITATIONS

The survey is limited to dry farming at the time of the summer rains. Cultivation under irrigation and on flood plains, and combinations of such systems with dry farming, are only discussed incidentally. This is not to say that irrigated and flood-plain cultivation are unimportant--indeed, increased production in the future will partly be dependent on increasing the length of the growing season by methods such as these. But the agroclimatology of flood plains and crops under irrigation is a complete study in itself, and is quite distinct from dry farming, which forms the subject of this survey.

9. PHYSICAL ENVIRONMENTAL CONDITIONS

Crop production is affected by soil compositions and by the presence of other living organisms, as well as by climate. This survey is concerned only with climatic influences. The physical characteristics of soils are however taken into account, in so far as they control the amount of water the soil can store for later use. The amount of available plant nutrients they contain -- which of course largely determines the extent to which climate potentials can be realized—is not discussed, though it is mentioned in the pedologists' contribution to the technical report.

10. MULTIDISCIPLINE APPROACH

The problems are approached simultaneously from the climatic and agronomic points of view. Subdivisions of the area suggested by these two disciplines have many similarities, without ever being completely the same. Where the differences are pronounced it means that either soils or man and animals have intervened. An example of this intervention will be found later when millet is discussed.

11. REPORTS OF THE SURVEY

Two reports have been prepared, both with the same general outline: a technical report, containing the individual contributions of the co-workers, a contribution by a team of pedologists from ORSTOM on the soils of the Area, and another by a botanist-ecologist on the vegetation in Senegal -- and the general report: a shorter, integrated version of the technical report, written by one of the co-workers.

12. PLAN OF THE REPORTS

The reports are in four parts: In the first a brief account of the aims and methods of the survey is followed by general considerations of the characteristics of the Area. The second part is an analysis of the climatic factors involved: their physiological and agronomical import and their occurrence and seasonal variation in the Area. In the third part,

the needs and tolerances of the main crops of the Area are discussed in terms of the agro-climatic factors defined in the analysis. The crops selected are millet, sorghum, groundnut, cotton, maize, and cowpea. In each case the occurrence and distribution of specific climatic needs are re-examined.

Finally, the fourth part contains conclusions, and recommendations, where recommendations seemed called for.

GENERAL CHARACTERISTICS OF THE SURVEY AREA

1. BOUNDARIES

The actual limits of the Area* investigated cannot be drawn with precision. From the point of view of the climatic analysis this Area exists primarily as a collection of points from which information is available and which serve as a basis to define zones** and gradients by interpolation. From the point of view of the agronomic analysis, certain stations, regions and subregions -- all too few -- provided yield and production data comparable with meteorological data.

Figure 1 shows the basic map used in this study. On it, the dots representing the 35 meteorological observing stations which provided the data for the main climatic analysis are surrounded by a dotted line. Squares represent agricultural research stations.

A semiarid zone, which forms the main object of this study, has been sketched out on the map. (The climatic characteristics and corresponding agricultural and cultivation potentials of such a zone are given later in the text.) It will be seen that some of the main climatic reference stations are outside it. Agadès and Gao, which are clearly outside, have been included to represent desert and subdesert conditions for the sake of comparison. Tahoua and N'Guigmi are borderline cases on the subarid side, whilst Fort Archambault, Moundou and possibly Kaduna are in a similar position on the semihumid side.

The semiarid zone sketched out is a strip of land about 4,000 km long, extending from the Atlantic Ocean to the frontier between the Republic of Chad and the Sudan. Its width varies between 300 and 800 km. Parts of eight countries constitute this zone, none being entirely inside it, although Upper Volta very nearly is. The countries are, from west to east: Senegal, Mali, Upper Volta, Ghana, Niger, Nigeria, Cameroon and Chad. Thus slices of the extreme north of Togo and Dahomey are probably also in the zone, although no basic data from these territories were included in the analysis. This applies also to the southern portion of Mauritania.

Very approximately, the semiarid zone extends over two million square kilometres, and its population exceeds 30 million.

* When in the text reference is made to the Area (Capital "A"), the semiarid area, or the area of investigation, it is primarily the semiarid zone of cultivation systems (which corresponds to the briefing of the study group) which is meant -- although, to define the Area itself better, adjacent climates and cultivations are sometimes taken into consideration.

** In this report the words "zone", "zonally", and "zonal" are used to imply not simply a surface of land some of whose characteristics are uniform, but, specifically, an elongated strip lying parallel with the Equator.

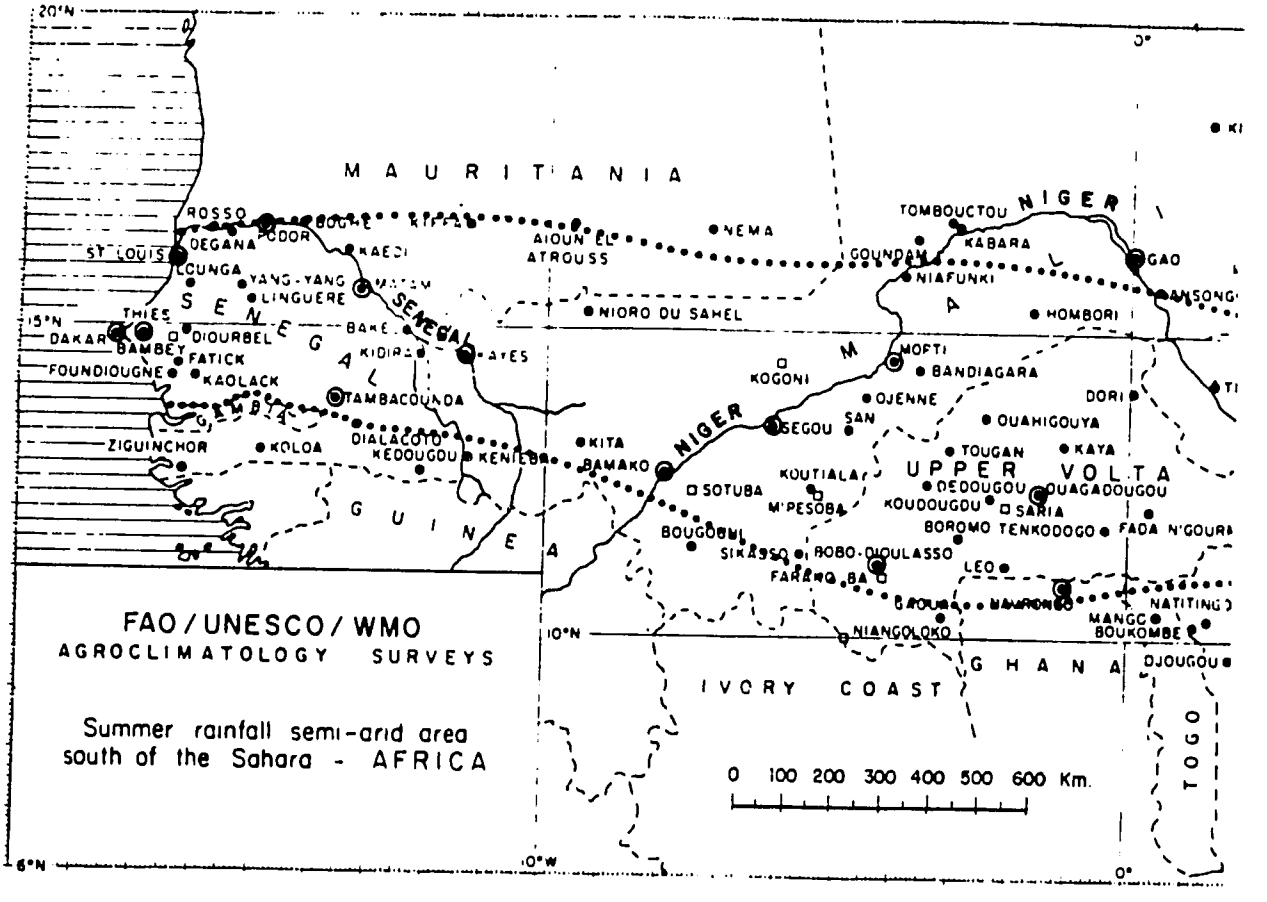


Figure 1 -- The dotted lines show the approximate boundaries of the semiarid zone, which is the area primarily investigated. Meteorological synoptic stations (black dots) and agricultural research stations (squares) are shown together with

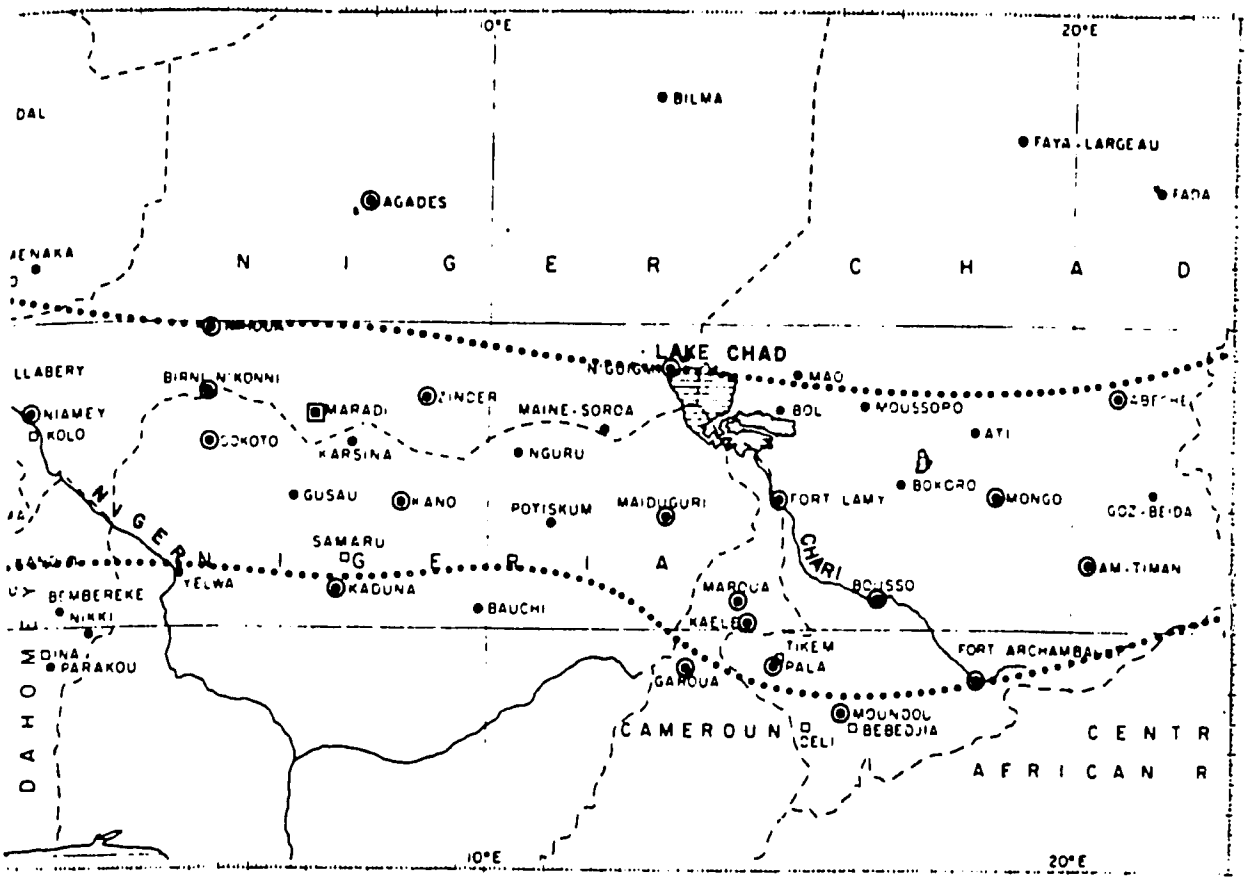
2. HYDROGRAPHY AND RELIEF

The hydrography of the Area is dominated by three great river basins. From west to east they are the basins of the Senegal, of the Niger and of the rivers which feed Lake Chad.

The River Senegal springs from the mountains of Guinea, being formed by the confluence of three great rivers running northwards. It then slows down, running from east to west and ending in a delta stretching from Podor to the sea.

The Niger dominates a large part of the Area. It also springs from the mountains of Guinea, running north-east at first. In Mali it branches into many channels forming a vast flood plain including large lakes. Then, running on a narrower bed, it describes an immense loop, finally flowing in a south-easterly direction through Nigeria. In the east of the Area the Niger comes to flood in winter and early spring.

Lake Chad is fed from the south by two great rivers, the Logone and the Chari, flooding from September to January. It spreads over 25,000 km^2 with a depth of 3 to 5 metres.



political boundaries. The 35 stations which provided sufficient information for the main climatic analysis are surrounded by a line. The position of the most important rivers and of Lake Chad is also shown.

The water level shows an annual variation of about 85 cm with a maximum in January and a minimum in July. (See Figure 1.)

Relief is slight, both with respect to height and extent, and may be separated into four types: First, sand dunes which rarely exceed 20 m and are mostly found north of the 500 mm mean annual isohyet and away from alluvial plains. Second, banks emerging from the flood plains. Third, a system of low plateaux, extensive and poorly drained, found mostly in the central zones. Lastly, dispersed remnants of old mountain chains, a few hundred metres in height, and mostly on the northern boundaries of the Area. To the south of the Area, more important high ground is found, mainly in Chad, Cameroon and Nigeria.

METEOROLOGY AND CLIMATE

Climate is accumulated weather, and the study of both is included in meteorology. An understanding of the main mechanisms which control the weather of the Area will add to an appreciation of the essential nature and seasonal unfolding of its climate. These mechanisms will be briefly described here, beginning with a simplified account of the features of the general circulation of the atmosphere which are directly involved.

3.1 General circulation

Probably the most permanent and static features in the general circulation affecting our Area, and, for that matter, the whole globe, are the tropical anticyclones which form two belts encircling the earth on either side of the Equator (Figure 2).

In these anticyclones, air is settling down slowly -- subsiding -- and it arrives at the surface hot and dry. There the atmospheric pressure is relatively high, and the air tends to move outwards, part of it northwards and part towards the Equator, to compensate this excess pressure.

It should be mentioned that the anticyclonic belts are not continuous, but broken up into individual anticyclones, which have preferred positions: there is a large, intense one usually centred over the Azores and there are others in North Africa, as shown in Figures 3 (a) and (b).

The direction in which anticyclones rotate is determined by a general law: all fluids in motion along the surface of the earth tend to be deflected by the earth's rotation -- to the right of the direction of motion in the northern hemisphere, and to the left in the southern hemisphere. Consequently, the wind circulation round the anticyclones of the northern hemisphere is clockwise, while in the southern hemisphere it is anticlockwise. The winds on the Equator side of both anticyclonic belts will therefore blow from east to west. They are commonly called the "trade winds".

The trade winds, issuing from the high-pressure zones of the two hemispheres, tend to converge towards each other. The intertropical zone (ITCZ) where this convergence takes place receives much heat from the sun; so that the air, as it converges and grows warmer, begins to rise. As it rises over the ITCZ, decreasing pressure causes it to expand and grow cooler, its moisture condenses, clouds are formed, and rain begins to fall. Freed of its moisture, and heated by the release of its latent heat of condensation, this current of rising air is eventually deflected polewards. Part of it feeds the descending air masses over the anticyclonic belts, which are relatively dry and hot. Thus we have complete circulation cells in the vertical plane, resulting in zones of different weather at the surface: the warm and moist ITCZ and the hot and dry anticyclones (Figure 2).

The ITCZ and the tropical anticyclones move north and south with the seasons. The displacement of the ITCZ over the Area tends to follow the zenithal position of the sun with a time lag of four to six weeks.

3.2 The seasons

In the summer, the relatively low pressure of the ITCZ is sufficiently far north of the Equator to develop anticlockwise circulations. The oceanic trade winds of the southern hemisphere cross the Equator, moving towards this low pressure. They are laden with readily precipitated moisture evaporated from the ocean and are commonly called monsoons.

The monsoon is opposed by the dry north-easterly trade winds issuing from the anticyclones over the north of Africa, generally called the harmattan. The meeting line of these two winds is the intertropical discontinuity (ITD), or front (ITF). The ITCZ, where these opposing winds meet, is also sometimes called the intertropical discontinuity (ITD) and the intertropical front (ITF), according to the form it takes. A typical summer meteorological surface chart is shown in Figure 3 (a).

In the winter, the harmattan dominates the whole of the Area. A typical winter situation is shown in Figure 3 (b).

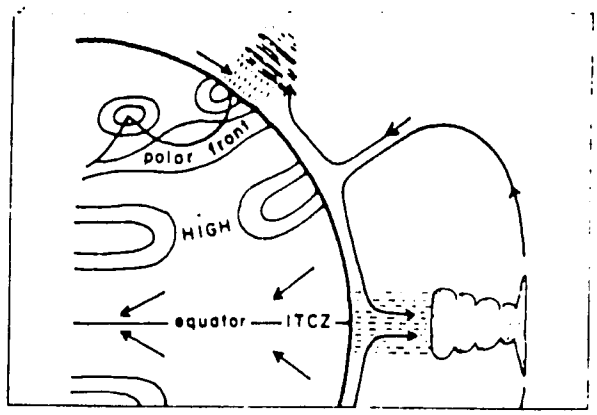


Figure 2 -- The general circulation, showing a cross-section of the atmosphere to the right and the surface of the earth to the left. Descending arrows, surface isobars and "HIGH" mark the position of the northern belt of anticyclones. Ascent of air and resultant weather are shown over the ITCZ. Arrows converging towards the Equator represent the trade winds.

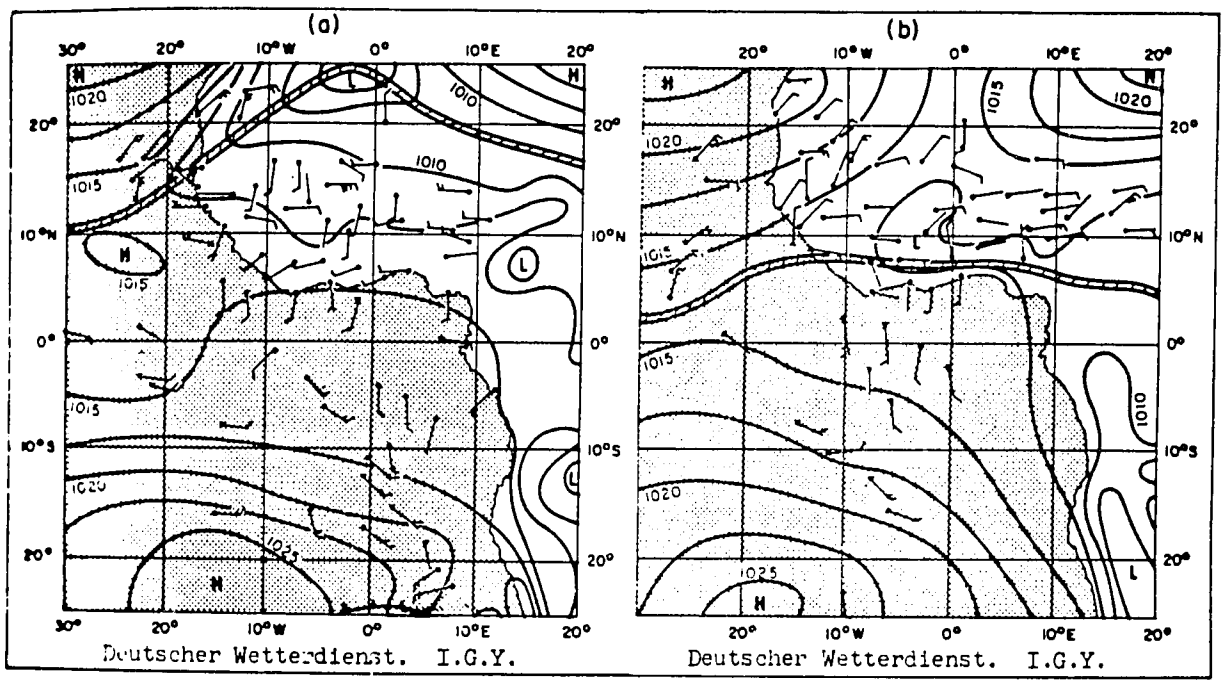


Figure 3 -- Surface charts for 1200 GMT. (a) 11 August 1958; and (b) 11 December 1957. H, anticyclone; and L, low pressure. The double line shows the position of the ITF (intertropical front). Lines of equal pressure in millibars are shown. Arrows indicate wind direction and the number of barbs, wind strength. (a) shows the monsoon crossing the Equator and (b) the harmattan blowing across the Area.

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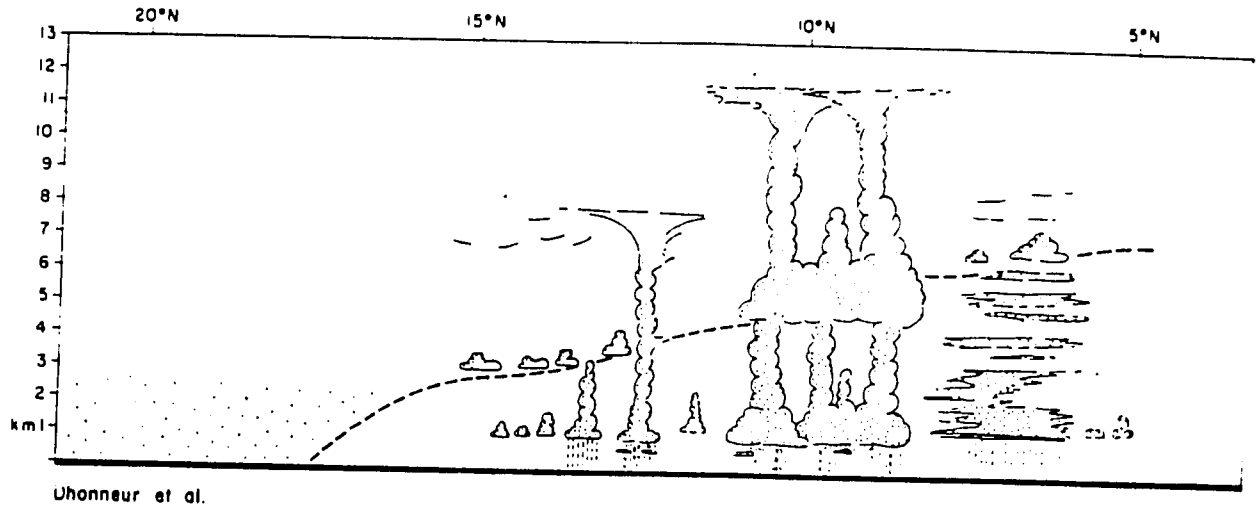

Figure 4 -- Diagrammatic vertical cross-section through Area from north to south in early summer. From left to right: dry, hazy harmattan; surface boundary between harmattan and monsoon, or ITF which, shown as a dotted line, slopes upwards and southwards; small cumulus; scattered showers; disturbance line shown head-on; more continuous cloud layers with lighter rain.

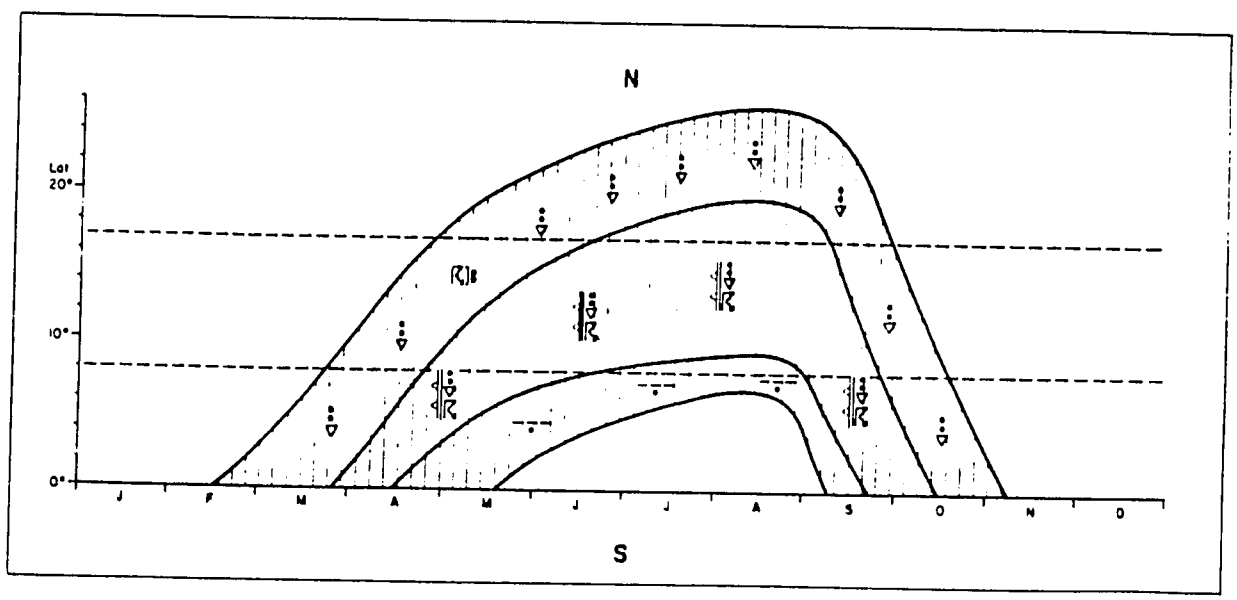

Figure 5 -- Diagram showing the north-south movement of the monsoon weather zones during the twelve months of the year. The semiarid area lies between the two dotted lines. An arbitrary distinction is made between zones of scattered showers ( ) and thunderstorms ( ), of disturbance lines ( ), and of more continuous rain with overcast (-·-). The time lag relative to the zenithal position of the sun causes maximum northward displacement to occur in August.

It is important to realize that rain does not generally fall on an area until the ITD has moved north of it sufficiently for an established pattern of convection to occur (see Figure 4). As shown in Figure 5, the whole of the Area receives rainfall during the summer, but during the rest of the year it is dry.

3.3 Nature of the summer rainfall

Three zones which are shown in Figure 4 and Figure 5 may be distinguished in the monsoon precipitation area, going from north to south. A zone of scattered showers, a zone of disturbance lines (which is by far the most important) and a zone where the cloud cover is more extensive and the rain more steady. The boundaries between these zones are neither sharp nor always to be found.

Disturbance lines are responsible for the larger part of the rain received by the Area. Their origin is not yet properly understood but seems to be associated with high ground. Variations in the moisture and strength of the monsoon current may play a part in their formation.

Structurally, they are composed of bands of active cumulonimbus clouds, aligned from north to south, and often more than 200 km in length, moving from east to west at the speed of the middle layers of the harmattan; that is, about 25 knots.

They are self-regenerating and can last for several days, bringing rain to hundreds of thousands of square kilometres. The high-intensity downpour, which lasts for a few hours, is preceded by a sharp transition from the usual south-westerly monsoon wind to easterly gusts of air cooled by evaporation of the rain.

This heavy rain may be followed by several hours of less intense precipitation when an extensive layer of medium clouds juts back from the main body of the storm clouds (Figure 6). In the section on rainfall intensity in Part II, The Analysis, a recording of the rainfall from a disturbance line, Figure 29, shows the main showers followed by much less intense rain.

3.4 Other sources of rain

In the most southerly rainfall zone, air is sometimes lifted over relatively larger areas, causing more continuous precipitation of lesser intensity. This type of precipitation is commonly found in the south of the survey area only, although it is understood that, at times, air will rise simultaneously over wide areas further north giving rise to widespread and intensive precipitation.

Besides these there are other phenomena of rarer occurrence which bring rain to the Area in summer, and in winter as well. On the Atlantic coast the northerly winds associated with the vast and quasi-permanent Azores anticyclone sometimes bring in winter, at a similar height, relatively cold air which may give rise to instability at those heights, with extensive cloud, and sometimes rain, this weather being known as "Heug".

Areas of bad weather may also arise in the west-moving stream of the trade winds in the northern hemisphere when the ITCZ is sufficiently far south to make this stream broad. These disturbances moving west across the Atlantic sometimes give rise to hurricanes affecting the eastern seaboard of the American continent.

The rain belt of the monsoon may sometimes completely cross the south of the Area, [illegible] drier weather in the middle of the summer rains. This is known as "the little dry [illegible]", and its occurrence is in fact one of the criteria which delimit the southern boundary of the Area.

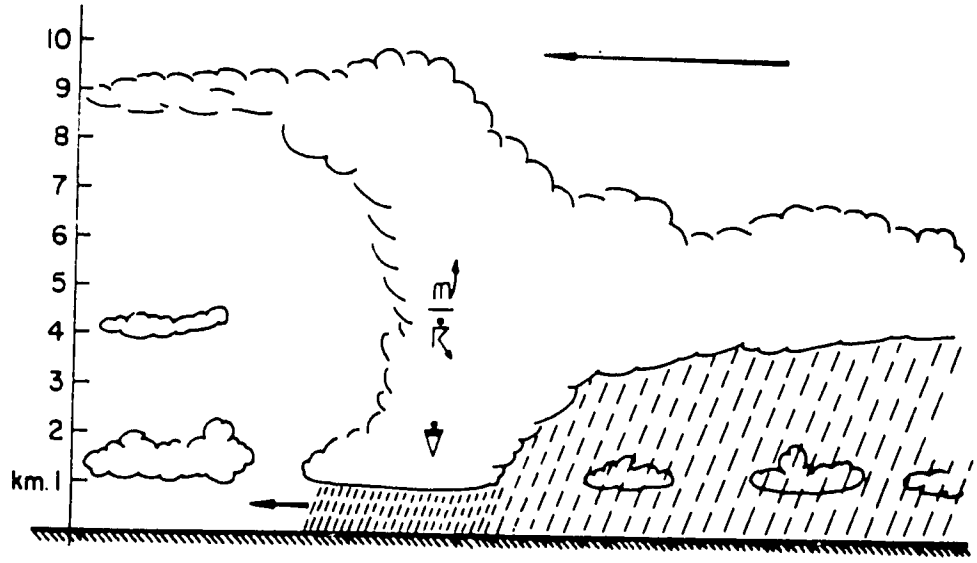

Figure 6 -- Diagrammatic vertical cross-section through a disturbance line along its direction of displacement. The shorter arrow near the surface, ahead of the rain, indicates where gusts of cool easterly winds are felt. These are followed by heavy rain and, later, by lighter rain falling from a sheet of medium cloud trailing behind. Meteorological symbols indicate occurrence of heavy rain, thunder, lightning and turbulence. (After Tschirhart.)

It will be plain that the rains of the Area are mainly due to one general circulation feature, namely, the summer northward movement of the intertropical convergence zone, and that the ultimate mechanism bringing down this rain is largely the disturbance line. As a result of this, and of the lack of geographical diversity, the rainfall régime is of pronounced regularity at the broad scale at which it is being discussed here, especially in a central zone which will be defined later.

3.5 Other agroclimatological factors

This sketch of the meteorology of the Area also throws some light on the distribution and seasonal variation of other factors of importance to agriculture besides rainfall.

3.5.1 Winds

The wind régime reflects the seasonal alternation of dry north-easterlies and more humid south-westerlies. This is well shown by Figure 7, two charts of vector mean winds at 500 m with their constancy. (Wind constancy is defined as the rate of the vector mean speed to the mean speed of the wind, irrespective of direction.) At the beginning of the rains, the change is not irreversible, and temporary returns to harmattan conditions may seriously affect young crops.

North of the ITF the most common positions of the anticyclonic cells cause differences in mean wind strength, direction and humidity which are not distributed zonally. These significantly affect crop production.

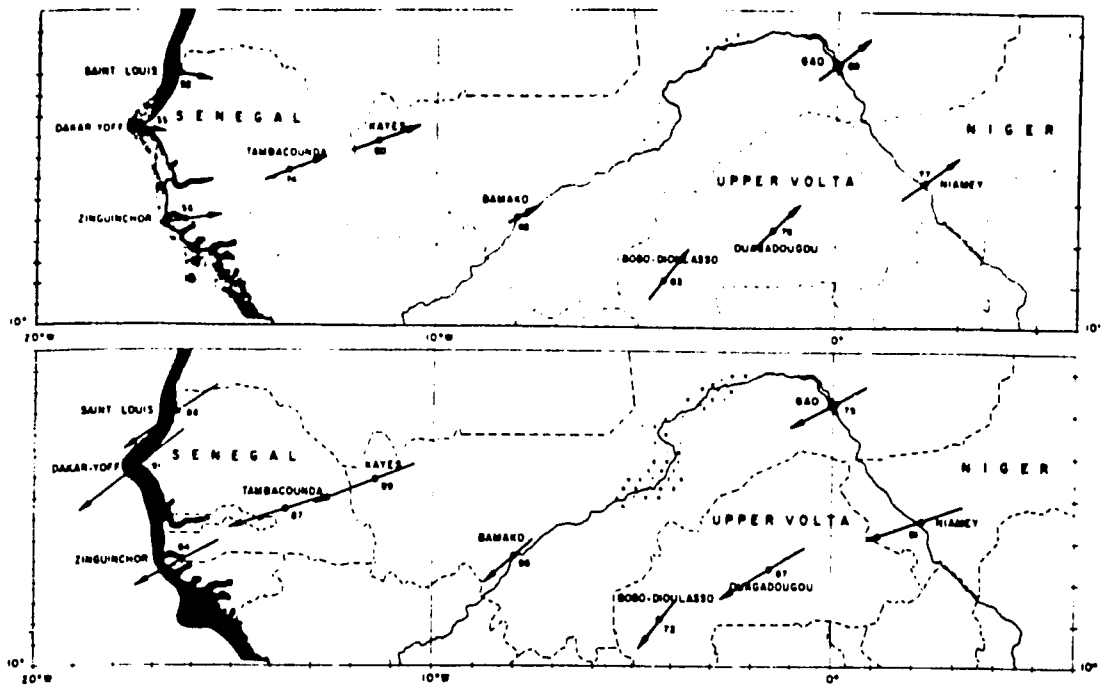

Figure 7 -- Monthly mean vector winds expressed as 10-hour displacement vectors, together with constancy. The lengths of the arrows minus the head represent the displacements. The upper map shows the situation in August and the lower shows the same area in January, illustrating the change from monsoon to harmattan.

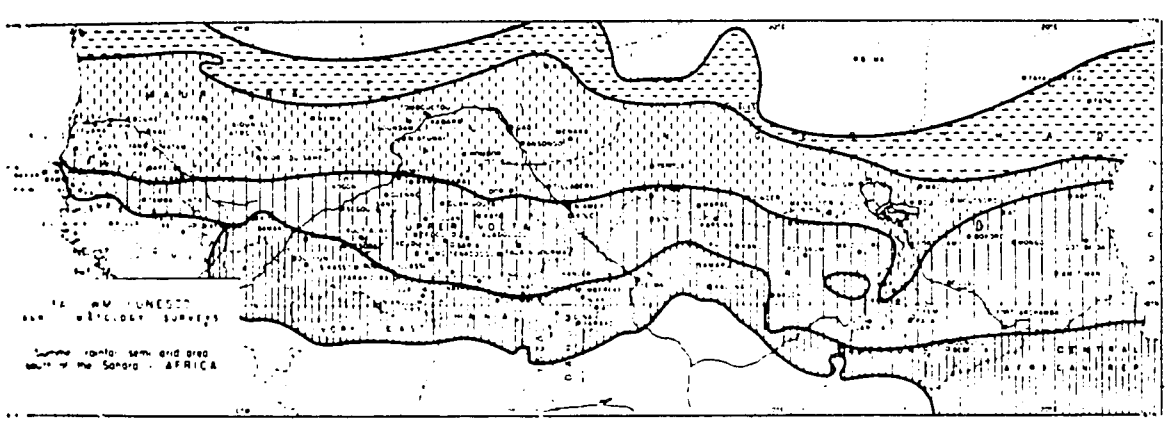

Figure 8 -- Vegetation of the Area as described in the Vegetation Map of Africa. From north to south: The dotted area is desert virtually devoid of vegetation. The horizontal dashes represent subdesert steppes with some Acacia and Commiphora. Vertical dashes represent wooded steppe with abundant Acacia and Commiphora. Vertical lines represent relatively dry woodlands and savannas, and closer vertical lines more humid woodlands and savannas with abundant Isoberlinia.

3.5.2 Temperatures and humidities

Like rainfall, these important factors are discussed in detail in Part II (The Analysis). In the Area, over which the initial radiation input is fairly constant, the temperatures of the atmosphere near the surface are largely controlled by the position of the ITF and attendant weather phenomena.

Temperatures are in the first place representative of the air masses advected; they are lower in monsoon air and high in the harmattan. This difference is increased by the cloudiness of the monsoon cutting out sunshine, and by the rainwater on the ground evaporating and absorbing latent heat.

Similarly, monsoon air is initially more humid and, at the surface, this humidity is increased by evaporation.

3.6 Conclusions

3.6.1 Zonation of Area

Because of the zonal alignment of the ITF during its annual northward movement and retreat, which controls the time during which the monsoon acts, the gradients of the main climatic parameters, such as the amount and duration of the rains, the nebulosity and the humidity and temperature of the air, are aligned from north to south. These meridional gradients are smooth. The transition along them does not proceed in steps.

Generally, there are no geographical features of coast or relief to disturb these gradients. Exceptions are the coast of Senegal, where the general meridional alignment is nevertheless preserved, and the main rivers, which introduce confined discontinuities.

Where it is convenient to break up the Area into subdivisions according to some climatic parameter, these subdivisions will have the shape of long strips, arranged zonally across the gradients. It is well to bear in mind that these zones represent surfaces covered by a given segment of climatic gradients -- not by uniform conditions.

3.6.2 Climate and its classification

The amount of solar energy incident outside the atmosphere over the Area is high throughout the year, though showing some winter reduction in the north. Together with the atmospheric circulation features already described, this results in a consistently warm climate, dry in winter, and with summer rains.

This is a clearly recognizable type which can be described as tropical, semiarid, with summer rains. It is defined in the various systems of classification evolved by geographers. According to Köppen, it is a transition from BShw to Aw -- hot steppe with dry winter to tropical savanna with dry winter. According to Thornthwaite, it is a transition from DA^1 to C_1A^1 -- semiarid megathermal to dry subhumid megathermal -- these expressions being defined quantitatively in terms of rainfall and potential evapotranspiration. Or, using Landsberg's dynamic scheme, which subordinates geography to meteorology, it ranges from (AE)S to (AE) Tc, both climates of which the major circulation patterns are a combination of quasi-stationary anticyclones and the Equatorial convergence, and the secondary features are respectively: typical monsoon, and predominating trade winds with continental influence.

Auberville has used the expressions "saharian", "sahelian", soudanian", and "guinean" to describe climatic zones as reflected in the vegetation south of the Sahara. A further subdivision is brought in by the use of compound expressions like "sahelio-saharian".

Mean annual rainfall provides the nearest approximation to a definition of these descriptive terms, which are in current use in the French-speaking parts of the Area. The "sahelio-saharian" zone may be taken as falling between 200 and 500 mm and the "sahelio-soudanian" between 500 and 900 mm, whilst the "soudano-guinean" goes from 900 to 1200 mm.

The utility and drawbacks of systems of classification in studies such as this are discussed at the end of this report.

4. VEGETATION

The general distribution of the vegetation of the Area in its present state is zonal, in unison with the climate, and from north to south, passes from wooded and grass steppe to woods and savanna, relatively dry at first.

In this context, according to the definitions given by the Vegetation Map of Africa (UNESCO, 1958) savannas have perennial grasses, at least 80 cm high and with some flat leaves, and are usually burnt annually, whilst steppes have mainly annual plants, shorter and less liable to burning.

Figure 8, extracted from the Vegetation Map of Africa, illustrates this generally zonal distribution. Particularly noticeable amongst the departures from it is the southward encroachment of steppe on savanna along the meridian of Lake Chad, which corresponds to a relatively more abrupt and more variable rainfall season.

Men have greatly decreased the number of trees in the Area, especially in cultivated as opposed to pastoral regions.

A sample survey of the vegetation found in the Area was provided by an FAO expert in the field with the help of two cross-sections at right-angles in Senegal, meeting at the Ferlo fossil valley. The position of these two cross-sections is given in Figure 9, a map of Senegal which also shows the position of different vegetation subregions.

A north-to-south section, at about 15 W, from the river Senegal to the frontier of Senegal with Gambia shows (Figure 10 (a)) that once the flood plain has been left, the vegetation is a herbaceous cover, mostly of short-lived annuals with some trees, small and widely spaced. This vegetation is commonly associated with the descriptive name "sahelio-saharian". Southwards there is a gradual transition to taller grasses with a higher proportion of perennials which habitually burn during the dry season, and to a more arboriferous type of savanna associated with the name "soudano-sahelian".

Land use is mainly pastoral. The relatively small cultivated areas carry millet on sandy soils and sorghum on soils with more clay. To these essentially subsistence cultivations may be added cowpea, water melon, red sorrel and groundnut, a cash crop in favoured locations.

A west-to-east cross-section along the 15½° parallel, penetrating about 70 km inland (Figure 10(b)), shows first a rapid transition from the littoral savana to that of the continental dunes. The vegetation of the latter is considerably modified in the west by the cultivation of groundnut, fields of which alternate with fallows. Trees have been eliminated with the exception of the larger Acacia raddiana. The fallows are invaded by post-cultural species.

Further east, beyond the groundnut sector, the number of trees increases as a pastoral area is entered. Prominent amongst them is a small spiny Balanites, often hacked by the shepherds, and sometimes to death, to feed their animals during the dry season.

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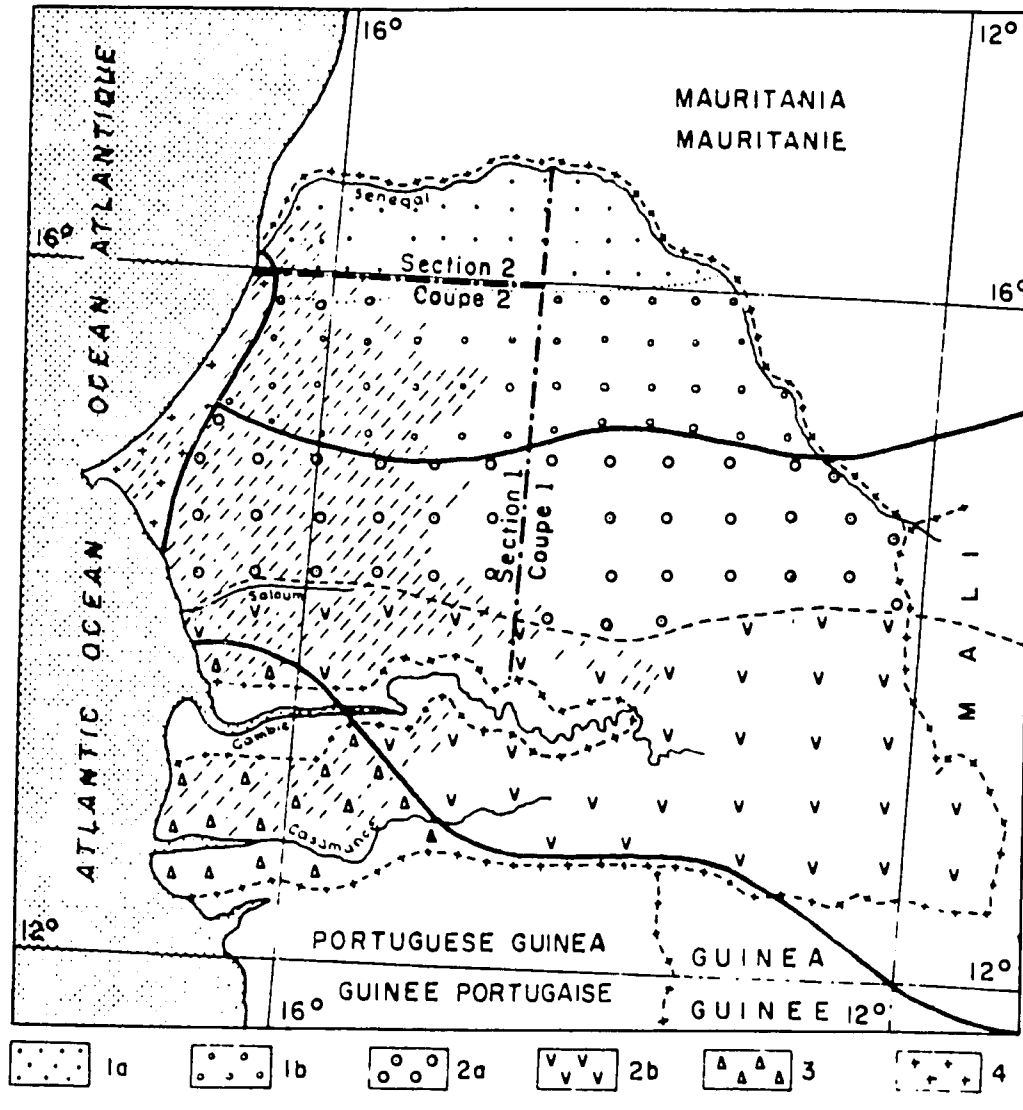

Figure 9 -- Vegetation regions of Senegal. Diagonal hatching denotes groundnut cultivation area. Apart from a narrow coastal belt, 4, the vegetation is differentiated into zones following fairly closely the mean annual isohyets: 1(a), steppe, and 1(b), 2(a), and 2(b), savanna and woodland of increasing density. The position of the two cross-sections is indicated. 3(a) is outside the semiarid area. (After J. Trochain.)

Near the fossil Valley of the Ferlo, at the end of the section, the land becomes clayey, and is covered, sometimes exclusively, with Acacia seyal, which makes a pure, though well spaced, vegetative cover.

Along both sections seasonal ponds occur, formed by surface drainage into hollows with impermeable soil horizons. These ponds are surrounded by trees and denser undergrowth.

5. SOILS

It should be repeated that, though of course both the physical characteristics and the chemical composition of soils are of importance in enabling agroclimatic potentials to be realized (see Figure 11), a study of their chemical composition does not come within the terms of reference of this agroclimatic survey.

5.1 Origins

The pedologists' contribution to the technical report states that present climate is the most important factor in controlling soil formation; other factors are vegetation, paleoclimates -- mainly the alternately wet and dry tertiary and quaternary climates -- past and present hydrography and relief, and finally the nature of the parent rocks and soil materials.

5.2 Physical characteristics

The capacity of soils to store water depends on their structure and texture; that is, on the size and arrangement of the particles of which they are composed. The soils which predominate in the Area are sandy compared to those found further south.

5.3 Zonation

The soils of the Area are subdivided into two main groups which, very broadly, are zonally separated: the semiarid brown soils and the ferruginous and ferralitic soils. The ferralitic soils barely touch the south of the Area.

The semiarid brown soils are generally found north of the 500 mm mean annual isohyet, where the rain is insufficient to cause appreciable migration. They are relatively homogeneous in texture throughout their shallow depth, thereby allowing uniform infiltration of water and, possibly, deep drainage.

In the ferruginous soils, found between 500 and 1,200 mm, some migration and recomposition of iron and clay have taken place, resulting in the formation at shallow depths of a less pervious horizon, which tends to restrict deep drainage. The nature and degree of importance of this horizon seem to vary with the length and intensity of the dry season and the amount of annual rainfall. Figure 11 is a summarized map of the main soil types.

5.4 Heterogeneous nature of physical characteristics

However, over and above this zonation the texture and structure of soils also [illegible] to a great extent on the materials from which they have developed. For this reason there are, throughout the Area, soils with various proportions of sand, silt and clay and, consequently, various water absorption and retention capacities. The physical characteristics of the soils of the Area which affect the availability of water to crops are therefore heterogeneously distributed within the various climate zones, but soils with sandy texture are the most common.

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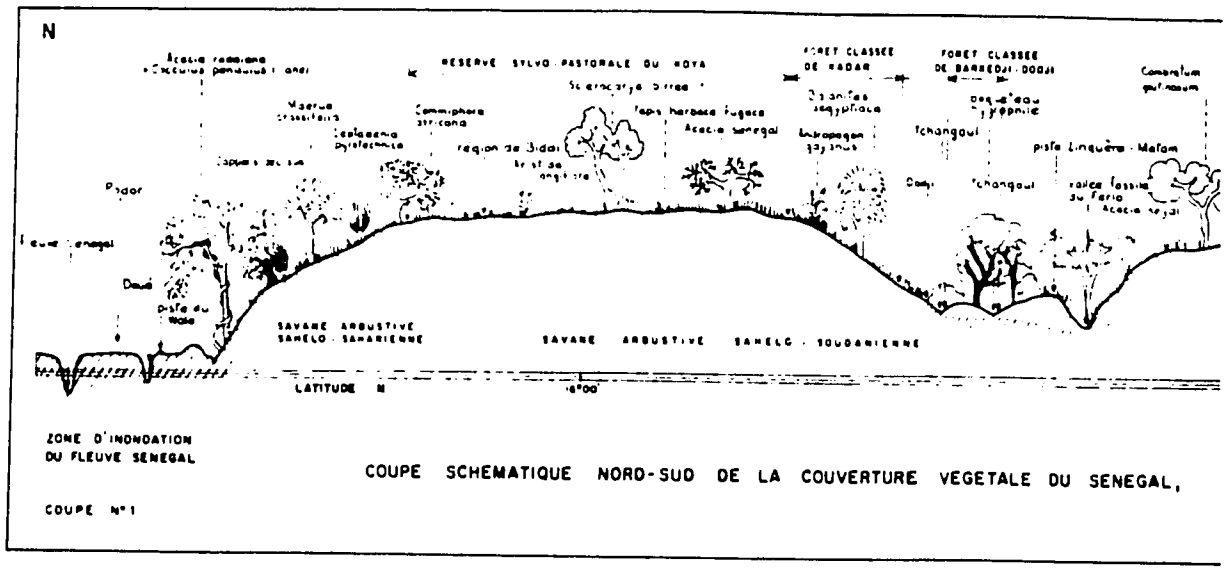


Figure 10(a) -- Diagrammatic cross-section of the vegetation in Senegal from Podor on the flood plain of the river Senegal in the north to the frontier, with Gambia in the south. The herbaceous cover increases gradually in

5.5 Water absorption

A comparison of the rates at which rainwater falls and water is absorbed by the top layer of the soil determines the extent of water storage in the soil and surface runoff.

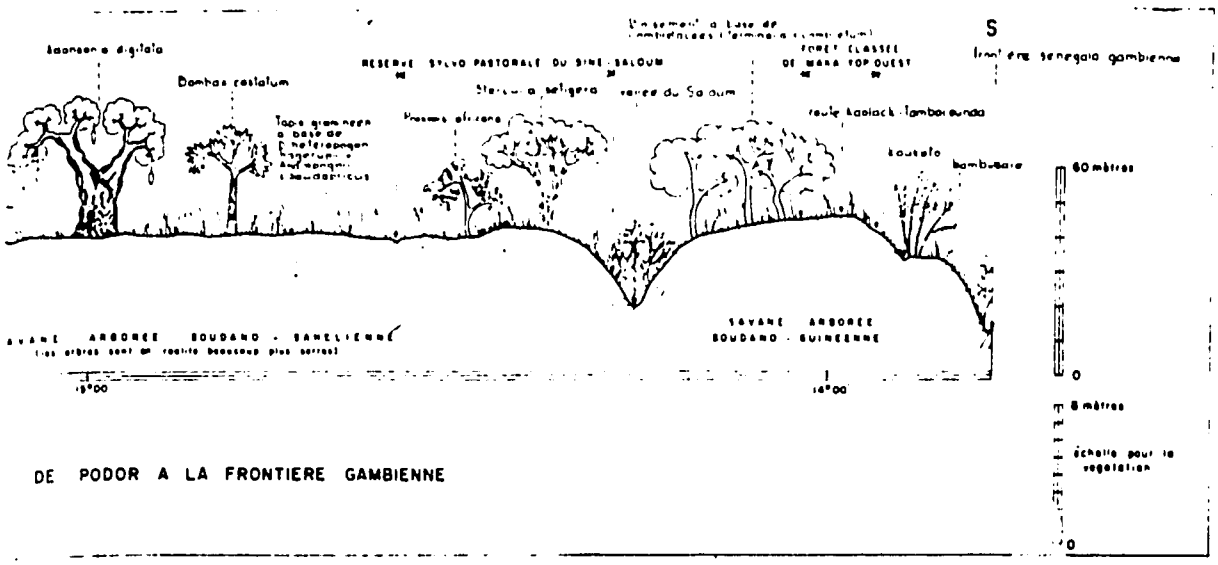
Of the five rates of water absorption by the top-layer soil samples given in the report of the pedologists, four vary between 8 and 16 $mm.h^{-1}$.

Rainfall intensities are discussed in detail in Part II. An average figure for the Area is 4 $mm.h^{-1}$.

In the case of a vertisol, which is a clayey soil with deep cracks when dry (soils of this type are unevenly distributed all over the soil mosaic of the Area), an initial permeability of 40 $mm.h^{-1}$ is quoted, typical of the reaction of such soils to the first rains, when they are cracked and dry. This permeability soon drops to 2 $mm.h^{-1}$ when the soil has swollen and the cracks have closed.

5.6 Storage

The amount of water stored in the ground and subsequently available to crops is generally taken to be the difference between field capacity and wilting point.(Field capacity is the amount held against gravity after excess has drained away, and wilting point is reached when plants can no longer draw moisture from the soil.) Both these values and the resultant storage vary considerably. In this analysis, an average amount equivalent to a depth of 100 mm has been chosen when assessing water budgets.



height and perennial species predominate in the south as opposed to annuals in the north. Different scales are used for ground and vegetation heights. The change in the spacing of the trees, which are much closer in the south, is not represented.

6. AGRICULTURE AND CULTIVATION

The principal characteristics of the agriculture of the area surveyed are that it is very extensive (extensive, as opposed to intensive cultivation implies the temporary exploitation of large areas at a low technical level), that soil fertility is restored by fallows, that cultivation and animal husbandry are separate, and that little or no use is made of intensification techniques such as fertilizers, plant protection, plant introduction, or mechanization.

These characteristics, largely imposed by the climate, become more pronounced and unavoidable the further north one goes. The importance of animal husbandry also increases northwards, until a zone is reached, peopled by nomads, where it is virtually the only agricultural activity.

6.1 Cultivation systems

Within this single agricultural system, different cultivation systems can be recognized, also dictated by the climate and also zonally located. Their boundaries are diffuse and tend to fluctuate with the weather and no sharp and continuous line of demarcation should be sought between them. Also, these systems have been defined in terms of climate only, and it must be realized that soils and people may intervene.

South of the desert or arid zone, where no crops can be grown without irrigation, is found a zone, which here will be called subarid, characterized by mono-cultivation of millet. Its boundary with the desert is particularly irregular, as privileged drainage

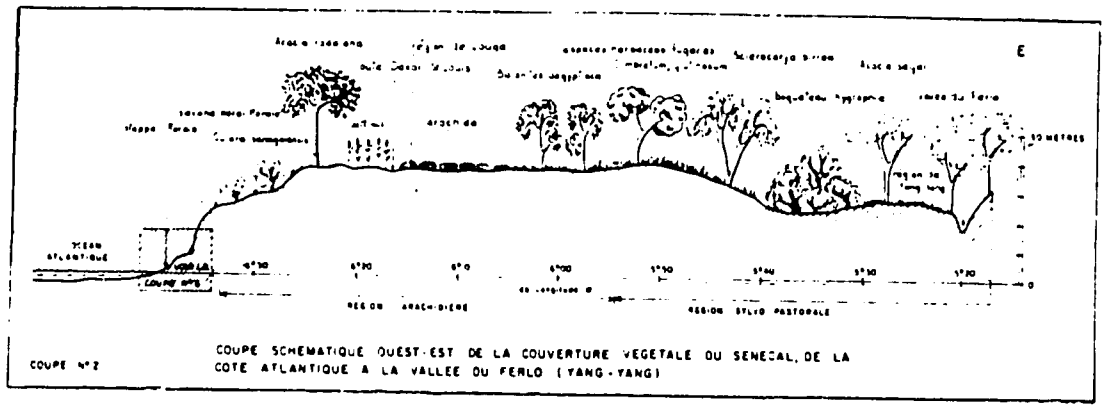


Figure 10(b)-- Diagrammatic west-to-east cross-section of the vegetation in Senegal starting from the Atlantic coast. It crosses relatively dry woodlands and savannas, cleared for groundnut cultivation in the west. The scale of the vegetation, though not indicated, is larger than that of the height of the ground above mean sea-level. The short grass cover is mainly annual.

basins with good soils form enclaves in the arid zone, penetrating far to the north. Next to the subarid zone is a wider zone, here called semiarid, which is the primary object of this study. Its subsistence crops are primarily graminae and leguminous grains, its main cash crops are cotton and groundnut, and the duration of the growing season precludes consecutive cultivation of main crops. In the increasingly humid zones to the south, consecutive cultivation of main crops within a single year becomes more and more widespread. Eventually, roots, subsistence crops and typical humid-zone cash crops like cocoa characterize zones outside the survey area. The zonation of possible cultivations in the Area is shown in Table 1; this table also shows characteristic values of rainfall, effective rainfall and of the Thornthwaite-Penman index of aridity (discussed in Part II, under the heading Availability of Water, section 2.3).

7. CONCLUSIONS

The influence of present-day climate with its meridional gradients appears to be paramount in the Area and is reflected in its soils, in its vegetation and, consequently, in its agriculture and cultivation systems.

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TABLE 1

ZONATION OF POSSIBLE CULTIVATIONS IN TERMS OF CLIMATE

	CULTIVATIONS		Mean annual rainfall (mm)	Effective rainfall (mm)	Index of aridity
	Main	Secondary			
	SUBARID ZONE - Millet S		250	200	-50
SEMIARID ZONE	REGION A		350	250	-45
	Millet S Cowpea	Cowpea			
	REGION B		550	475	-40
	Millet M Sorghum S - M Groundnut S - M	Millet S Sorghum S Cowpea			
	REGION C		800	600	-30
	Millet M - L Sorghum M - L Cotton	Millet Sorghum Cowpea Maize S			
	REGION D		1 000	750	-10
	Sorghum L Maize L Millet L Groundnut L Cotton	Millet S Sorghum S Cowpea Maize S Tubers			0
	(SUBHUMID ZONE)				

NOTE : North is at the top. S, M and L refer to short, medium and long growing cycles. The terms "effective rainfall" and "index of aridity" are defined in Part II.

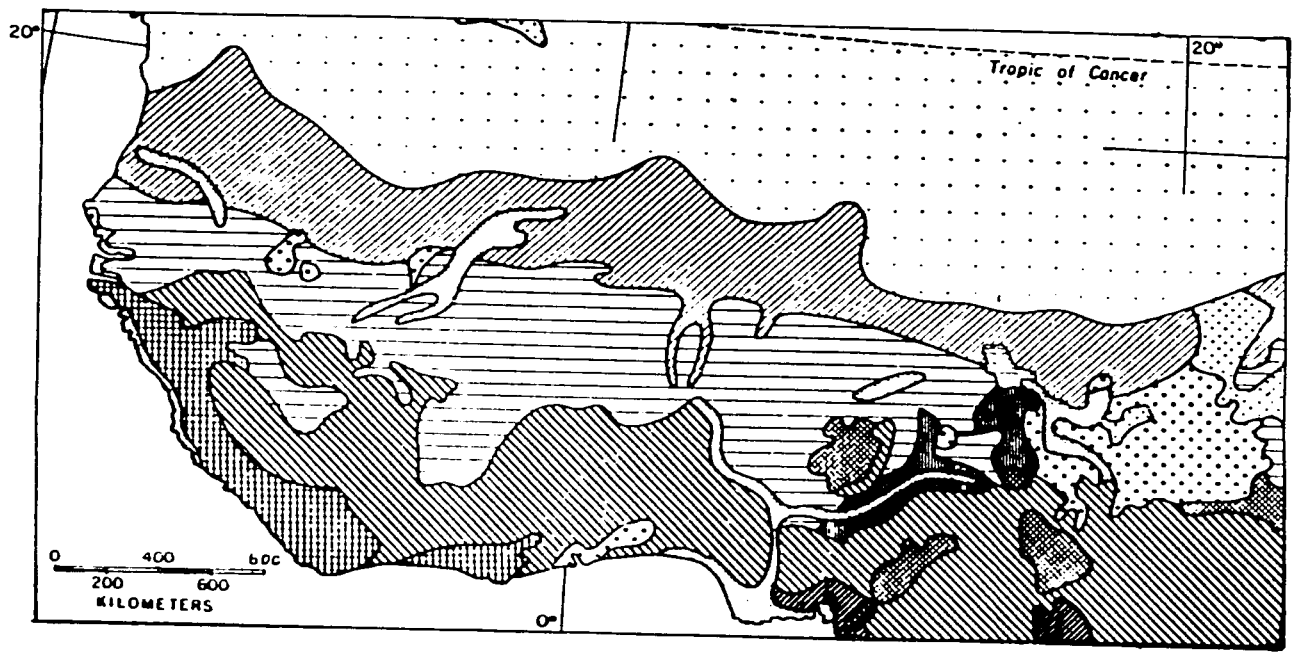

Figure 11 - Main soils of the Area, summarized from The Soil Map of Africa South of the Sahara, published by the Inter-African Pedological Service of the Commission for Technical Cooperation in Africa South of the Sahara

- Desert soils
- Alluvial soils
- Reddish-brown lateritic soils
- Brown soils and lithosols
- Red-yellow latosols

PART II

THE ANALYSIS

Part II, which discusses the nature and occurrence of the climatic factors which are thought to be of importance, is subdivided into three main chapters dealing successively with rainfall characteristics, the availability of water, and the supply of heat and light.

RAINFALL

1. ANNUAL RAINFALL

In the Area, owing to the fact that other climatic factors do not vary much, annual rainfall is probably the most important simple climatic index of productivity: it is certainly the one most commonly used by agriculturists.

1.1 Distribution

Mean annual isohyets (lines of equal rainfall) display the zonal alignment and the meridional gradients discussed in the first part of this report. They are shown on Figure 12 with an amount of detail commensurate with the scale of the chart.

Two departures from the zonal pattern are discernible. First, on the coast of Senegal, the rainfall gradient, 300 mm per 100 km approximately, is about twice as steep as 1,500 km further inland, to the east. This steeper gradient in Senegal offers increased possibilities for diversification of cultivation. On the other hand, it seems to be associated with higher variability of rainfall.

A spreading of the isohyets, rapid at first, with a maximum in eastern Mali, can be seen in Figure 12, and Figure 13 gives cross-sections of the actual mean annual rainfall gradients.

Secondly, the isohyets dip southwards from the Atlantic coast to the longitude of Lake Chad, beyond which the dipping is reversed as far as the Sudan borders. The maximum amplitude of the distortion is about 3° of latitude.

This means that the same amount of mean annual rainfall will be associated with differing latitudes, and therefore differing variation in length of day. The differences, though small (as will be seen later in Table 18) may be significant, especially in association with the delay in the timing of the rains which occurs in the west of the Area. This is discussed again in Part III.

2. ANNUAL RAINFALL VARIABILITY AND PROBABILITY

No consideration of mean annual rainfall can be complete without taking into account the variation from year to year, and attempting to deduce from it the probabilities of obtaining given amounts.

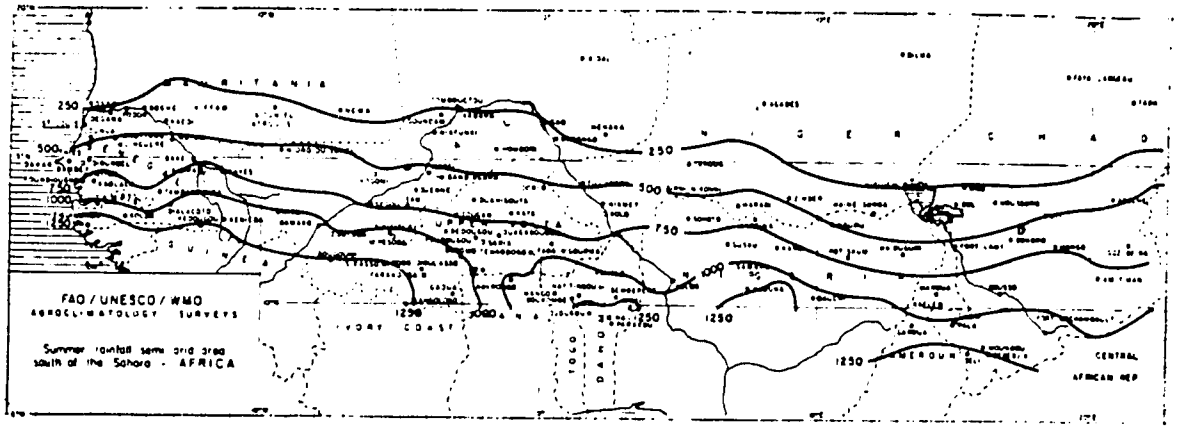

Figure 12 -- Mean annual isohyets of the Area
(After Météorologie Nationale (1958) and national sources)

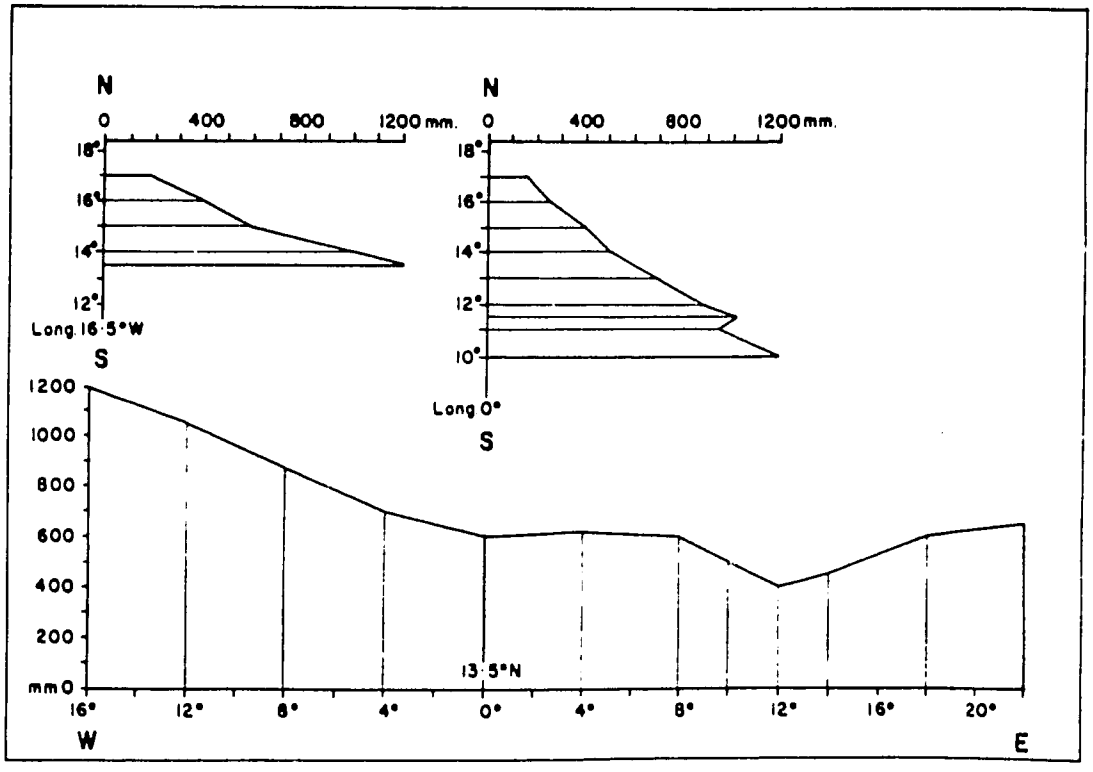

Figure 13 -- Mean annual rainfall gradients. Above, meridional,(left) near the coast of Senegal and (right) about 1,600 km inland. Below, zonal, across the Area.

This problem, which is specially important when change in agricultural production is contemplated, was approached both empirically and theoretically. A thirty-year series, 1931-1960, was analysed.

2.1 Empirical method. Quintiles

It is assumed in this approach that past frequencies of occurrence of annual rainfall amounts can be directly projected on to the future.

The thirty values are arrayed in order of magnitude and separated into five groups of six values each. The values separating the groups, known as "quintiles" and here represented by the highest values of the first four groups taken in increasing order, represent amounts expected to be exceeded 4, 3, 2, and 1 years out of 5 (or likely to be exceeded with a probability of 80, 60, 40 and 20 per cent respectively) (Brooks and Carruthers, 1953; Grisollet, Guilmet and Arléry, 1962). In addition, the 15th value, in so far as it represents the median, will probably be exceeded one year in two or with a probability of 50 per cent.

Quintile and extreme values for places in the Area which broadcast "CLIMAT" reports are published by WMO in their Climatological Normals (CLINO) publication (WMO, CLINO, 1962). The tabular form used in this survey for arraying and quintile determination is shown on the left of Figure 14.

2.2 Theoretical method. Normal distribution

In the theoretical approach, the 30-year sets, each looked upon as a sample of an infinitely large number of values, were fitted to a theoretical function representing their frequency distribution.

The function used was the Gaussian or normal distribution of which the parameters, the standard deviation and the mean, provide a way of estimating the probability of occurrence of any given value.

The fit to the Gaussian distribution of the 30-year sample was simply tested by comparing the values of the median with the mean and checking the position in the array of the values, mean plus and mean minus one standard deviation, which correspond approximately to values expected to be exceeded with a probability of 16 per cent and 84 per cent respectively. In a normal distribution, the interval between these two values would include rainfall amounts to be expected two years out of three; and the interval between the mean plus and the mean minus two standard deviations would include rainfall amounts to be expected 19 years out of 20.

The working of this theoretical approach and its comparison with the array may also be seen on the form illustrated in Figure 14. On the other side of this figure there is an alternative form used for estimating graphically the standard deviation and fit of the sample. In practice, this graphical method was found sufficiently accurate and more rapid than numerical computation.

The fit to the Gaussian distribution was generally good. A modification of the sample sometimes needed was to disregard the highest value, as suggested by Griffiths (1960).

2.3 Annual variability distribution in the Area

The extent of variability is expressed by the size of the departures from the mean, of which standard deviation is a measure. The standard deviation divided by the mean yields

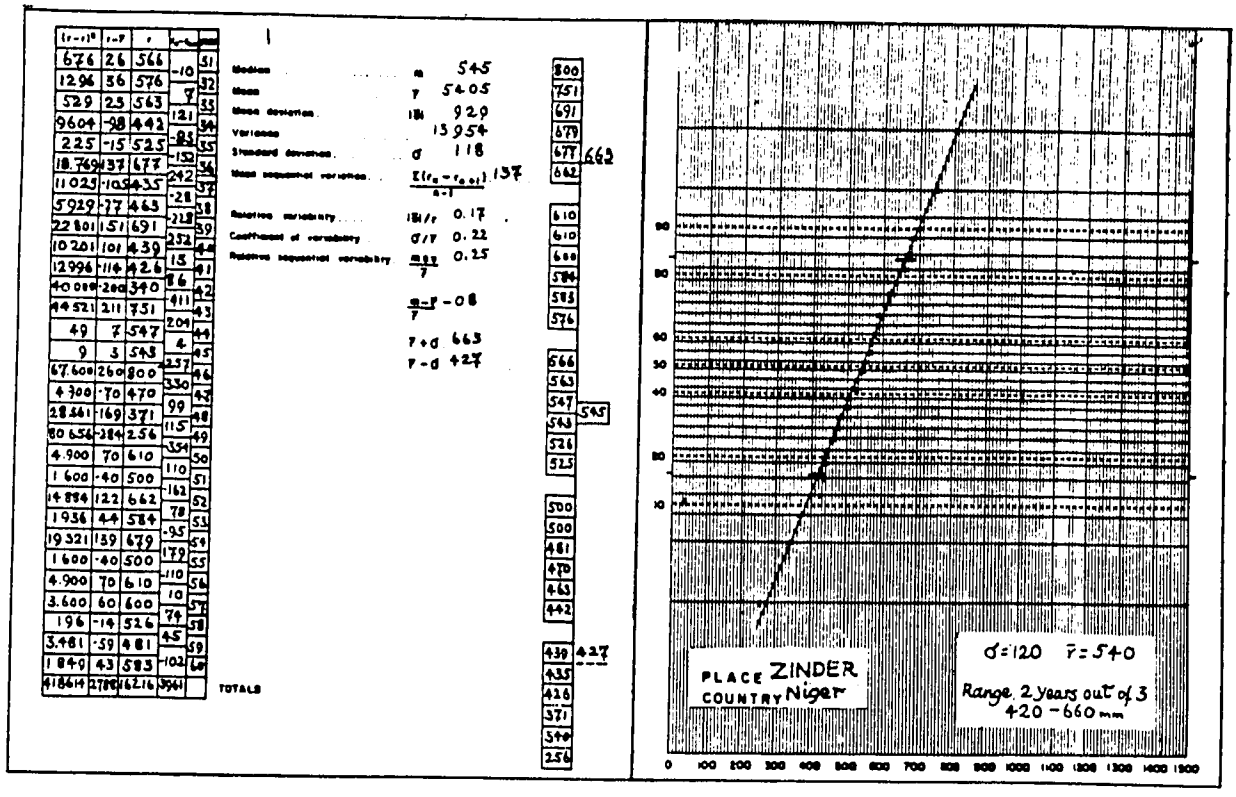

Figure 14 — Left: standard form for arithmetical calculation of variability of 30-year sample and fit to normal distribution. Right: graphical estimation of the same characteristics.

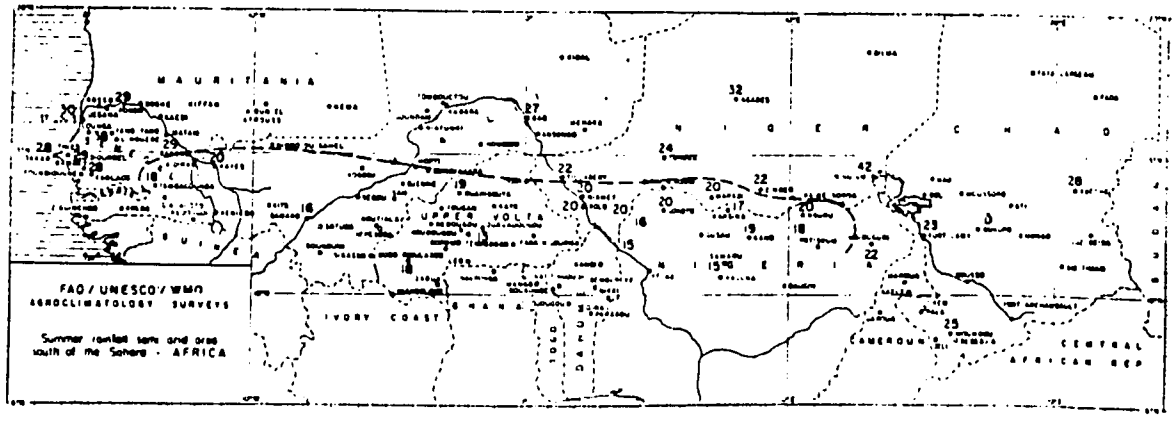

Figure 15 -- Surface distribution of coefficient of variability. The broken line indicates the part of the Area where the coefficient is less than 20.

a coefficient of variability which makes it possible to compare the interannual variability of places with different mean annual rainfalls.

The coefficient of variability was calculated for 36 places in the Area for the period 1931-1960. Its spatial distribution is seen in Figure 15. As is generally the case, variability increases with decreasing rainfall and therefore from south to north in the Area. This increase accelerates beyond the northern limits of the subarid zone.

There are, however, two regions where interannual variability of rainfall is relatively high. The first is in West Senegal, where it might be attributed to additional general circulation features, of which one result, the higher rainfall gradient, has already been quoted. The second is in the east, in Chad, and particularly to the north of the Lake where, unfortunately, a complete series of annual rainfall is available from only one station, N'Guigmi.

By contrast, there is a region, central with respect to longitude, with an annual rainfall of more than 500 mm, where the coefficient of variability is everywhere less than 20 per cent, uniformly low for such a wide area. In Figure 15 this area is partly bounded by a broken line.

2.4 Probability diagram

Rainfall expectations within this central region were described by means of a diagram (Figure 16), based on the following assumptions: mean annual rainfall between 500 and 1,000 mm, coefficient of variability 22.5 per cent at 500 mm and 15 per cent at 1,000 mm, no skewness or shifting of the mean on the high values side of the median. This diagram can be used to evaluate probabilities for places within the region whose mean annual rainfall is estimated from incomplete records.

3. MONTHLY RAINFALL AND RAINFALL FOR SHORTER PERIODS

3.1 Seasonal variation of monthly mean rainfall

Monthly mean rainfall is probably the best index of the average variation of rain during the year. The unsatisfactory nature of averages for shorter periods will be discussed later in this section.

The monthly mean rainfall figures for every station analysed in the Area show a maximum in August. This is in agreement with the general picture given in Part I. Figure 17, which shows monthly mean rainfall for two stations in the Area -- one in the north and the other in the south -- illustrates this, and also shows that, though the amounts involved are different, the pattern remains the same.

The surface distributions of the monthly rainfall amounts show this same seasonal variation superimposed on a zonal arrangement of increasing amounts. This is illustrated in Figure 18 where monthly mean isohyets for the beginning, the peak and the end of the rainy season are shown. Figure 18 also shows the lag in the onset and, to some extent, in the termination of the rains in Senegal, in the extreme west of the Area.

The actual duration of the rains, which varies with annual rainfall amounts, will be discussed under the heading Availability of Water.

It should be pointed out at this stage, however, that once the ground is saturated, any rainfall in excess of potential evaporation would tend to run off. In August this occurs at the monthly scale everywhere in the survey area. For a given annual rainfall a sharing

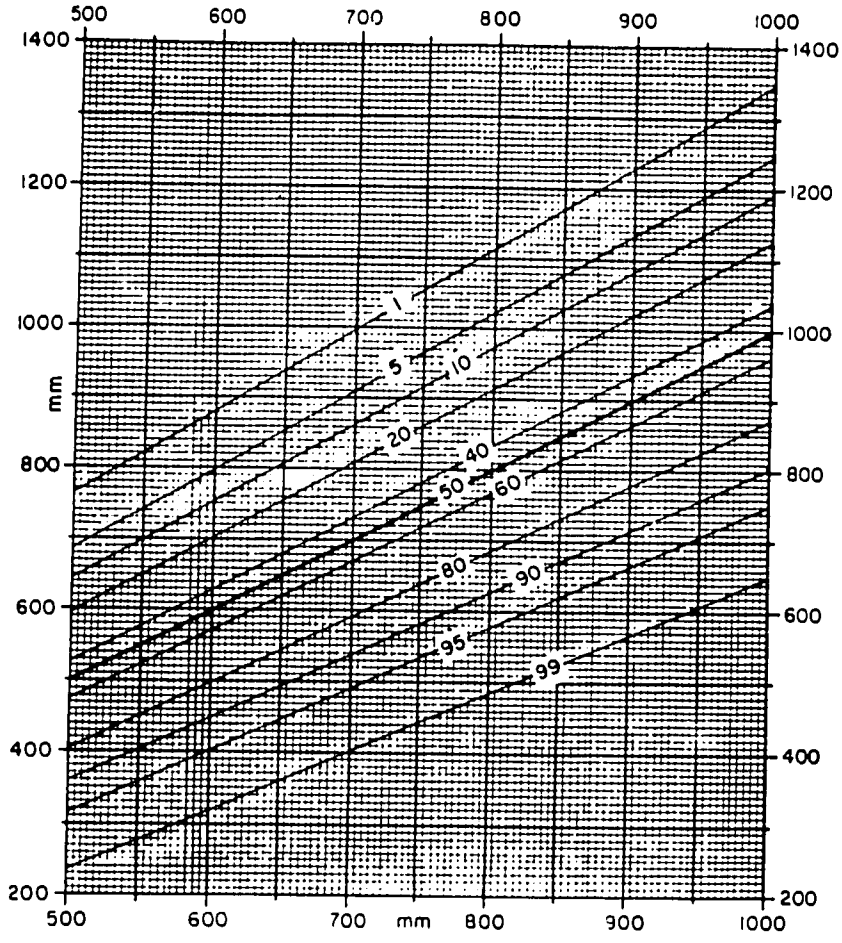

Figure 16 -- Rainfall probability diagram for low variability zone in centre of Area. Mean annual rainfall is along the base of the diagram. The diagonal lines indicate the number of years in 100 when corresponding amounts, to be read on the sides, will be equalled or exceeded.

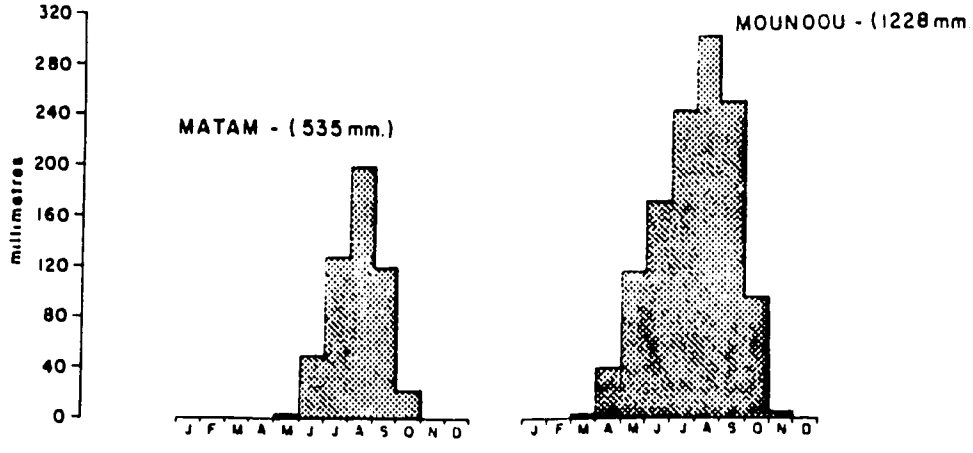

Figure 17 -- Seasonal variation in monthly mean rainfall at Matam in north Senegal and at Moundou in south Chad, showing the similarity of the distribution pattern.

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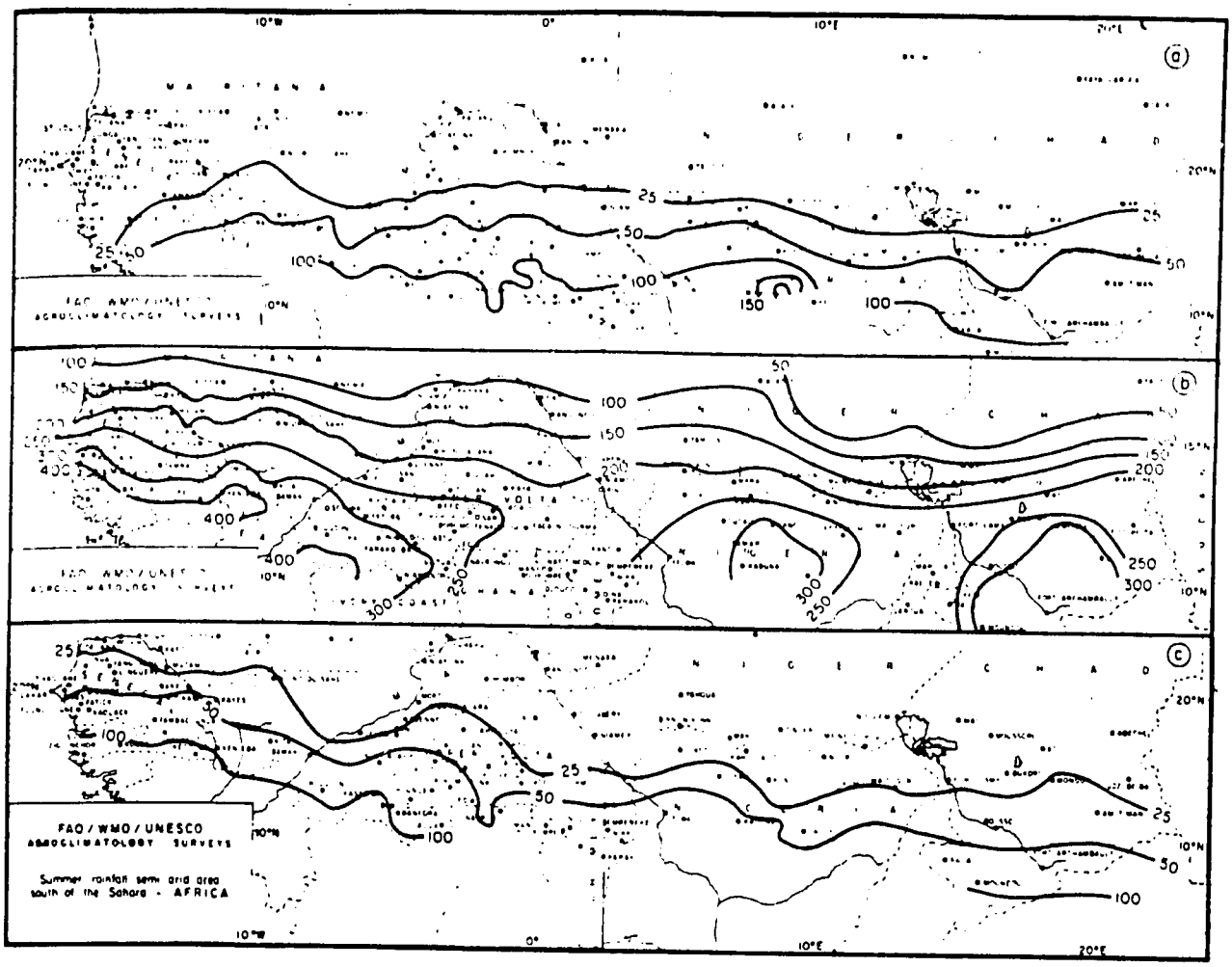

Figure 18 -- Monthly mean rainfall: (a) May, (b) August, (c) October. (After Météorologie Nationale (1958).)

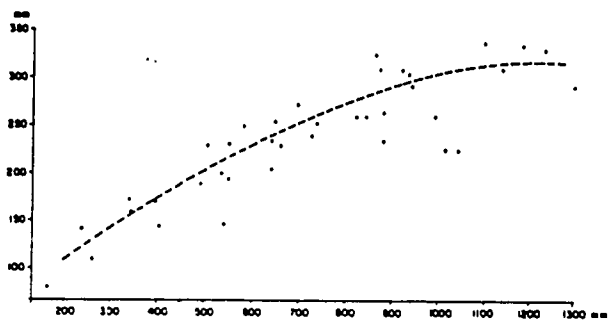

Figure 19 -- August v. annual rainfall.

of the rain more evenly between the summer months and an avoidance of a very high August amount would appear to be desirable characteristics from the point of view of utilization of water by dry farming crops. But for cultivation in drainage basins or perennial pastures, rainfall concentration may be an advantage.

The relation between August and annual rainfall gives an idea of the degree of concentration of annual rain in the middle of the season. In Figure 19, August and annual rainfall have been plotted, and it is seen that, as annual rainfall increases, there is a gradual falling off in the relative importance of August rainfall, which approaches a maximum whilst rainfall for other months is still increasing. This implies that rain is in general better spread in the south of the Area.

The surface distribution of the ratio between August and annual rainfall, illustrated in Figure 20, shows, apart from an increase with decreasing rainfall, two maxima, in north-west Senegal and the Lake Chad area.

Where the annual rainfall is small and the vegetation can thrive only in privileged drainage basins, this more abrupt distribution of the annual rainfall might, in fact, be an advantage.

3.2 Mean rainfall for periods shorter than a month

For the purposes of planning agricultural operations, a month is too long an analysis period, particularly when the growing season can be as short as 80 days. The rainfall during ten-day periods, weeks, or even pentads should also be analysed.

However, with periods approaching more and more to the average duration of one rainstorm (which is relatively very short in our zone, commonly a few hours), an increasingly large number of years are needed to yield an average which settles to a truly representative value. This is demonstrated in Figure 21, which shows mean rainfall variation during the year for a period of 36 years at Samaru, in northern Nigeria, in terms of averages for three periods of decreasing duration.

The monthly mean amounts form a pattern similar to that of Figure 17. The ten-day mean amounts show irregularities (such as a low in the first ten days of June, too early to represent the "little dry season") which are not thought to indicate a systematic annual variation, but are probably the results of a few heavy falls.

The daily amounts show a pattern much obscured by "noise", and it is clear that, owing to the occurrence of falls within a day of as much as 15 times the daily mean, 30 years is insufficient to allow the averages to settle down to a nearly constant value.

The means over 30 years of shorter and shorter intervals are therefore less and less informative, whilst the numbers to be calculated (and thus the work involved) increase in proportion. It is not thought that representative means for periods shorter than a month are obtainable from 30-year series. (It will be seen later that graphical interpolation was used to obtain representative daily means.) This is not to say that the frequency of occurrence of given amounts, in other words the variability, for these shorter periods is not worth considering. Indeed, this is the type of rainfall information of most direct use for agricultural operations.

4. VARIABILITY OF MONTHLY RAINFALL

The empirical and theoretical methods for calculating variability and deriving probabilities of yearly rainfall are generally applicable to monthly amounts, subject to some

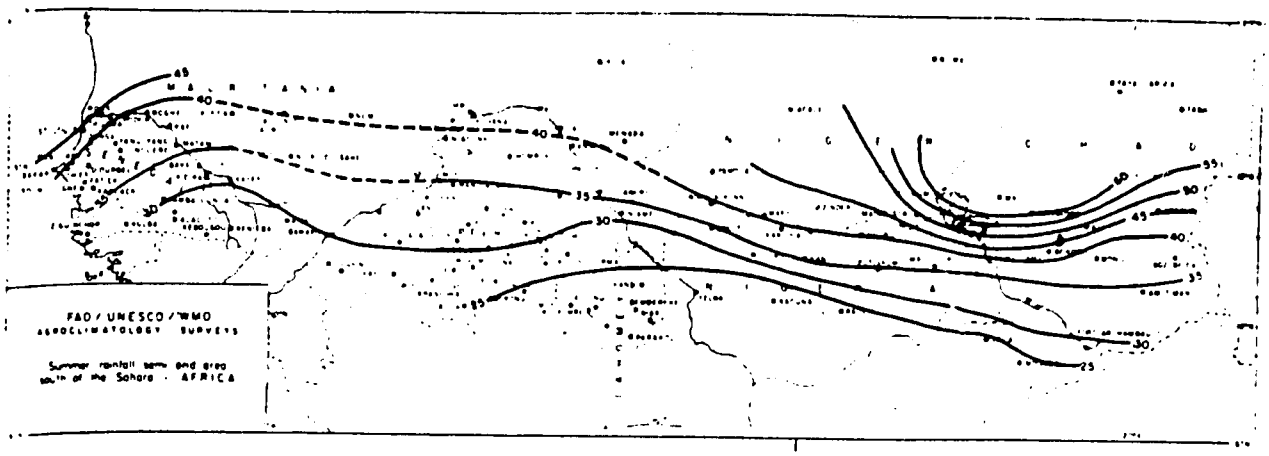

Figure 20 -- Surface distribution of ratio between August and annual mean rainfall.

reservations. The volume of work involved tends to prohibit a comprehensive treatment of all the data available in the Area, and only a few examples can be given, in the hope that they may be useful in further studies of local conditions.

Concerning the empirical approach, WMO's CLINO gives monthly quintiles for a number of stations in the Area. Monthly quintiles for May and August at a place with moderate rainfall and at another in the subarid zone are shown in Table 2. It is seen that in August, when it invariably rains, the distribution is similar to that of the annual values, although the variability is greater. In May null values occur, especially at the drier place. The distribution is truncated on the dry side. Such a series can still be arrayed and limits and quintiles determined but their meaning, especially within the zeros sector, is less clear. At N'Guigmi the probability of dry Mays is two years in five, but the amount exceeded one and two years out of five is, in both cases, nothing.

It is not possible to fit truncated series directly to a normal distribution. Preliminary modifications of the sample or other distributions may be used. This will be discussed further in the next paragraph, instances of the use of appropriate functions being given.

5. VARIABILITY OF RAINFALL FOR PERIODS SHORTER THAN A MONTH

In this survey of a wide area, it would be hard to obtain meaningful information on seasonal rainfall for shorter periods by working out averages for these periods. (This point was discussed in paragraph 3.2.) Graphical interpolation from monthly means was found preferable. This makes an analysis of the variability of the amounts obtained during these shorter periods all the more important, although this analysis is affected by certain limitations, and may demand special treatment.*

* In other words, when the periods considered are shorter than a fortnight, a preliminary analysis should completely discard the use of averages and proceed directly to arraying.

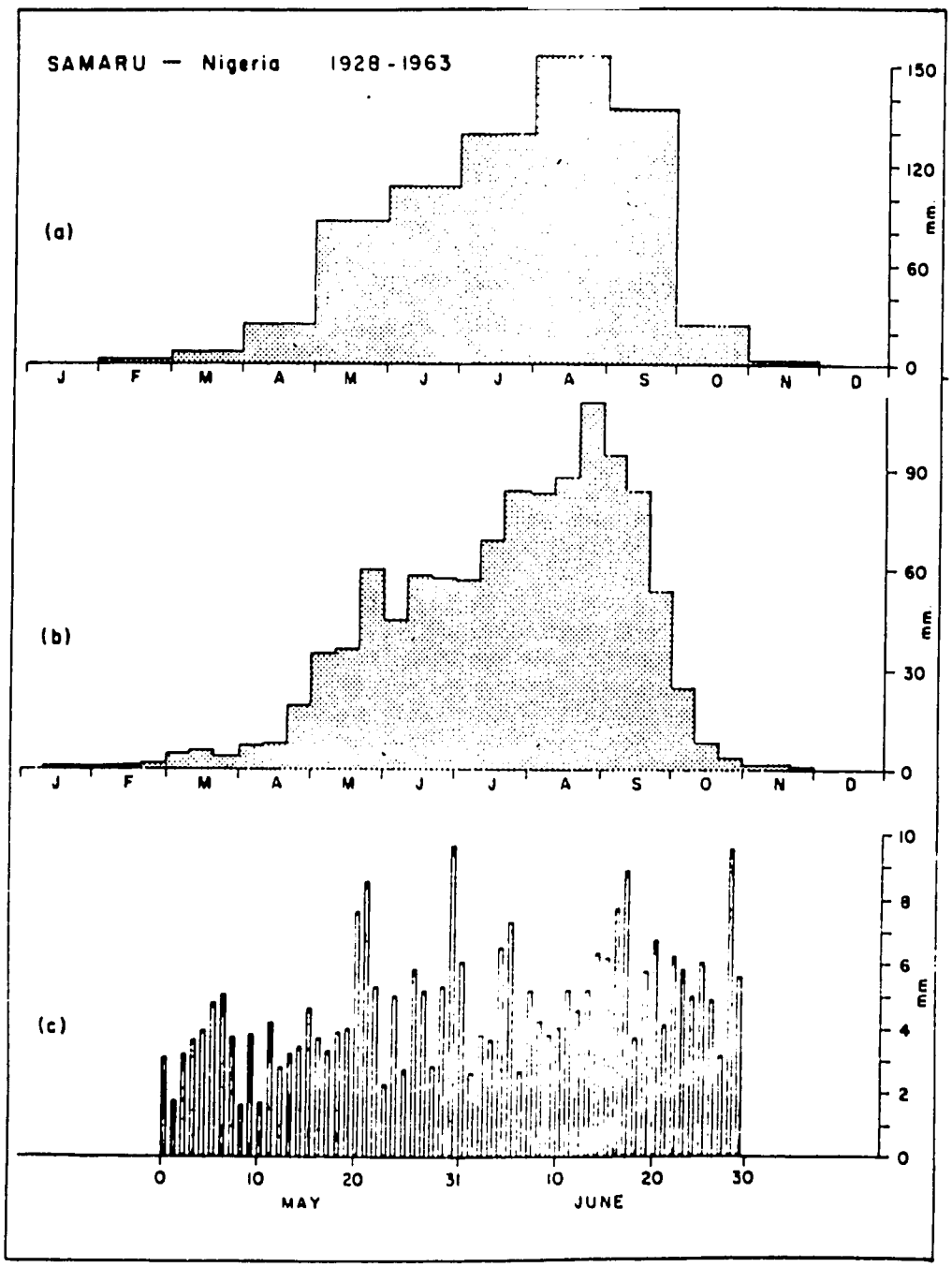

Figure 21 - Means of rainfall amounts for periods of one month, ten days and one day.

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TABLE 2

MONTHLY RAINFALL CHARACTERISTICS AT TWO STATIONS IN NIGER AT THE BEGINNING AND FOR THE WETTEST MONTH OF THE SUMMER RAINS

		a	b	I	II	III	IV	V	VI	c	d	e
Niamey	August	195	201	75	136	170	210	247	434	73	36%	3%
640 mm	May	30	37.7	0	12	21	34	57	114	29.4	78%	26%
N'Guigmi	August	130	141	35	71	99	166	191	318	72	51%	8%
235 mm	May	0.3	6.5	0	0	0	2	6	90	-	-	-

(a) median; (b) mean; II to V quintiles; I and VI extremes; (c) standard deviation; (d) coefficient of variability: $\sigma/\bar{r}$; (e) skewness index: $m-\bar{r}/\bar{r}$.

TABLE 3

PENTAD RAINFALL QUINTILES AND EXTREMES AT THE SAME TWO STATIONS AS TABLE 2 DURING AUGUST

NIAMEY 640 mm

	1	2	3	4	5	6
VI	110.8	130.7	85.7	130.2	102.4	210.9
V	54.0	63.7	54.5	52.8	52.6	38.7
IV	29.1	24.0	33.5	31.0	25.9	30.1
III	20.0	16.9	19.8	19.3	20.0	22.0
II	7.8	11.3	10.9	3.1	17.4	10.1
I	1.5	0	1.4	0	0	1.5

N'GUIGMI 235 mm

	1	2	3	4	5	6
VI	96.1	120.3	143.6	117.9	81.6	60.2
V	39.2	33.7	68.1	39.1	25.1	34.0
IV	8.3	23.5	38.0	22.3	6.4	15.4
III	4.5	14.4	29.2	5.7	1.5	3.0
II	0	1.8	11.0	0	0	0.7
I	0	0	0.6	0	0	0

1 to 6, number of pentad; II to V, quintiles; I and VI, extremes.

STATION	I	J	NX	NNX	XBAR	GAMMA	BETA	PCP LVL	PROB
955595	11	01	30	034	1.09467	5.24382	.88009	0 OR T	.11765
								00.20	.77304
								00.40	.65274
								00.60	.54380
								00.80	.44948
								01.00	.36955
								01.20	.30263
								01.40	.24710
								01.60	.20126
								01.80	.16362
								02.00	.13282
								02.20	.10766
								02.40	.08715
								02.60	.07049
								02.80	.05698
								03.00	.04600
								03.20	.03715
								03.40	.02993
								03.60	.02415
								03.80	.01951
								04.00	.01564

Figure 22 - Weekly precipitation probabilities for Samaru, Nigeria, calculated with an electronic computer by the US Weather Bureau at their National Weather Record Center, Asheville, N.C.

I. Climatological week number beginning 1 January.
J. Number of weeks in the period.
NX. Number of years with 0.01 inch or more.
NNX. Total number of years.
XBAR. Gamma distribution mean.
PCP.LVL. Specified precipitation levels in inches.
PROB. Probability for specified level or more.
GAMMA and BETA parameters of the function.

In Table 3 arraying of five-day amounts recorded during the month of August for the same two stations as in Table 2, Niamey and N'Guigmi, shows that null values appear at both places during the wettest month of the year.

Although these pentad data series are truncated, it is thought that the empirical approach -- arraying -- is sufficient to meet most practical requirements, especially if water balance estimates and the frequency of wet and dry spells of given lengths have been worked out as well.

However, if operational considerations require fitting to a distribution law, the sample may be modified to fit a log normal function.

Another useful function for analysing short-period averages which require smoothing and consideration of null values is the incomplete gamma function. It involves resorting to approximation methods and therefore, for practical use, an electronic computer is required. Figure 22 is a photograph of a sample of such an analysis, yielding weekly probabilities, at Samaru, in Northern Nigeria. It was done for this survey by the Climatology Department of the U.S. Weather Bureau.

6. RAINFALL INTENSITY

Intensity, or the rate at which rain falls, affects the amount of water made available to crops.

6.1 Mean amounts in 24 hours

In the semiarid Area the average amount of rain per rainy day does not seem to depart very far from 14 mm, as shown in Table 4.

This is also illustrated in Figure 23, where it can be seen that the proportion between number of rainy days and mean annual rainfall is fairly consistent. This would suggest that most of the rain is due to disturbance lines of approximately equal intensity everywhere.

There is, however, a seasonal variation in the monthly mean amounts of rain per rainy day at any given place with smaller amounts at the beginning and at the end of the rainy season.

6.2 Maximum amounts in 24 hours

Some specific works of analysis are available for the Area concerning the maximum amounts likely to fall in 24 hours. In an outstanding analysis, Brunet-Moret of ORSTOM (1963) fitted data of daily rainfall amounts from 71 stations in the Area to a truncated log normal distribution. The parameters of this distribution are the mean and the standard deviation of the logs of the daily amount and, thirdly, the probability of occurrence of a rainy day, estimated graphically by trial and error.

The values of the highest fall in 24 hours to be expected during a given number of years obtained with this theoretical approach compare well with the amounts observed in the past.

In the central area, where variability is low, there is also good agreement between lines of equal rainfall and lines showing equal 24-hour maxima expected to occur once a year. This is shown in Figure 24, where it is also shown that agreement is less good on either side of the central area.

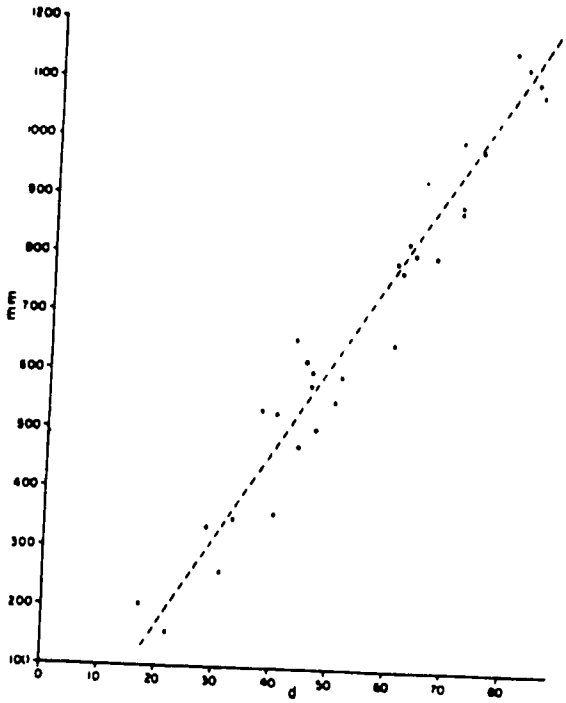


TABLE 4

ANNUAL MEANS

	(a)	(b)	(c)
	mm	d	mm
AGADES	158	22	7 2
PODOR	336	28	12 0
ZINDER	531	40	13 6
TAMBACOUNDA	873	61	14 2
GAROUA	985	74	13 3
MOUNDOU	1210	79	15 3

(a) rainfall, (b) number of days of rain of 0.1 mm or more, (c) rainfall per day of rain.

← Figure 23 -- Number of days of 0.1 mm of rain or more v. mean annual rainfall.

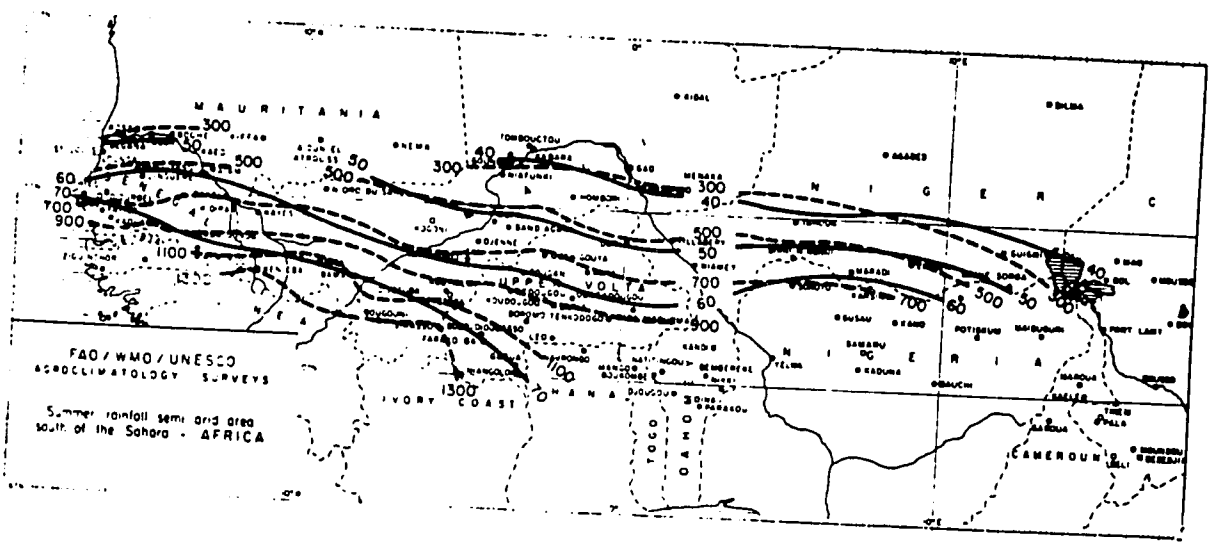


Figure 24 -- The broken lines indicate mean annual rainfall and the plain lines the highest amount expected to fall in 24 hours once a year.

7. DIURNAL VARIATION OF RAINFALL

The times of the day and night at which most rain falls affect crop productivity since they control the rate of evaporation and of photosynthesis by altering temperatures and sunshine.

Available data show that maximum intensity occurs at different times of the day at different places. This is illustrated in Figure 25, where three stations of approximately the same annual rainfall are compared. This difference in timing agrees with what was said in Part I: precipitation is mainly due to disturbance lines, not diurnal heating. These disturbance lines move across the country, sometimes for several days; so that the time of precipitation depends on the distance of a place from the source areas of these disturbance lines, whose occurrence would presumably be controlled by diurnal heating of the source areas.

Supporting evidence is provided by the diurnal intensity régime of Kano and Zinder which, situated approximately on the same meridian, across the path of disturbance lines, shows maxima at the same hours (Figure 26).

8. HOURLY INTENSITIES

A study by Delorme (1963) shows that rain, which is almost exclusively of a showery nature, falls everywhere in the Area at a mean intensity of 4 $mm.h^{-1}$, except at the beginning and end of the season. Table 5 shows monthly mean intensities extracted from Delorme's study.

4 $mm.h^{-1}$ is at least twice as high as in western Europe. This relatively high rate is not the result of exceptionally heavy rains, but of the preponderance of medium to high intensities, and the rarity of low intensities such as are associated with drizzle.

A rainfall intensity of 4 $mm.h^{-1}$ is two or three times less than the permeability of most soils in the Area. This means that until field capacity is reached rain is, on the average, within the absorbing powers of soil.

The relatively high mean intensities also imply that for an equal amount of rainfall there probably is more sunshine during the rainy season than in areas of lesser intensities.

9. INTENSITY-DURATION

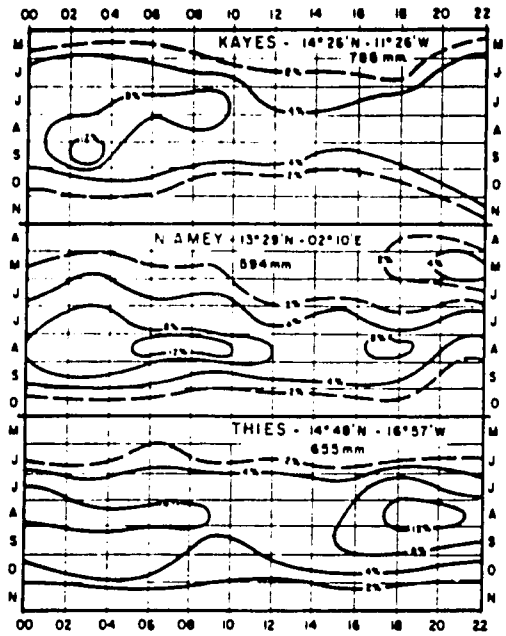
From data obtained from rainfall recorders, the probability of occurrence of various amounts of rainfall during specified, relatively short intervals can be estimated. Some studies of this problem in the Area are available.

Intensity-duration curves for Kano, in northern Nigeria, shown in Figure 27, were extracted from a study by the British West African Meteorological Service, Nigeria (195?).

The curves were obtained from autographic records for a period of eight years by fitting the data to a logarithmic function involving four constants specific to the station. They give the highest amounts expected during specified intervals for periods of up to 10 years.

Intensity-duration characteristics for the Area were also evaluated by Brunet Moret (1963), who used all available tilting-bucket-pluviograph data, but discarded records from siphoning apparatus.

The amount of data available was not thought to justify fitting to a theoretical function, and only empirical distribution was assessed.



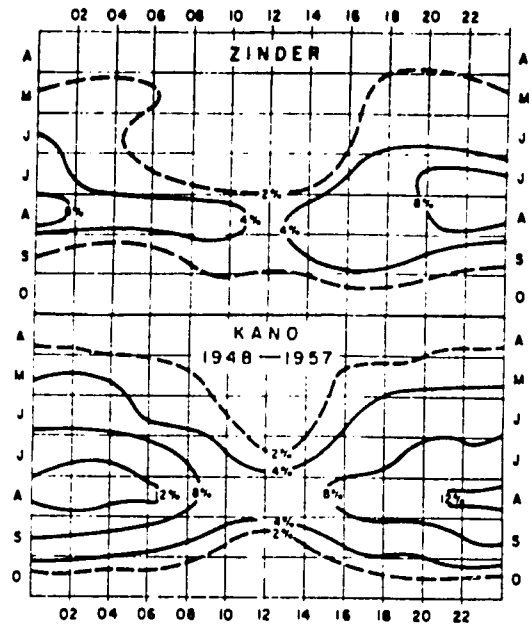


Figure 25 -- (left) Diurnal rainfall variation at three places in the Area with approximately the same mean annual rainfall and showing maxima at 0300, 0800 and 1900 hours respectively. The percentages denote occurrence of rain at hourly observation.

Figure 26 -- (right) Diurnal rainfall variation at two places on approximately the same meridian, and both showing maxima in the middle of the night.

TABLE 5

MEAN INTENSITIES IN MM/HOUR DURING MONTHS WHEN IT RAINS FOR MORE THAN 10 HOURS. (~~AFTER DELORME~~ (1963).)

OUAGADOUGOU	1 6	5·1	5·1	3·5	3 4	4·6	4·1	3 9
BOBO-DIOULASSO	4·2	6 2	6·0	4·4	5·4	5·4	3 0	4·9
BAMAKO	—	3·1	4 7	4·1	4·6	5·0	3 9	4 2
GAO	—	—	3·3	4·4	5·5	3 2	—	4 1
KAYES	—	—	4·0	4·2	4·8	4 1	3 2	4·1
NIAMEY	—	3 2	4·0	4·0	3 8	3·1	—	3 6
ZINDER	—	4 1	3 9	4 4	5 2	4 3	—	4 4
DAKAR	—	—	—	3 1	3 2	5 2	3 4	3 7
THIES	—	—	2·0	3 7	4 3	4 6	3 2	3 5
	2 9	4·3	4·1	4·0	4 5	4 4	3 5	4·04

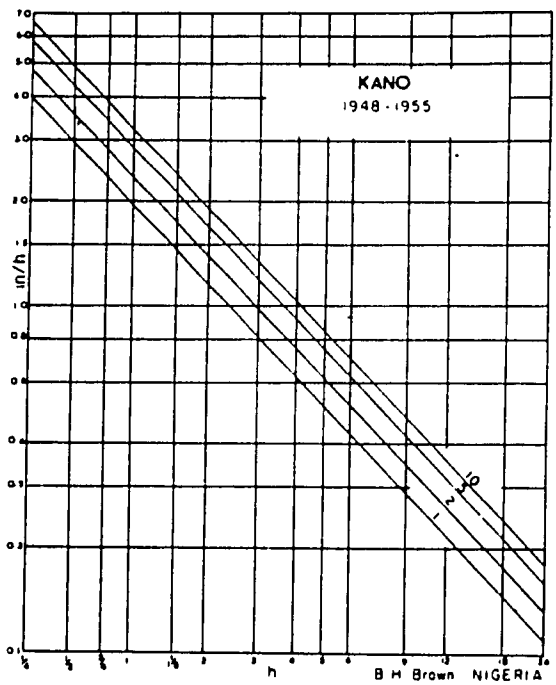


Figure 27 -- Maximum intensities to be expected during specified intervals in a given number of years. The diagonal lines indicate the number of years considered. The ordinate gives the intensities in inches per hour and the abscissa the intervals in hours and fractions of hours. In one hour a little less than two inches can be expected once a year.

Mean intensity-duration, plotted on double logarithmic paper, yielded curves similar to those for Kano with, however, a definite break in the alignment of the points (Figure 28). These reflect the change from the intense precipitation of the main body of a disturbance line to precipitation of less intensity often coming from trailing medium cloud in its wake (as shown in Figure 6 in the first part of this report).

In Figure 29 a recording of the successive rainfall amounts collected during the passage of one of these storms illustrates well this sharp change in intensity.

Combining the probabilities of maximum amounts in 24 hours discussed in section 6 above, with these intensity-duration characteristics, Brunet Moret constructed diagrams indicating the maximum amounts to be expected during specified intervals of time once in a specified number of years. These diagrams are discussed in greater detail in the Technical Report.

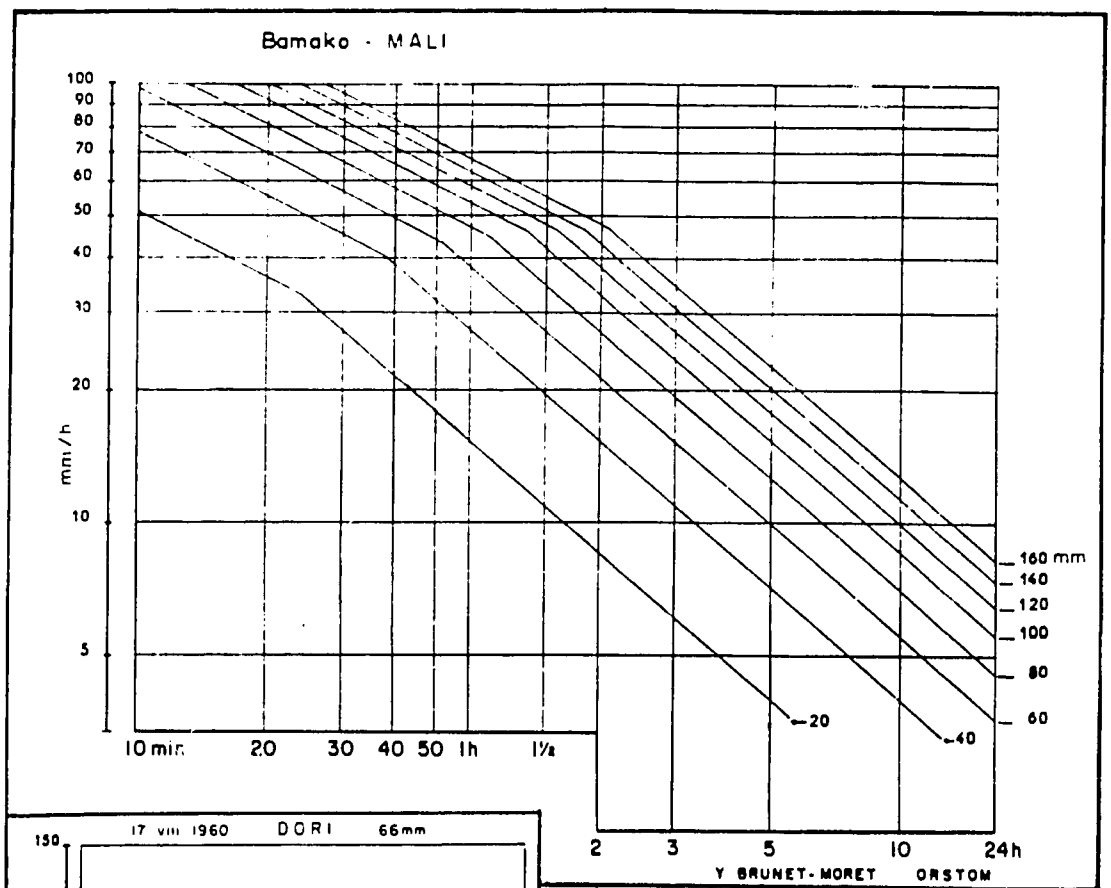
10. SPATIAL VARIABILITY

Two sample studies of the differences between rainfall amounts falling during the same periods on different parts of the Area were carried out, the scales involved being very dissimilar.

10.1 Mesoscale (medium scale): Niamey Ville and Niamey Aero

Daily rainfall at Niamey and at its airfield, a few kilometres away, during the year 1953 showed an average difference amounting to 62 per cent of their combined daily mean, whilst for annual rainfall the difference was 11 per cent.

This shows clearly that for day-to-day comparison of rainfall with biological variables at a given spot, rainfall at a meteorological station a few kilometres away cannot be assumed to be representative.



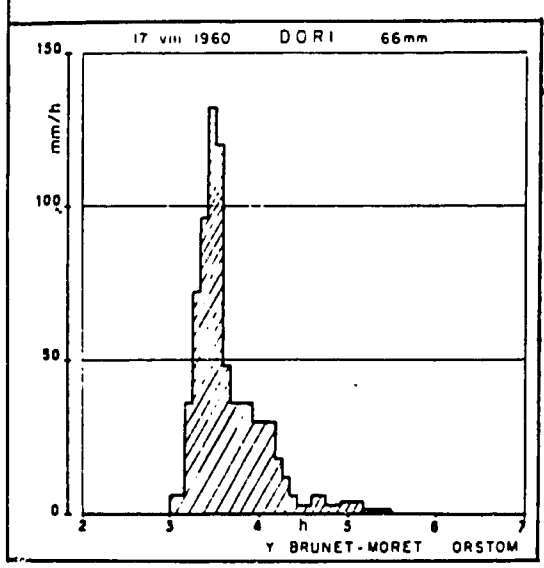


Figure 28 - (Above) - Mean intensity durations corresponding to given daily rainfalls, indicated by diagonal lines. Durations of intervals considered are shown at base of diagram in hours and minutes and intensities in millimetres per hour on the side.

Figure 29 - (Left) - Histogram of a disturbance line, showing transition from main shower to trailing precipitation.

As the period for which rainfall amounts are considered increases from days to pentads, weeks, ten-day intervals and so on, records from places some distances apart become increasingly more acceptable as representations of local conditions.

10.2 General circulation scale: Senegal and Chad

On a broad geographical scale, and for periods such as a growing season, spatial variability can have important economic implications, since it affects the extent of the occurrence of famine in marginal areas.

Mean annual rainfall averaged from three stations in Senegal and Chad respectively, at both zonal ends of the Area, showed a negative correlation coefficient of -0.51 over a period of 10 years. This coefficient, though not statistically significant, indicates that there is a tendency for drought or excessive rainfall not to occur everywhere along the savanna belt simultaneously. Famine resulting from drought in marginal areas might therefore not be felt in all the countries of the Area in the same year.

On the other hand, correlation between each of the groups and one of its stations, Dakar and Fort-Lamy respectively, was in both cases positive, and statistically significant in the case of Fort-Lamy.

11. SPELL ANALYSIS

The grouping of wet days and dry days has an important effect on actual crop water balance and photosynthetic activity. Sample studies were carried out using daily rainfall data from Niger collected by ASECNA (undated, 196?).

11.1 Wet spells at Zinder

The monthly mean number of spells of different number of days of rain were estimated for the period 1931-1960.

A large proportion of the rainy days occur singly (33-70 per cent), or in groups of two days (17-28 per cent). The occurrence of single wet days is least in August and greatest at the beginning and end of the season. The monthly mean occurrence of three-day spells is less than one for all months, and spells longer than three days have not been recorded outside July, August and September.

The occurrence of wet spells was also expressed as a percentage of all the days of the month, wet or dry, as shown in Table 6. It is seen that in August nearly half of the days are wet and about one quarter of these days are grouped in spells of two or more days.

Table 6 also gives the probabilities of a day of rain being followed by a dry day in terms of the number of consecutive wet days which have already occurred. Such local studies of wet-spell occurrence have many practical applications in terms of agricultural operations. Later in the analysis, figures for sunshine amounts will also be given in connexion with evapotranspiration estimates.

11.2 Interannual variability of wet spell occurrence

The frequency distribution of the annual occurrence of wet spells in May was also determined. Results are tabulated in Table 7. It is seen, for instance, that there are 3 chances in 30 of no spells of one day occurring, and 2 chances in 30 of 6 such spells, although the mean occurrence is $2\frac{1}{2}$ times.

TABLE 6

ZINDER 1931-1960

	Length of spell - days					
	1	2	3	4-5	6-8	8
M	8.0 11.9	2.9 3.9	1.0 1.0			
J	14.1 21.1	4.7 7.0	2.3 2.3			
J	16.9 33.2	7.1 16.3	4.2 9.2	3.1 5.0	1.9 1.9	
A	14.8 43.3	9.2 28.5	7.9 19.3	9.4 11.4	1.9 2.0	0.1 0.1
S	14.0 26.2	7.4 12.2	2.8 4.8	2.0 2.0		
O	1.7 2.4	0.4 0.7	0.3 0.3			

Note to Table 6:

Top rows, monthly mean percentage occurrence of wet days forming part of spells of given lengths. Below, monthly mean percentage occurrence of one day of rain following a wet spell of a length indicated in the column to the left. For percentages in column 1 this length is 0. In May, for instance, the occurrence of a wet day at the beginning of a wet spell of any length is 11.9 per cent. The occurrence of a wet day following another is 3.9 per cent. The probability of two wet days being followed by a third is 1 per cent.

TABLE 7

OCCURRENCE OF WET SPELLS IN MAY, AT ZINDER, 1931-1960

	Spells of one day							Mean
Number of spells Number of years	0 3	1 6	2 9	3 5	4 3	5 2	6 2	2.5
	Spells of two days							
Number of spells Number of years	0 19	½ 1	1 9	2 1				0.5
	Spells of three days							
Number of spells Number of years	0 28	½ 0	1 2					0.1

½ means a spell shared with an adjacent month.

TABLE 8

QUINTILES AND EXTREMES OF ANNUAL RAINFALL AND SLIDING TWO-YEAR MEANS

BAMBEY Senegal 1931-1960 682 mm

Quin.	Sliding means 2 year	Years
I	1123	1267
II	762	784
III	713	726
IV	629	565
V	548	493
VI	455	410

TABLE 9

OCCURRENCE OF GROUPS OF CONSECUTIVE YEARS BELOW SELECTED ANNUAL RAINFALL

BAMBEY Senegal 1931-1960

500 mm		600 mm			Upper limits
2	3	2	3	4	Number of years in group
2	0	1	1	2	Occurrence

11.3 Dry spells at Zinder

Analysis of the dry spells at the same place and during the same period was confined to a calculation of the monthly mean number of dry spells of different lengths.

Generally, dry spells are longer than wet spells, as could be expected. In August, dry spells of more than 10 days did not occur, but dry days were grouped in spells of all the intervening lengths up to 10.

Dry spells of more than 30 days did occur after the first rains but not during the end of the wet season. Analysis of such long spells cannot be expressed as monthly means.

Dry spell consideration is probably more effective in conjunction with water balance estimates. A sample analysis will be given later.

12. CONSECUTIVE DRY YEARS

A sample analysis of the occurrence of groups of dry years at Bambey in Senegal started with the arraying of sliding two-year means. The distribution, shown in Table 8, appears similar to that of the annual amounts with a reduced variability.

The occurrence of spells of years with less than selected annual rainfall amounts was also tabulated (Table 9). Twice, two years with less than 500 mm followed each other, presumably causing food shortage. On two occasions four consecutive years had less than 600 mm, presumably altering the boundaries of cultivation of marginal areas.

It would be informative to assess the actual effect of these consecutive dry years on regional production and crop distribution. At the same time, it is realized that the gradual improvement in cultivation techniques and storage facilities will steadily decrease the adverse effect of droughts.

13. SUMMARY AND CONCLUSIONS

Rainfall, the most important single climatic parameter in the Area, is distributed zonally in all respects, with some irregularities which, though slight, are significant from an agronomic point of view.

(i) A central zone comprising parts of Niger, Mali, Upper Volta and Nigeria shows a variability coefficient for annual amounts of less than 0.02. In this central region days of rain are mostly isolated except in August, when spells of two days are about as frequent.

(ii) On average, rain falls fairly uniformly at an over-all intensity of 14 mm per rainy day and 4 mm per hour of rainfall. Typical maximum falls once a year are 50 mm in 24 hours and 35 mm in one hour for a mean annual rainfall of 600 mm in the centre of the Area.

(iii) The time of day when most rain falls varies from place to place. Two places close to each other may have very different daily rainfall amounts, although their annual amounts are closely similar.

(iv) No evidence was found that very dry years were grouped in spells of more than two years and two-year sliding means appear to be normally distributed.

(v) Some evidence was found that annual droughts tended not to occur simultaneously along the whole semiarid belt. This may be of economic importance.

(vi) Finally, it is thought that the very typical monsoon summer rainfall of the Area shows fairly uniform characteristics. These are sufficiently repetitive to be assessed with the accuracy needed for application to agricultural problems whenever the rainfall requirements are sufficiently well defined.

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AVAILABILITY OF WATER

1. POTENTIAL EVAPOTRANSPIRATION ESTIMATES

1.1 General considerations

In the Area, even more so than in that of the previous inter-agency survey, the availability of water, with regard both to timing and quantity, is by far the most important factor controlling crop production.

This availability does not depend on rainfall alone. Rainfall must be balanced against the amounts which can be evaporated (potential evaporation) from the soil or vegetation, or lost by runoff or deep drainage.

Potential evaporation, the maximum amount of water which can be evaporated, depends on the amount of energy supplied by the sun to provide the necessary latent heat.

The actual amount of water rising through a plant to be evaporated by the leaves, thus making various processes of metabolism possible, depends in the first place on the quantities available to the roots. However, even if water is plentiful, the amount evaporated by the plants may actually decrease, when potential transpiration increases beyond certain limits, because wilting of leaves occurs.

In this case, potential evapotranspiration is no longer the maximum amount of water which the crops can use, but a demand for water from the atmospheric environment to which the crops cannot respond (Geslin, 1964).

Evaporation, actual or potential, can be estimated at various scales in space and time. Here, because of the size of the Area and the nature of the survey, it is the properties of the atmospheric climate, over periods basically no shorter than a month, that are being considered. (Atmospheric climate means that observed from properly sited thermometer screens, raingauges and other standard instruments.) No attempt is made to consider the intricacies of microclimate, whose diversities are due to differences in relief and exposure and also to the mosaic of soils with different physical properties such as texture and thermal capacity.

1.2 Method

Potential evaporation can be measured directly by means of special instruments -- evapotranspirometers or lysimeters -- deduced from the readings of evaporimeters, or estimated from measurements of meteorological elements.

Very few direct measurements were available from the Area, and the only evaporation data available in sufficient numbers for a survey were those obtained from Piche evaporimeters in screens. These were not considered appropriate for our purposes and recourse had to be made to the third method.

Amongst the formulae available, that of Penman was selected (this was also used in the first survey) because of its soundness and general applicability (Penman, 1963). It involved a relatively large number of meteorological elements, and the calculations are relatively long but all the intermediate estimates came to be of use in this study. The technical report contains practical details of its working and tables.

The formula used was that originally evolved by Penman to compute evaporation from a free water surface, Eo, but with a reflection coefficient of radiation by the surface of 25 per cent instead of 5 per cent, allowance also being made for the extra roughness of a crop compared with open water. This gives E_T, which Penman defines as "a measure of the transpiration rate from an extensive short green cover completely shading the ground and adequately supplied with water." It should be noted that here, because of the high values involved, E_T may sometimes have, as explained above, a somewhat different biological meaning, whilst its physical integrity remains unaltered. Here it is with E_T that we are concerned, which will hereafter be called evapotranspiration for the sake of international usage.

There are two main terms in the formula, representing the advected drying power of the air and the net energy available. The terms are weighted according to their relative importance by a factor which, itself, varies with temperature and pressure.

There are also six variables, two of which vary with latitude and time and may be called geographic, and four meteorological variables: temperature, vapour pressure, sunshine and wind speed.

1.3 Data

Ten years was considered to be the minimum period for the estimation of monthly mean potential evapotranspiration in the Area. The decade 1953-1962 was chosen, in preference to 1951-60, because of the relative abundance of data in 1961-1962.

From the various available sources, sufficient data on the four meteorological variables were collected from the following 35 stations:

Senegal	Dakar Yoff	14°44'N	17°30'W
	Matam	15 38N	13 13W
	Saint-Louis	16 03N	16 27W
	Thiès	14 48N	16 57W
	Tambacounda	13 46N	13 41W
Mali	Bamako	12 38N	08 02W
	Gao	16 16N	00 03W
	Kayes	14 26N	11 26W
	Mopti	14 31N	04 06W
	Segou	13 24N	06 09W
Upper Volta	Bobo-Dioulasso	11 10N	04 18W
	Ouagadougou	12 21N	01 31W
Ghana	Navrongo	10 53N	01 05W
Niger	Agadès	16 59N	07 59E
	Birni N'Konni	13 48N	05 15E
	Maradi	13 28N	07 05E
Niger (ctd.)	N'Guigmi	14 15N	13 07E
	Niamey	13 29N	02 10E
	Tahoua	14 54N	05 15E
	Zinder	13 48N	09 00E
Nigeria	Kaduna	10 36N	07 27E
	Kano	12 03N	08 32E
	Maiduguri	11 51N	13 05E
	Sokoto	13 01N	05 15E
Cameroon	Maroua	10 28N	14 16E
	Kaélé	10 05N	14 27E
	Garoua	09 20N	13 23E
Chad	Am-Timan	11 02N	20 17E
	Abéché	13 51N	20 51E
	Bousso	10 29N	16 43E
	F. Archambault	09 08N	18 23E
	Fort Lamy	12 08N	15 02E
	Mongo	12 11N	18 41E
	Moundou	08 37N	16 04E
	Pala	09 22N	14 55E

1.4 Distribution of the variables

The values and the spatial and seasonal variation of the meteorological variables are of interest, not only in so far as they affect the estimates of potential evapotranspiration, but also because they are part of the descriptive climatology of the Area.

Here these characteristics are described mainly by a series of maps, whose scale and lack of detail were chosen to correspond approximately to the accuracy expected from observations and calculations. A more striking presentation would confer on the estimates a degree of reality which they do not possess.

The periods chosen, besides the whole year, are April to October, which represents an average growing season for the Area; August, which is its climax; and November to March, representing the dry northern winter season.

It will be seen (Figure 30) that temperatures, humidity and sunshine are distributed zonally. The north-south temperature gradient, which is slack in any case, is reversed in winter, but not sufficiently to even out the slightly warmer temperatures of the north, $28°C^{\pm 2}$ being an annual mean applicable to the whole Area.

Vapour pressure shows important seasonal and spatial variations, extremes being 28 mb in the south in August and 7 mb in the north in winter (Figure 31).

The saturation deficit shows similar humidity gradients but in winter the lower temperatures of the north, as they decrease the saturation values, even out the gradient (Figure 32).

The duration of sunshine expressed in relation to maximum possible amount is consistently high. Even in August, in the south, the percentage is 40 (Figure 33).

The wind speed, here considered as a purely scalar quantity, is the only variable which is not distributed zonally. Besides a maximum on the coast of Senegal, it consistently shows a maximum in north Mali and a minimum in south Chad (Figure 34).

A sample calculation of the relative influence of the four meteorological factors on the E_T estimates under given conditions was carried out using mean values at Fort Lamy (Table 10). This shows that, with the possible exception of sunshine, the increase is not linear and the elements are interdependent.

It is of interest to note that (in theory) when the vapour pressure is very low, as occurs before the rains, further reduction does actually reduce E_T, as loss of energy to outer space more than compensates for the increased drying power of the air.

1.5 The estimates

The annual, seasonal, and monthly potential evapotranspiration estimates for the 35 reference stations in the Area are given in Tables 11 (a) and (b).

The seasonal variation is very characteristic of a summer-rains tropical climate and, within the Area, only varies in degree.

It is illustrated in Figure 35. Both the amounts due to the advected drying power of the air (A) and the net energy (E_{AT}) are seen to increase at the beginning of the year. Later, increased cloudiness and humidity and, eventually, a drop in temperature brought about by the monsoon rains depress both terms, but the aerodynamic term earlier, longer and to a greater extent. Both terms are again reduced by the oncoming of the northern winter.

In fact, there are two maxima and two minima, the summer rains minimum being lower than that of the dry winter even in the north of the Area.

Figure 36 shows that the pattern remains the same from north to south with, however, a decrease in spring and autumn maxima and an increase in the duration of the summer minimum.

TABLE 10

CHANGES IN POTENTIAL EVAPOTRANSPIRATION EXPRESSED IN MM OF WATER PER DAY BROUGHT ABOUT BY SMALL DEPARTURES FROM APRIL AND AUGUST AVERAGE VALUES OF THE METEOROLOGICAL VARIABLES

FORT LAMY Chad 1953 - 62													
		E_T r=0.25	TEMP. °C		VAPOUR PRESSURE mb					INSOLATION n/N		WIND m/s X 3	
	INCREMENT			+1		+2	-2	-4	-6		+0.05		+0.5
APRIL	AVERAGE 1952-63	7.22	32.6		12.7					0.71		11	
	DIFFERENCE E_T			+0.15		-0.06	0	-0.01	-0.03		+0.12		+0.13
AUG.	AVERAGE 1952-63	3.74	26.0		26.7					0.46		8.4	
	DIFFERENCE E_T			+0.28		-0.19	+0.20	+0.18	+0.17		+0.11		+0.03

In April, the driest month, further reduction in vapour pressure actually results in a slight decrease in E_T.

In space, the distribution of E_T reflects that of the variables and it is illustrated in Figure 37 (a) to (c) for the same periods.

It will be seen that the annual amounts vary from 1,500 to 2,200 mm.

The amounts which can be evaporated during the seven months of the wet period give some idea of the amount of water which can circulate through the crops. This notion will be approached with more precision later on in this section.

The August amounts, shown in Figure 37 (c), are seen to be much smaller than the rainfall shown in Figure 18 (c) except in the extreme north and, in fact, outside the semi-arid Area.

In the winter E_T is irregularly distributed, and fairly uniform over the Area.

The interannual variabilities of E_T during the decade 1953-1962 at Fort Lamy, as well as that of rainfall and of the meteorological variables, were calculated and are shown in Table 12.

Potential evapotranspiration is seen to be four times less variable than rainfall. Of the meteorological elements, temperature is the least variable and wind speed the most.

The same calculations for Fort Archambault, in the south, with much higher and less variable rainfall show comparable disparities in interannual variability between E_T, R and the meteorological variables. For the month of May, at the beginning of the rains, at the same place, interannual variabilities are greatly increased but, again, show similar disparities.

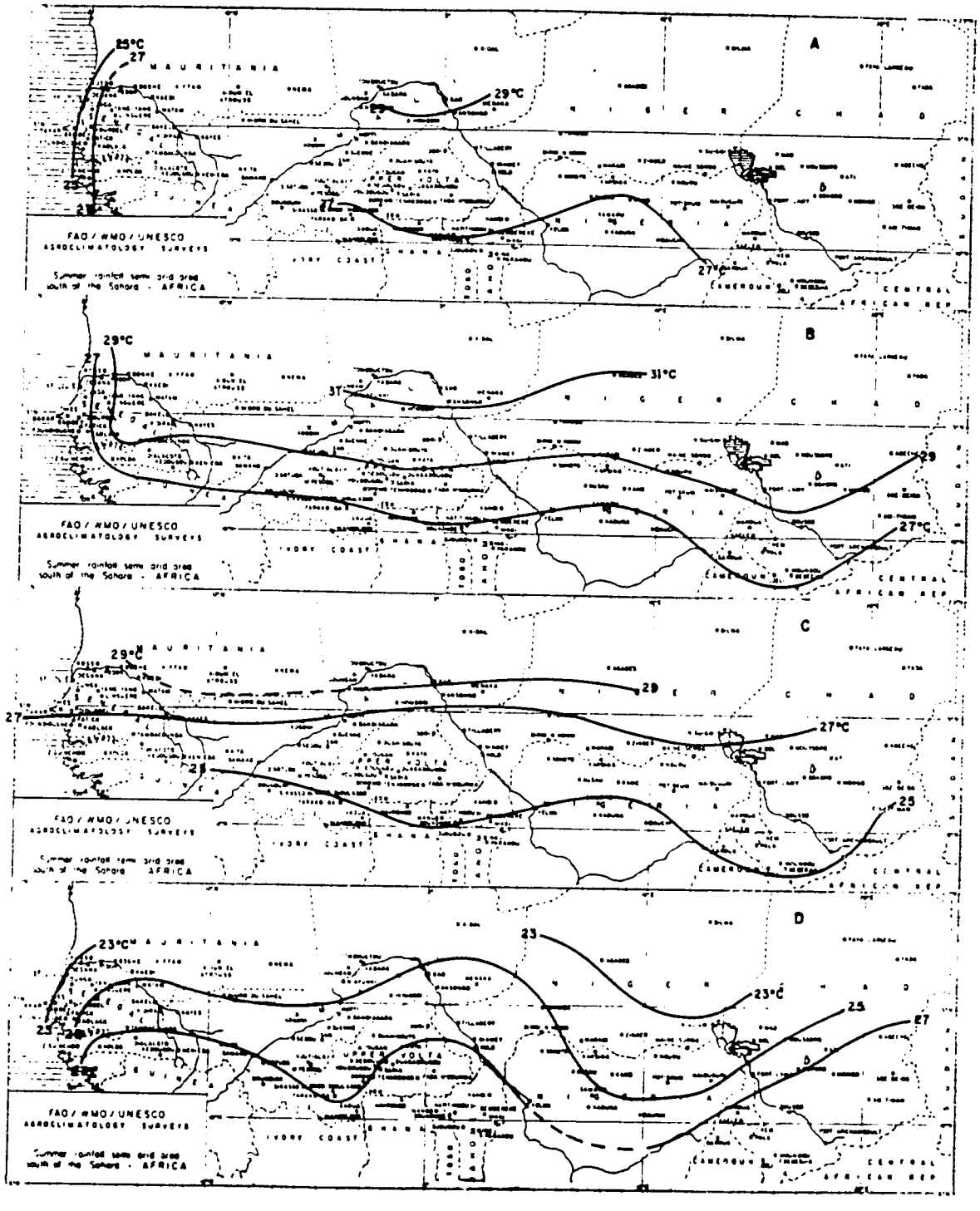

Figure 30 — Mean screen temperatures in Celsius. A, year; B, April-October; C, August; D, November-March. The north-south gradient is slack and reversed in winter.

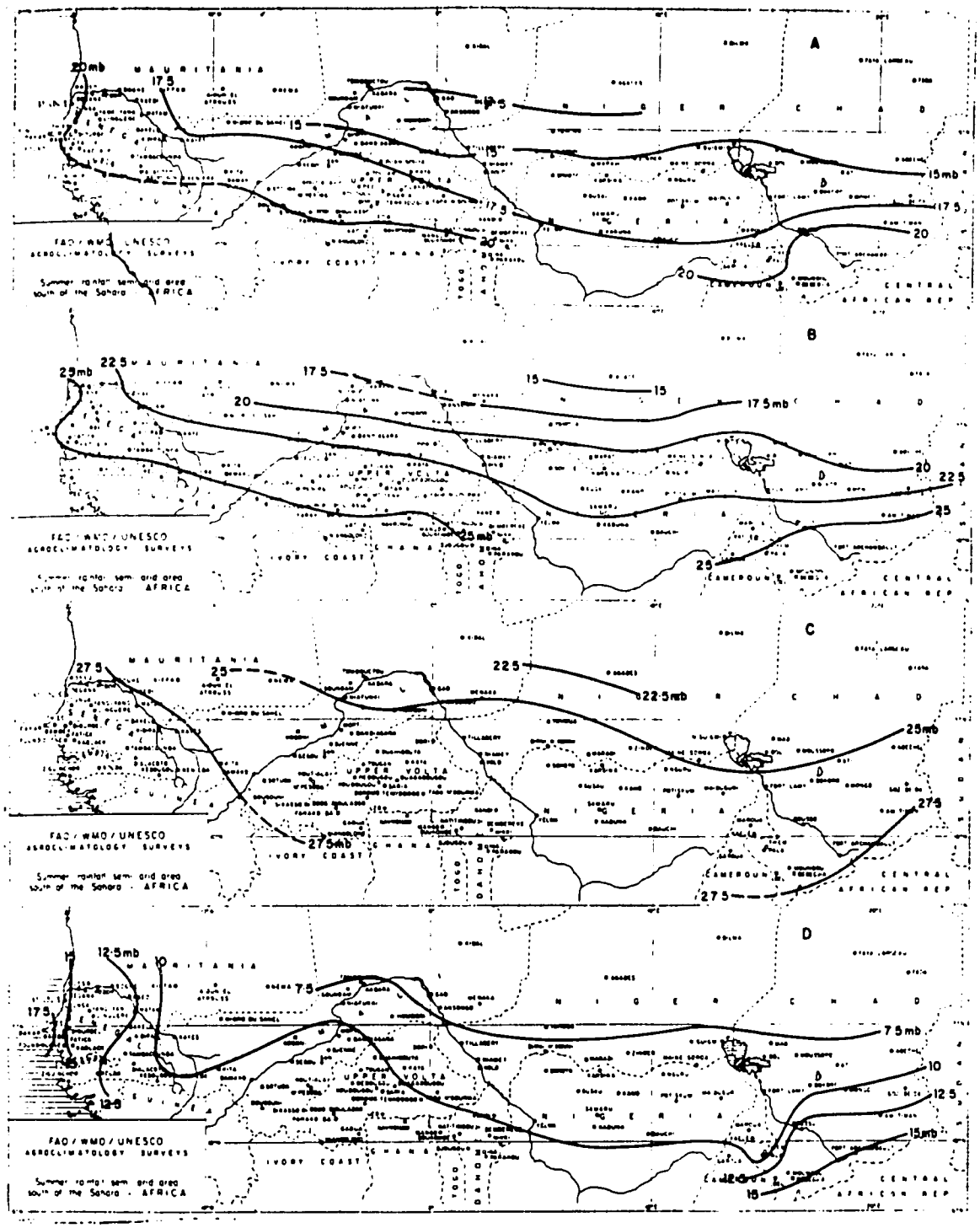

Figure 31 -- Mean screen vapour pressure in millibars. A, year; B, April-October; C, August; D, November-March. The seasonal variation with humid summers and dry winters is great, but the same gradient is maintained throughout.

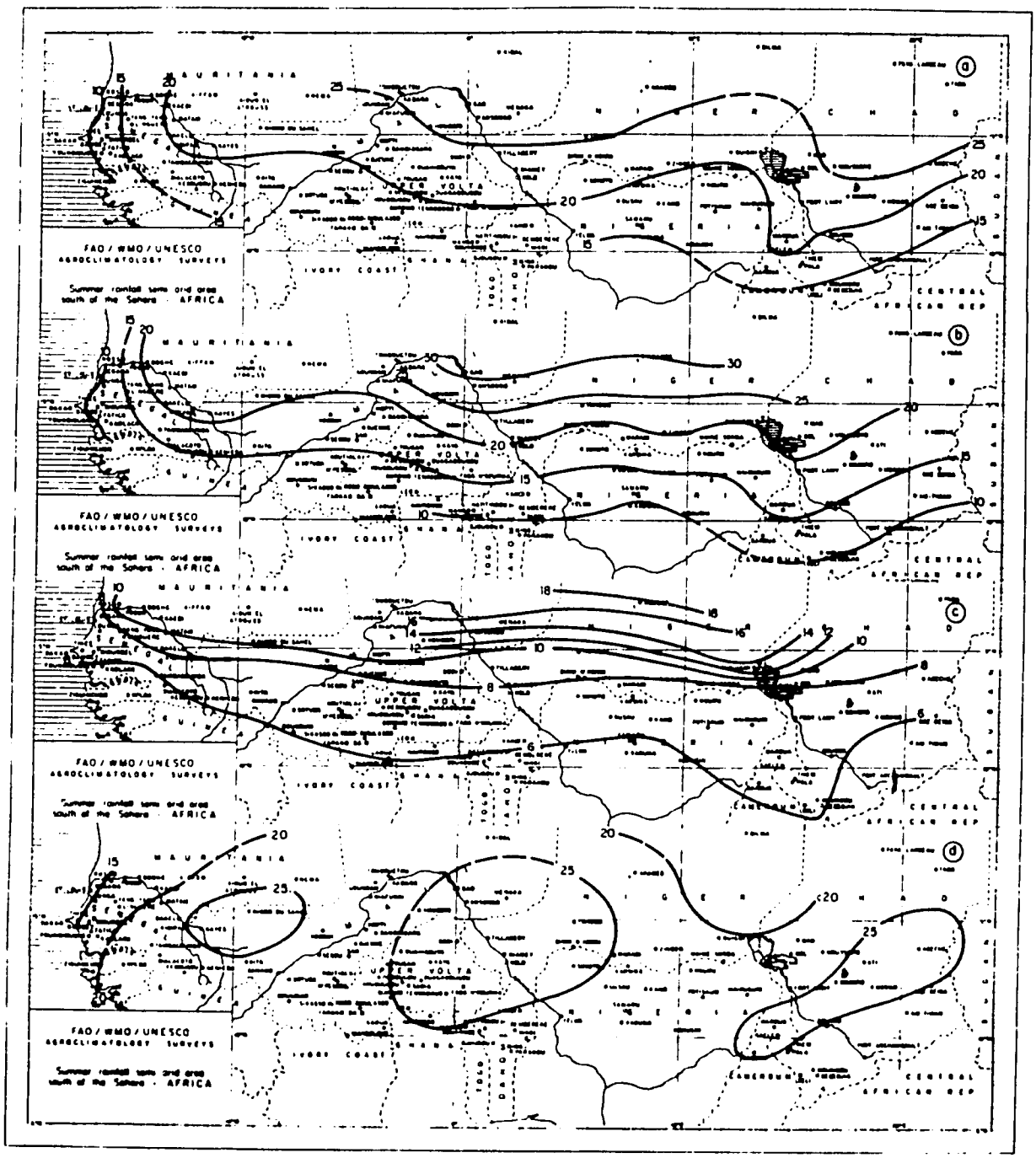

Figure 32 -- Mean saturation deficit in millibars. (a) year; (b) April-October; (c) August; (d) November-March.

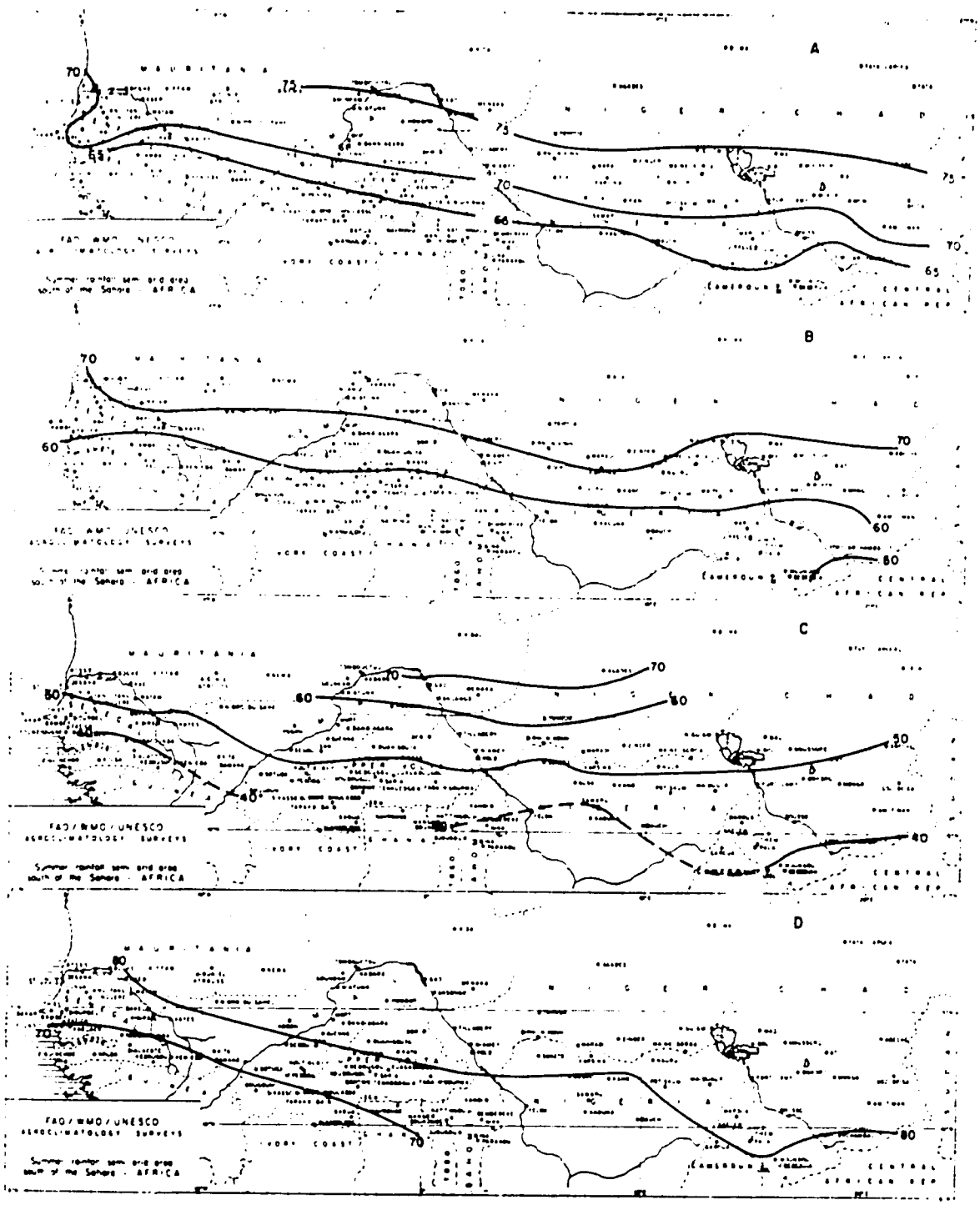

Figure 33 -- Ratio of observed to possible sunshine expressed as a percentage. (A) year; (B) summer rains season; (C) August; (D) winter. At all seasons there is an increase from south to north. The August percentages are generally the lowest and those of the winter the highest.

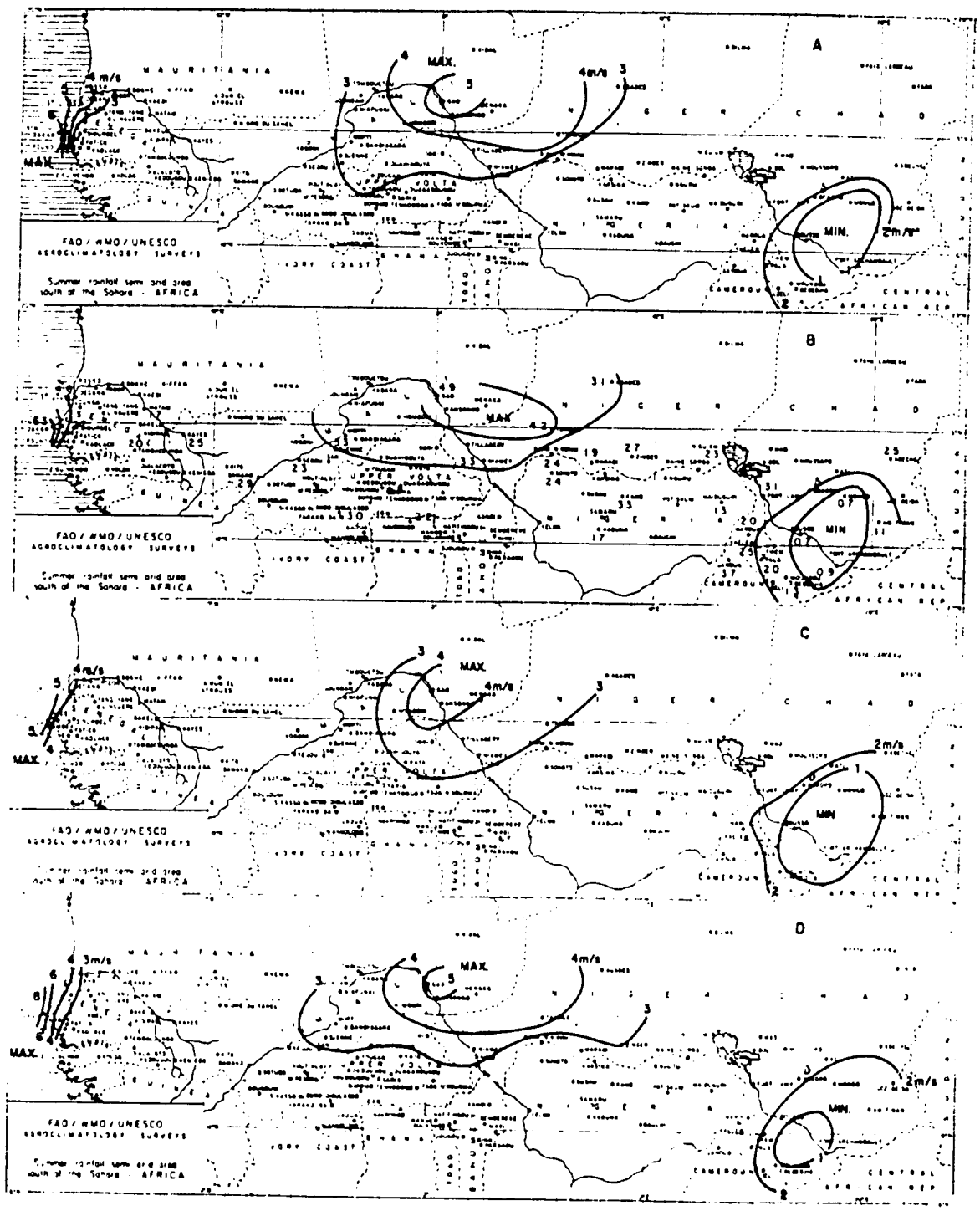

Figure 34 -- Mean scalar wind at 2 metres above the ground in metres per second. (A) year; (B) April-October, summer rains season; (C) August; (D), November-March, winter. The main features are, at all seasons, a maximum in northern Mali and another on the Atlantic coast, and a minimum in southern Chad.

TABLE 11 (a)

MONTHLY, ANNUAL AND SEASONAL MEAN POTENTIAL EVAPOTRANSPIRATION, IN MILLIMETRES

	J	F	M	A	M	J	J	A	S	O	N	D	Annual Total	A/O Total	N/M Total
Senegal															
Dakar Yoff	142.3	133.8	154.8	172.8	166.2	165.3	159.3	141.1	142.5	149.1	148.8	151.3	1827.3	1096.3	731.0
Matam	94.9	104.7	141.7	156.0	177.6	186.0	155.6	135.5	136.0	137.0	104.4	91.5	1620.9	1083.7	537.2
St. Louis	130.8	128.5	170.2	155.1	147.3	141.0	145.4	140.1	138.0	140.7	127.2	125.9	1690.2	1007.6	682.6
Tambacounda	124.6	133.3	171.7	175.8	193.1	146.1	113.7	106.3	106.2	119.0	111.6	113.7	1615.1	960.2	654.9
Thies	133.6	146.2	191.0	191.7	179.5	154.2	136.1	115.0	119.7	129.0	117.6	121.3	1724.9	1025.2	699.7
Mali															
Bamako	150.4	162.4	204.3	198.6	184.8	151.5	124.0	111.0	118.5	135.2	128.7	134.9	1774.3	1023.5	750.7
Gao	141.4	164.6	213.0	219.6	245.8	228.9	210.8	177.0	183.3	181.6	147.3	140.7	2254.0	1447.0	807.0
Kayes	134.5	139.2	185.4	196.8	216.1	177.9	144.5	118.1	124.5	133.6	122.1	121.2	1818.9	1116.5	702.4
Mapti	146.3	163.0	210.2	222.9	210.8	188.0	154.7	138.9	135.9	147.6	135.0	129.3	1953.3	1169.5	783.8
Segou	137.6	148.4	183.8	181.5	195.6	171.0	140.4	122.8	127.5	142.3	132.6	128.3	1811.8	1081.1	730.7
Nigeria															
Maiduguri	144.5	159.0	200.9	208.5	207.7	172.2	134.5	112.8	129.6	156.2	148.8	132.4	1907.1	1121.5	785.6
Sokoto	129.3	134.7	168.3	180.9	182.9	162.3	129.6	112.2	124.2	145.7	132.6	120.9	1723.6	1039.8	685.8
Kaduna	195.3	185.9	192.8	174.0	156.6	121.8	106.0	94.6	112.8	133.6	143.1	172.1	1786.6	997.4	889.2
Kano	129.3	138.9	175.8	196.5	204.6	164.1	135.8	114.7	133.2	151.3	134.7	122.1	1801.0	1100.2	700.8
Cameroon															
Maroua	130.5	151.5	184.8	179.1	179.8	141.3	122.1	104.8	111.3	140.4	134.1	129.0	1708.7	978.8	729.9
Garoua	147.3	159.0	213.0	211.8	186.6	140.7	127.7	118.7	119.4	152.8	158.4	146.6	1882.0	1057.7	824.3
Kaele	151.6	162.7	193.1	189.9	185.1	147.3	125.2	110.4	114.0	136.1	146.1	145.7	1807.2	1008.0	799.2
Ghana															
Navrongo	141.7	145.0	177.6	171.9	164.9	138.9	120.0	114.1	117.9	145.1	138.0	126.5	1701.6	972.8	728.8
Niger															
Agadès	138.0	161.0	191.0	202.5	217.9	204.3	202.4	177.9	169.8	169.0	145.2	129.9	2108.9	1343.8	761.1
Birni N'Konni	142.0	152.6	181.4	187.2	199.0	182.7	146.9	130.8	135.9	149.7	133.8	131.7	1873.7	1132.2	741.5
Maradi	116.9	122.4	153.1	166.5	186.6	176.1	144.2	121.2	130.5	134.2	114.9	107.3	1673.9	1059.3	614.6
N'Guigmi	118.7	128.5	161.2	171.6	184.4	179.4	168.3	146.0	146.4	149.7	126.3	110.7	1791.2	1145.8	645.4
Niamey	161.2	167.4	207.1	208.8	219.5	202.8	156.2	131.1	137.4	171.1	157.8	142.9	2057.3	1226.9	830.4
Tahoua	182.9	186.2	211.7	224.1	239.3	227.4	186.0	151.6	164.1	189.4	185.7	159.0	2307.4	1391.9	925.5
Zinder	137.6	153.4	184.5	191.7	198.1	184.5	157.5	127.7	146.1	167.1	144.3	129.9	1926.4	1172.7	743.7
Chad															
Am Timan	118.4	117.6	148.5	159.0	159.7	128.4	108.2	99.5	108.6	123.1	112.8	104.8	1488.6	886.5	602.1
Abéché	141.1	152.3	189.4	205.8	202.9	175.2	151.9	118.7	137.7	163.7	155.7	131.8	1926.0	1155.7	770.3
Bousso	115.9	128.7	150.7	157.8	142.0	123.3	107.6	94.9	105.9	122.8	115.2	104.5	1469.3	854.3	615.0
F.Archambault	113.2	123.2	149.7	151.2	142.9	108.6	91.5	92.7	98.7	117.2	118.2	112.8	1419.9	802.8	617.1
F.Lamy	145.7	161.6	205.8	216.3	212.4	175.2	137.3	115.9	133.2	159.2	157.2	140.4	1960.2	1149.5	810.7
Mongo	111.6	126.8	146.9	149.7	160.6	133.5	116.9	94.6	108.0	124.9	109.5	107.3	1490.6	888.2	602.4
Moundou	121.8	131.6	151.6	149.4	142.3	113.7	102.6	97.3	99.0	117.8	120.6	115.9	1463.6	822.1	641.5
Pala	128.7	134.7	169.0	164.4	147.2	125.1	111.9	103.5	106.2	132.1	163.2	130.5	1627.1	900.1	727.0
Upper Volta															
Ouagadougou	141.4	149.5	188.8	191.7	188.5	147.6	133.0	111.6	118.8	147.9	133.5	131.1	1783.4	1039.1	744.3
Bobo Dioulasso	147.6	157.4	188.2	170.7	163.1	130.5	118.2	113.7	116.4	137.3	132.7	106.1	1711.3	949.3	762.0

TABLE 11 (b)

MONTHLY MEAN POTENTIAL EVAPOTRANSPIRATION
EXPRESSED IN MILLIMETRES PER DAY

	J	F	M	A	M	J	J	A	S	O	N	D
Senegal												
Dakar Yoff	4.59	4.78	5.16	5.76	5.36	5.51	5.14	4.55	4.75	4.81	4.96	4.88
Matam	3.06	3.74	4.57	5.20	5.73	6.20	5.02	4.37	4.56	4.42	3.48	2.95
St. Louis	4.22	4.59	5.49	5.17	4.75	4.70	4.69	4.52	4.60	4.54	4.24	4.06
Tambacounda	4.02	4.76	5.54	5.86	6.23	4.87	3.67	3.43	3.54	3.84	3.72	3.67
Thies	4.31	5.22	6.16	6.39	5.79	5.14	4.39	3.71	3.99	4.16	3.92	3.59
Mali												
Bamako	4.85	5.80	6.59	6.62	5.96	5.05	4.00	3.58	3.95	4.36	4.29	4.35
Gao	4.56	5.88	6.87	7.32	7.93	7.63	6.80	5.71	6.11	5.86	4.91	4.54
Kayes	4.34	4.97	5.98	6.56	6.97	5.93	4.66	3.81	4.15	4.47	4.07	3.91
Mopti	4.72	5.82	6.78	7.43	6.80	6.29	4.99	4.48	4.53	4.76	4.50	4.17
Segou	4.44	5.30	5.93	6.05	6.31	5.70	4.53	3.96	4.25	4.59	4.42	4.14
Nigeria												
Maiduguri	4.66	5.68	6.48	6.95	6.70	5.74	4.34	3.64	4.32	5.04	4.96	4.27
Sokoto	4.17	4.81	5.43	6.03	5.90	5.41	4.18	3.62	4.14	4.70	4.42	3.90
Kaduna	6.30	6.64	6.22	5.80	5.05	4.06	3.42	3.05	3.76	4.31	4.77	5.55
Kano	4.17	4.96	5.67	6.55	6.60	5.47	4.38	3.70	4.44	4.88	4.49	3.94
Cameroon												
Maroua	4.21	5.41	5.96	5.97	5.80	4.71	3.94	3.38	3.71	4.53	4.47	4.16
Garoua	4.75	5.68	6.87	7.06	6.02	4.69	4.12	3.83	3.98	4.93	5.28	4.73
Kaele	4.89	5.81	6.23	6.33	5.97	4.91	4.04	3.56	3.80	4.39	4.87	4.70
Ghana												
Navrongo	4.57	5.18	5.73	5.73	5.32	4.63	3.87	3.68	3.93	4.68	4.60	4.08
Niger												
Agadès	4.45	5.75	6.16	6.75	7.03	6.81	6.53	5.74	5.66	5.45	4.84	4.19
Birni N'Konni	4.58	5.45	5.85	6.24	6.42	6.09	4.74	4.22	4.53	4.83	4.46	4.25
Maradi	3.77	4.37	4.94	5.55	6.02	5.87	4.65	3.91	4.35	4.33	3.83	3.46
N'Guigmi	3.83	4.59	5.20	5.72	5.95	5.98	5.43	4.71	4.38	4.83	4.21	3.57
Niamey	5.20	5.98	6.68	6.96	7.08	6.76	5.04	4.23	4.58	5.52	5.06	4.61
Tahoua	5.90	6.65	6.83	7.47	7.72	7.58	6.00	4.89	5.47	6.11	6.19	5.13
Zinder	4.44	5.48	5.95	6.39	6.39	6.15	5.08	4.12	4.87	5.39	4.81	4.19
Chad												
Am Timan	3.82	4.20	4.79	5.30	5.15	4.28	3.49	3.21	3.62	3.97	3.76	3.38
Abéché	4.55	5.44	6.11	6.86	6.54	5.84	4.90	3.83	4.59	5.28	5.19	4.25
Bousso	3.74	4.47	4.86	5.26	4.58	4.11	3.47	3.06	3.53	3.96	3.84	3.37
F.Archambault	3.65	4.40	4.83	5.04	4.61	3.62	2.95	2.99	3.29	3.78	3.94	3.64
F.Lamy	4.70	5.77	6.64	7.21	6.85	5.84	4.43	3.74	4.44	5.14	5.24	4.53
Mongo	3.60	4.53	4.74	4.99	5.18	4.45	3.77	3.05	3.60	4.03	3.66	3.46
Moundou	3.93	4.70	4.89	4.98	4.59	3.79	3.31	3.14	3.30	3.80	4.02	3.74
Pala	4.15	4.81	5.48	5.47	5.07	4.17	3.61	3.34	3.54	4.26	4.54	4.21
Upper Volta												
Ouagadougou	4.56	5.34	6.09	6.39	6.08	4.92	4.29	3.60	3.96	4.77	4.45	4.23
Bobo Dioulasso	4.76	5.62	6.07	5.69	5.26	4.35	3.94	3.79	3.88	4.43	4.28	4.39

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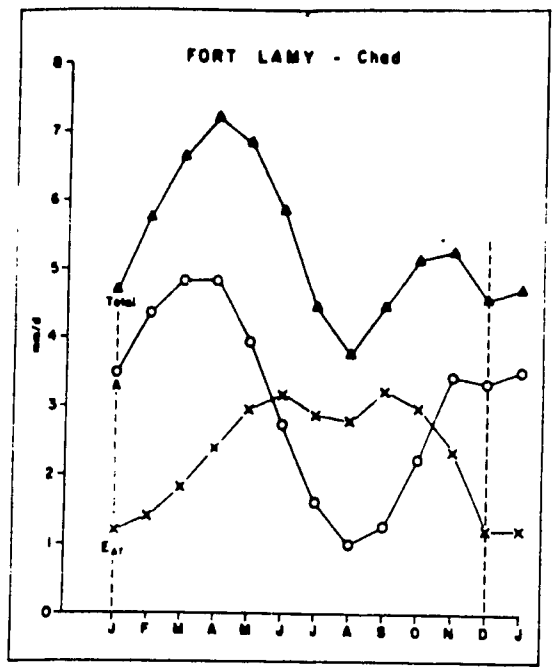

Figure 35 -- Seasonal variation of monthly mean potential evapotranspiration. A, advected energy, and E_{AT}, net energy terms.

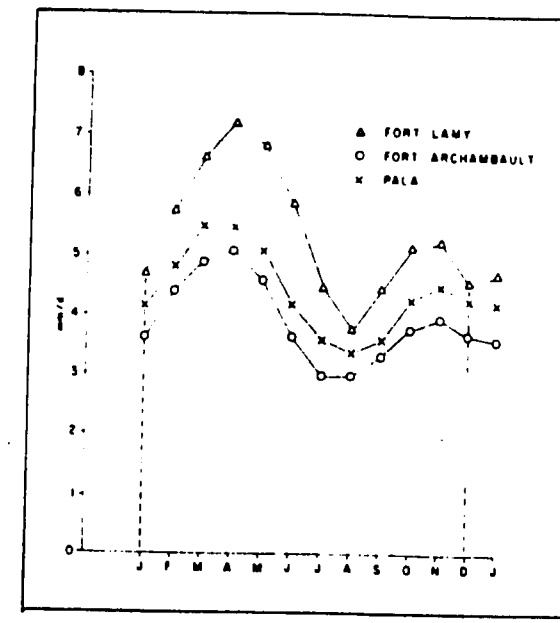

Figure 36 -- E_T at three stations in Chad, increasing in latitude from top to bottom.

2. THE WATER BUDGET

2.1 Method

The ten-year monthly mean evapotranspiration estimates were compared with monthly mean rainfall estimated from a 30-year period, to assess how rainwater is apportioned on the average. This apportioning was done numerically and with the help of histograms such as Figure 38.

Graphical smoothing made it possible to reduce the intervals of the time scale from months to as little as a day. The usefulness of this graphical estimation is reinforced by the difficulty in obtaining averages for short periods, as discussed in the section on rainfall.

The following availability-of-water parameters were obtained from this comparison:

Water deficit, WD, or excess of potential evapotranspiration over rainfall.

Water surplus, WS, or excess of rainfall over evapotranspiration.

Evaporation loss, EL, or the amount of rain falling early in the season on relatively dry soil and returned to the atmosphere without circulating through crops. It consists in fact of rain that has fallen before the beginning of the moist period (defined below). Monthly mean evapotranspiration loss was summed from estimates for shorter periods obtained from the graphical interpolation.

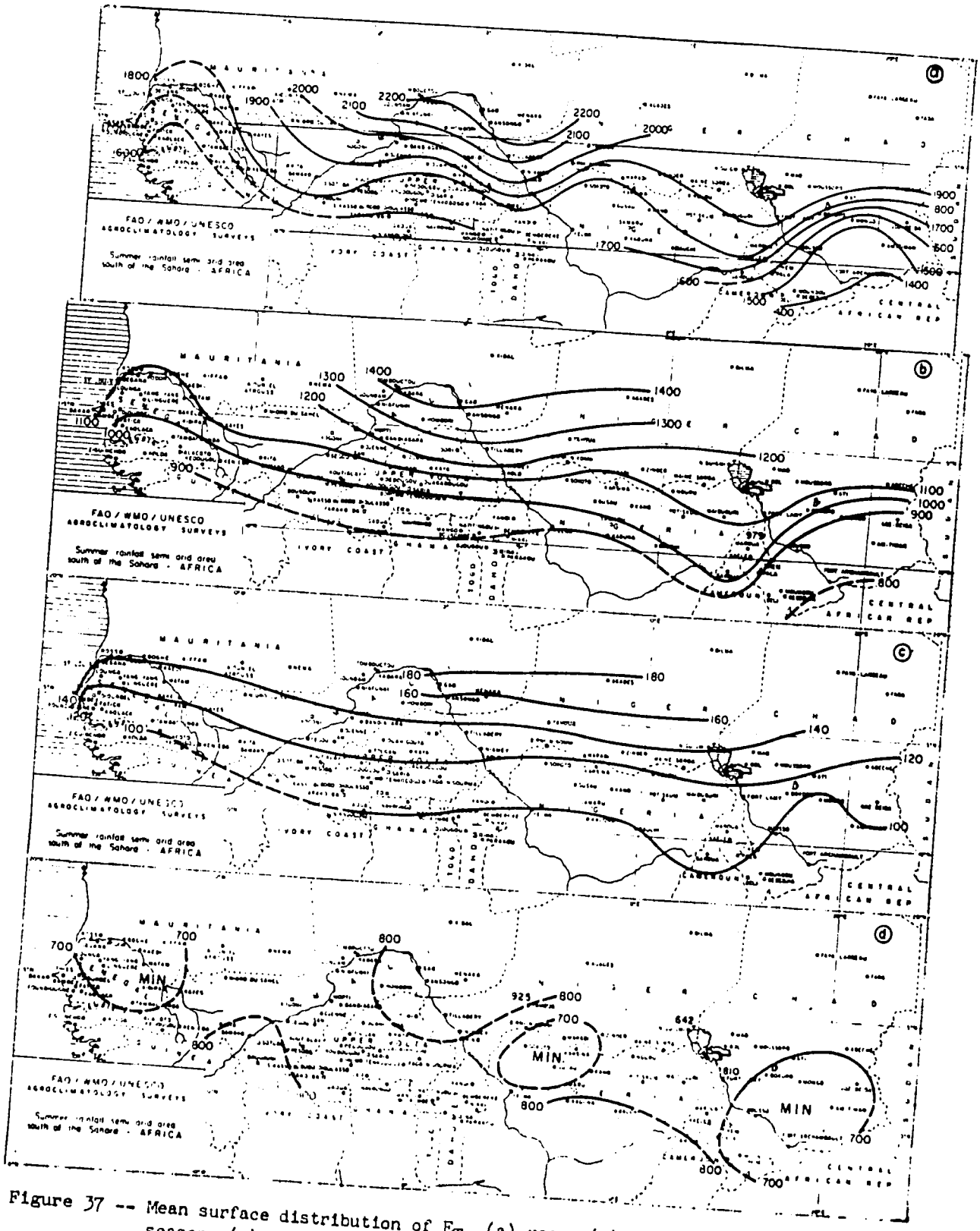

Figure 37 -- Mean surface distribution of E_T. (a) year; (b) July to October, the growing season; (c) August ; (d) November to March.

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TABLE 12

VARIABILITY OF RAINFALL AND EVAPOTRANSPIRATION AND ITS COMPONENTS FOR 1953-1962

Fort Archambault	P	E_T	T	E_d	S	W
Annual mean	1071 mm	1295 mm	27.6°C	21.8 mb	2630.7 h	2.9 m/s
Mean deviation	95.2	50.1	0.35	0.64	69.7	1.06
Relative variability	8.9%	3.9%	1.2%	2.9%	2.6%	36.5%
Maximum deviation	17.7%	10.5%	3.4%	5.2%	4.9%	49.2
Fort Archambault Month of May	**P**	**E_T**	**T**	**E_d**	**S**	**W**
Annual mean	100 mm	126 mm	29.4°C	25.6 mb	231.1 h	4.4 m/s
Mean deviation	42	8	0.63	1.16	7.98	2.1
Relative variability	42%	6.3%	2.0%	4.5%	3.4%	47.7%
Maximum deviation	73%	13.5%	4.4%	18.3%	8.3%	65.9%
Fort Lamy	**P**	**E_T**	**T**	**E_d**	**S**	**W**
Annual mean	683 mm	1789 mm	27.9°C	16.6 mb	3106 h	2.6 m/s
Mean deviation	121	72	0.31	1.17	122	0.37
Relative variability	17.7%	4%	1.1%	7.1%	3.9%	11.3%
Maximum deviation	45.0%	9%	3.6%	17.0%	9.0%	32.0%

Interannual variabilities of rainfall (P), evapotranspiration (E_T), temperature (T), vapour pressure (E_d), hours of sunshine (S), and wind speed (W).

It was assumed that the maximum amount of water which could be stored in the ground, to be made available later to the crops, was 100 mm. It is realized that this storage capacity varies with the texture and structure of the soil, as already discussed in Part I. Specific storage capacity can only be taken into account in a local study.

Ground charge (the amount of water entering the ground to be stored) and ground storage (the amount stored up to the assumed maximum) were both estimated.

Runoff, RO, is the water surplus left over after the ground has been fully charged. As calculated, it also includes deep drainage for which no assumptions were made.

Effective precipitation, EP, is water surplus minus evaporation loss and runoff; in other words, the mean amount of water deemed to have been made available to crops.

Mean annual and monthly amounts for these parameters for each station were tabulated as shown in Table 13.

2.2 Availability-of-water periods

Using the graphical interpolation of monthly mean evapotranspiration and rainfall, together with lines for the values $E_T/2$ and $E_T/10$, the number of days during which rainfall equalled or exceeded E_T, $E_T/2$ and $E_T/10$ was estimated. These availability-of-water periods were designated as follows:

Humid, when rainfall exceeds potential evapotranspiration.

Moist, when rainfall exceeds half potential evapotranspiration.

Intermediate, pre-humid and post-humid. The transition between moist and humid.

Taking water stored in the ground into consideration gave:

Moist plus reserve, and intermediate post-humid plus reserve.

Finally, the period extending between the points $E_T/10$ and $E_T/2$ at the beginning of the season was called preparatory.

2.3 Ratios and indices

Several ratios and indices were also considered:

P/M or annual rainfall divided by the length of the moist period in days.

EP/M, mean daily effective use of the rainfall during the moist period.

WS/P, RO/P and $EP/_P$, which may be looked upon as an index of rainfall efficiency.

The index of aridity devised by Thornthwaite, $\frac{60WD - 100WS}{ET}$, was also estimated, but using Penman's E_T.

In Table 14 (b) the mean values of these various parameters and indices at the 35 reference stations are given.

2.4 Agronomic meaning and range in the Area of these parameters and indices

It will be as well to bear in mind initially that here it is the atmospheric climate, applicable to fairly wide regions, which is being discussed so that the water budget involved is not only an average budget but a theoretical one.

Actual or real water budgets need to be studied in conjunction with a particular crop, on a particular soil, during a given year, and in terms of shorter intervals. This type of study is more agrometeorology than agroclimatology.

Between these two extremes, models may be constructed simulating water budgets for typical crops and soils. This work belongs to more detailed studies in agroclimatology.

The general aim should be to obtain models gradually closer to actual crop production. The general, theoretical approach must come first.

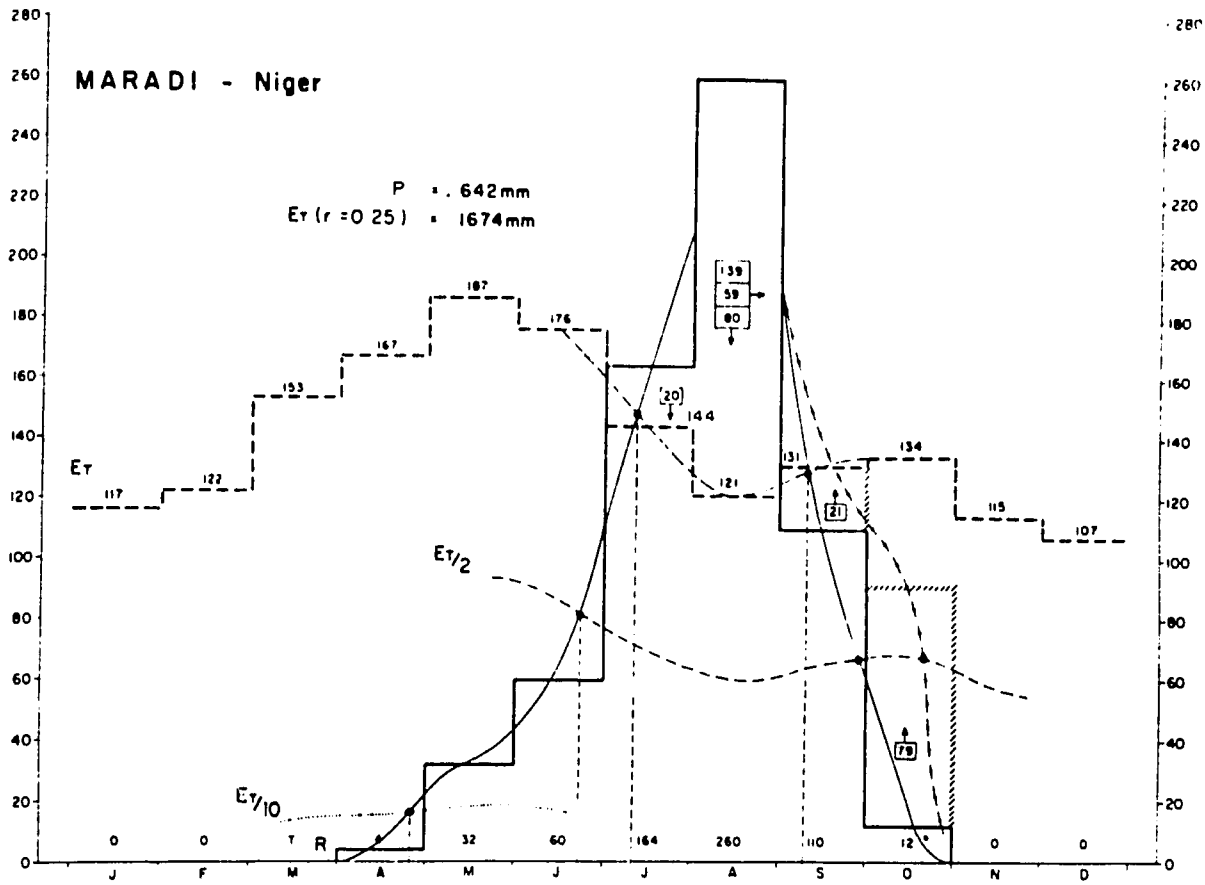

Figure 38 -- Monthly mean histograms of rainfall (plain line) and potential evapotranspiration (broken line) with smoothing for interpolation and comparison. Storage is indicated by a diagonally hatched histogram.

The point $P = E_T/10$ defines the beginning of the preparatory period which ends with the beginning of the first intermediate period. The two $P = E_T$ points limit the humid period. The first $P = E_T/2$ and the first $P = E_T$ points limit the first intermediate period. The second intermediate period without storage extends from the end of the humid period (second $P = E_T$ point) to the second $P = E_T/2$, and with storage to a point $P + st = E_T/2$ determined by the rainfall plus storage line (dashes with dots). The first and second intermediate and the humid periods together form the moist period, which can be considered with or without storage.

TABLE 13

TABULATION OF MONTHLY MEAN WATER BUDGET

Water Budget	MARADI Niger									Prep 54	Moist : 100				M+S= 123	Coefficients
											1st I= 20	Humid = 62		2nd I= 18	2nd I+S= 41	
	E_T r=25	P	Water deficit	Evap	Water surplus	Ground charge	Ground storage	Run off	Effect rainfall	B of P.	B of M.	B of H.	E of H	E of M	E of M+S	
January	117	0	117													
February	112	0	112													$\frac{P}{M} = 5.4$
March	153	0	153													
April	167	4	163	4						30th						$\frac{EP}{M} = 4.3$
May	187	32	155	32												$\frac{P}{E_T} = .38$
June	176	60	116	30					30		22nd					
July	144	164			20	20	20		144			11th				$\frac{WS}{P} = .25$
August	121	260			139	80	100	59	121							$\frac{EP}{P} = .81$
September	131	110	21			-21	79		131				10th	27th		
October	134	12	122			-79	0		91						20th	$\frac{RO}{P} = .09$
November	115	0	115													Thornthwaite/Penman index
December	107	0	107													
Year	1674	642	1181	66	159			59	517							HU +.09 | + 09 AR -.71 | - 43 Moisture - 34

N O T E: E_T is potential evapotranspiration, and P rainfall. All depths are given in millimetres. The lengths of the availability-of-water periods are given in days. The numbers in the columns corresponding to the periods are the days of the months for beginning or end of these periods. Bottom right, WS/ET (HU) and WD/ET (AR) are multiplied by 100 and 60 respectively and added to yield the moisture index.

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2.4.1 Water deficit

Water deficit is the amount of water which would need to be brought to a locality annually for continuous food production (in fact the maximum amount, since anything in excess would be wasted). This deficit occurs everywhere in the Area. It is greater, reckoned month by month, as it is here, because of the occurrence, during the humid months, of a surplus, which swells yearly figures.

Over shorter periods, the deficit would be greater still -- particularly, for instance, in the case of a daily budget. It would be possible to obtain maximum values for this deficit by considering rainfall intensities actually recorded -- from which maximum runoff could be calculated, but local topography and permeability of the soil would have to be taken into account.

At the monthly scale, water deficit ranges from 1,500 mm in the north to 900 mm in the south, although there the difference between annual rainfall and E_T may be as little as 300 mm.

2.4.2 Water surplus

Although rainfall nowhere exceeds E_T on a yearly basis, water surplus also occurs everywhere in the Area on a monthly basis. In fact its absence may be taken to coincide with the northern limits, the range being from 0 to about 500 mm in the south.

The agronomic meaning of water surplus is connected with that of runoff. The spatial distribution of these two quantities is illustrated in Figure 39.

2.4.3 Runoff

Runoff, as far as dry farming is concerned, may be looked upon as a water loss. It is a quantity which goes to reduce effective rainfall. On the other hand it may have beneficial effects either in the extreme north of the Area where the scanty rainfall is accumulated in drainage basins, or where, in conjunction with deep soils and long-rooted crops, it makes possible the establishment of perennial pastures.

Runoff, as estimated in this climatic analysis, begins to occur where mean annual rainfall exceeds 500 mm. It reaches a maximum of 450 mm in the south of the Area (enough to ensure continuous crop production at an acceptable rate of actual evapotranspiration if stored and spread appropriately over the year.

It is realized that actual runoff depends on rainfall intensities for very short intervals of time. Nevertheless, it is thought that the monthly estimates of this study have a basic and practical meaning.

Evaporation loss varies between 25 and 90 mm in the Area, being highest in the north where the rain is least.

2.4.4 Ratios and indices

The spatial distribution of effective rainfall and rainfall efficiency index EP/p are shown together in Figure 40.

Effective rainfall may be looked upon as a form of cumulative evapotranspiration. It is nearer to actual evapotranspiration values than sums of potential evapotranspiration accumulated for the duration of the growing season. During the humid period, the actual

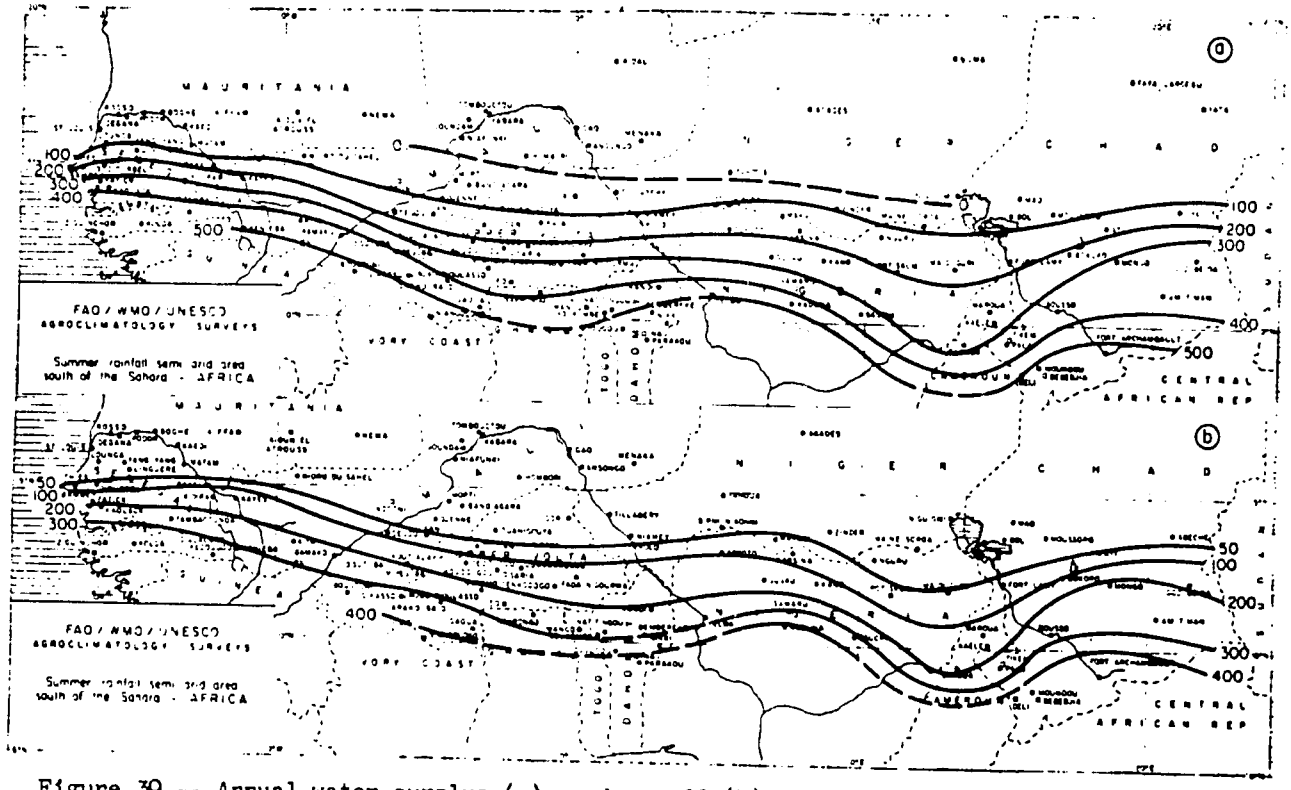

Figure 39 -- Annual water surplus (a), and runoff (b), estimated on a monthly basis.

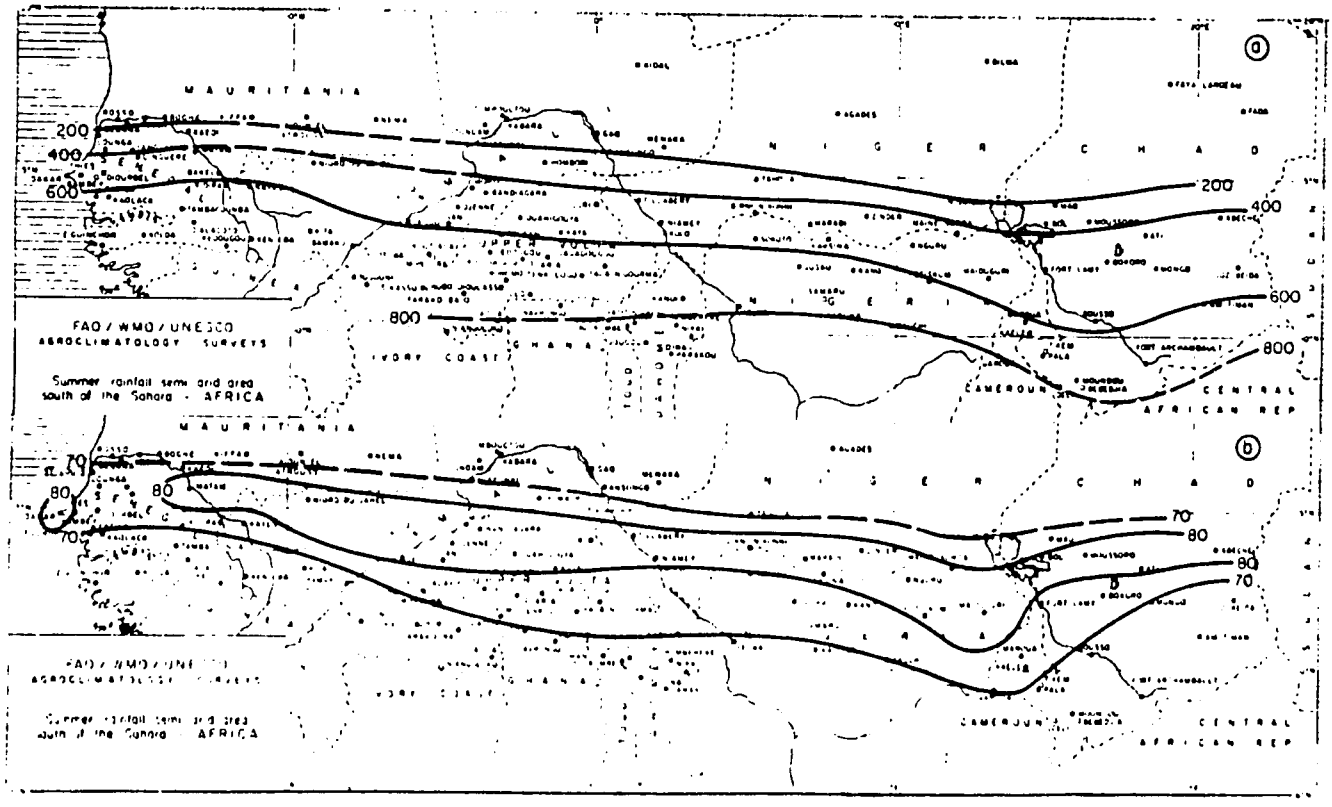

Figure 40 -- (a) Annual effective rainfall in mm estimated on a monthly basis, and (b) rainfall efficiency index EP/p.

evapotranspiration from a dense crop, the potential evapotranspiration E_T, and the effective rainfall will be the same. During the pre-humid period, rainfall is practically all used up by a fast developing and well-tended crop. It may also be argued that the rainfall occurring during the post-humid period, plus the amount stored in the ground, approximate to actual use during that period, and therefore to effective rainfall.

Annual effective rainfall is about 800 mm in the south of the Area, and 200 mm at the northern limit.

It is interesting to note that the rainfall efficiency index is highest, 80 per cent, along a central zone of about 600 mm rainfall. To the north it is reduced by evaporation loss, and to the south by excessive rainfall.

Of the other ratios, $P/_{ET}$, which varies from 0.2 in the north to 0.8 in the south, is discussed again in conjunction with pastures. A Thornthwaite index of aridity computed using Penman's E_T, partly out of historical interest, gives a range of -50 to zero for the Area.

$P/_M$ is fairly constantly equal to 5.5 mm per day in the Area. This provides an easy way of estimating the length of the moist period from annual rainfall, a better-known parameter. $EP/_M$ is slightly more variable than $P/_M$, since $EP/_P$ varies, but does not depart very far from 4 mm per day.

2.5 Agronomic meaning of the availability-of-water periods

The availability-of-water periods appear to be the water budget parameters of greatest agronomic interest in the Area.

The dates of their beginning and end at the 35 reference stations, and their duration in days, are all obtained by the graphical interpolation method, and are given in Table 14 (a).

2.5.1 The preparatory period

During the preparatory period, the ground is prepared for sowing. It is in general too soon to sow without undue risk of long dry spells which the seedlings could not survive.

Exceptions occur, in the north of the Area, where the growing season is very short; with crops which are particularly resistant to early drought; and with crops which have fine seeds, like millet or cotton, sowing at a rate of about 30 kg/ha, when the cost of resowing is relatively small. It will be noticed that all these three considerations apply to millet.

The duration of the preparatory period varies considerably in the Area, and the variations are neither zonal nor regular (Figure 41). It may last between more than 50 and less than 20 days. The longest periods are found around the 600 mm isohyet in a central zone in the eastern half of the Area. Generally, it decreases northwards with the length of the rains, and southwards, where more frequent rains soon take rainfall beyond the point $E_T/2$. The period is seen to be very much shortened in Senegal. This implies that a larger pool of labour and machinery would be needed there to prepare the same area of ground as in Niger. Moreover, where it is intended to lengthen the growing season by pre-humid irrigation, the possibilities are more favourable in Niger.

The timing of the onset is distributed zonally but retarded in the west (Figure 41).

TABLE 14 (a)

PLACE	Date							Number of days						
	P	B of Pr	B of M	B of H	E of H	E of M	E of M+S	Pr	I_1	H	I_2	M	S	M+S
Agadès	164	-	-	-	-	-	-	-	0	0	0	0	0	0
N'Guigmi	235	20.VI	23.VII	-	-	3.IX	3.IX	33	-	0	-	42	-	(42)
Gao	261	27.V	2.VIII	-	-	25.VIII	25.VIII	67	-	0	-	23	-	(23)
St.-Louis	346	21.VI	22.VII	7.VIII	25.VIII	28.IX	2.X	31	16	18	34	68	4	72
Tahoua	406	26.V	6.VII	-	-	8.IX	8.IX	41	-	0	-	64	-	(64)
Abéché	505	9.V	29.VI	18.VII	4.IX	15.IX	1.X	51	19	48	11	78	16	94
Matam	535	4.VI	30.VI	22.VII	9.IX	30.IX	17.X	26	23	49	21	93	17	110
Mopti	552	16.V	25.VI	15.VII	7.IX	27.IX	8.X	40	20	54	20	94	11	105
Zinder	548	5.V	25.VI	16.VII	4.IX	15.IX	3.X	50	21	50	11	82	18	100
Dakar Yoff	578	15.VI	9.VII	25.VII	20.IX	9.X	29.X	24	16	57	19	92	20	112
Birni N'Konni	600	4.V	23.VI	19.VII	8.IX	23.IX	22.X	50	26	51	15	92	29	121
Niamey	638	28.IV	20.VI	10.VII	6.IX	24.IX	16.X	53	20	58	18	96	22	118
Maradi	642	30.IV	22.VI	11.VII	10.IX	27.IX	20.X	53	19	61	17	97	23	120
Fort-Lamy	648	I.V	20.VI	10.VII	10.IX	26.IX	18.X	50	20	62	16	98	22	120
Maiduguri	659	3.V	17.VI	5.VII	11.IX	29.IX	17.X	45	18	68	18	104	18	122
Thiès	694	6.VI	30.VI	18.VII	1.X	13.X	8.XI	24	18	74	13	105	25	130
Segou	724	15.V	13.VI	2.VII	17.IX	30.IX	20.X	29	19	77	13	109	20	129
Sokoto	734	19.IV	10.VI	5.VII	21.IX	3.X	20.X	52	25	78	12	115	15	130
Kayes	821	15.V	11.VI	3.VII	21.IX	11.X	1.XI	27	22	80	20	122	21	143
Maroua	841	19.IV	25.V	22.VI	25.IX	6.X	24.X	36	28	95	11	134	18	152
Mongo	858	18.IV	16.VI	28.VI	25.IX	8.X	29.X	59	12	89	13	114	21	135
Kano	871	23.IV	28.V	25.VI	16.IX	30.IX	19.X	35	27	83	14	124	19	143
Kaélé	878	6.IV	24.V	21.VI	26.IX	8.X	20.X	48	27	97	12	136	12	148
Ouagadougou	882	15.IV	22.V	24.VI	22.IX	6.X	28.X	37	33	90	14	137	22	159
Am-Timan	919	10.IV	17.V	20.VI	24.IX	9.X	29.X	37	34	96	15	145	20	165
Bousso	931	14.IV	25.V	18.VI	28.IX	10.X	2.XI	41	24	102	12	138	23	161
Tambacounda	941	15.V	2.VI	19.VI	6.X	20.X	12.XI	18	17	109	14	140	23	163
Garoua	1013	I.IV	6.V	9.VI	1.X	14.X	1.XI	36	34	114	13	161	18	179
Pala	1044	28.III	8.V	5.VI	4.X	20.X	9.XI	41	28	121	16	165	20	185
Navrongo	1095	17.III	2.V	13.VI	3.X	14.X	2.XI	46	42	112	11	165	19	184
Bamako	1099	19.IV	26.V	17.VI	2.X	14.X	6.XI	37	22	107	12	141	23	164
F.-Archambault	1141	23.III	2.V	1.VI	8.X	23.X	17.XI	43	27	129	15	171	25	196
Bobo Dioulasso	1185	14.III	1.V	15.VI	3.X	17.X	6.XI	48	45	110	14	169	20	189
Moundou	1228	27.III	27.IV	24.V	11.X	27.X	21.XI	31	27	140	16	183	25	208
Kaduna	1298	19.III	22.IV	20.V	9.X	21.X	10.XI	34	28	142	12	182	20	202

To the left, mean dates of beginning and end of the availability-of-water periods at the 35 reference stations. The stations are arrayed in order of increasing mean annual rainfall listed in column P. Listed under B of Pr are the dates of the beginning of the preparatory period, and under E of M+S those of the end of the moist period with storage. M stands for moist period and H for humid period. To the right, mean number of days of those periods. I_1 is the pre-humid intermediate period and I_2 the post-humid. S is the number of days which can be added to M or I_2 owing to storage. Where there was no humid period M+S is in brackets.

TABLE 14 (b)

	Pot. Transp. (r=0.75) E_T mm	Rainfall P mm	Water Deficit WD mm	Evap. Loss EL mm	Water Surplus WS mm	Run-off RO mm	Effect. rainfall Ei mm	Moist plus storage M+S Days	P/M+S	EP/M+S	P/E_T	WS/P	EP/P	RO/P	Moisture Index Th
Agadès	1832	164	1669	164	0	0	0	0	-	-	0.09	-	-	-	-54
N'Guigmi	1808	235	1573	42	0	0	193	(42)	5.6	4.6	0.13	-	0.73	-	-52
Gao	2255	261	1994	151	0	0	110	(25)	10.4	4.4	0.12	-	0.42	-	-53
St.-Louis	1686	346	1361	88	21	0	258	72	4.8	3.6	0.21	0.06	0.74	-	-48
Tahoua	2307	406	1901	112	0	0	294	(64)	6.3	4.6	0.18	-	0.72	-	-49
Abéché	1927	505	1535	51	113	13	441	94	5.4	4.6	0.26	0.22	0.86	0.03	-42
Matam	1619	535	1150	90	67	0	445	110	4.9	4.1	0.33	0.12	0.83	-	-39
Mopti	1984	552	1488	49	56	0	503	105	5.3	4.8	0.28	0.10	0.87	-	-42
Zinder	1924	548	1480	62	104	4	482	100	5.5	4.8	0.28	0.19	0.88	0.01	-41
Dakar Yoff	1825	578	1375	51	128	28	499	112	5.2	4.5	0.32	0.22	0.83	0.05	-38
Birni N'Konni	1875	600	1376	71	101	1	528	121	5.0	4.4	0.32	0.17	0.88	-	-39
Niamey	2057	638	1519	93	100	0	545	118	5.4	4.6	0.31	0.16	0.85	-	-39
Maradi	1674	642	1191	66	159	59	517	120	5.4	4.3	0.38	0.25	0.81	0.09	-34
Fort-Lamy	1958	648	1470	78	160	60	510	120	5.4	4.3	0.33	0.25	0.79	0.09	-37
Maiduguri	1910	659	1410	62	159	59	538	122	5.4	4.4	0.35	0.24	0.81	0.07	-36
Thiès	1726	694	1276	33	244	144	517	130	5.3	4.0	0.40	0.35	0.74	0.21	-30
Segou	1823	724	1277	57	178	78	589	129	5.6	4.6	0.40	0.25	0.81	0.11	-33
Sokoto	1724	734	1188	91	198	98	545	130	5.6	4.2	0.43	0.27	0.74	0.13	-30
Kayes	1820	821	1252	53	253	153	615	143	5.7	4.3	0.45	0.31	0.75	0.19	-27
Maroua	1709	841	1145	50	277	177	614	152	5.5	4.0	0.49	0.33	0.73	0.21	-24
Mongo	1491	858	1000	75	367	267	516	135	6.4	3.8	0.57	0.43	0.60	0.31	-15
Kano	1802	871	1204	51	273	173	647	143	6.1	4.5	0.48	0.31	0.74	0.20	-25
Kaélé	1807	878	1193	72	264	164	642	148	5.9	4.3	0.49	0.30	0.73	0.19	-25
Ouagadougou	1786	882	1151	82	247	147	653	159	5.6	4.1	0.49	0.28	0.74	0.17	-25
Am-Timan	1514	919	913	92	318	218	609	165	5.6	3.7	0.61	0.35	0.66	0.24	-15
Bousso	1472	931	940	48	399	299	584	160	5.8	3.6	0.63	0.43	0.63	0.31	-11
Tambaoounda	1616	941	1065	22	390	290	629	163	5.8	3.9	0.58	0.41	0.67	0.31	-15
Garoua	1882	1012	1132	74	264	164	775	179	5.7	4.3	0.54	0.26	0.80	0.16	-22
Pala	1598	1044	930	72	376	276	696	185	5.6	3.8	0.65	0.36	0.67	0.26	-11
Navrongo	1703	1095	954	72	346	246	777	184	6.0	4.2	0.64	0.32	0.71	0.22	-14
Bamako	1804	1099	1156	49	451	351	699	164	6.7	4.3	0.61	0.41	0.64	0.32	-13
F. Archambault	1421	1141	793	23	512	412	706	198	5.8	3.6	0.80	0.45	0.62	0.29	+ 2
Bobo Dioulasso	1712	1185	956	73	429	329	783	189	6.3	4.8	0.69	0.36	0.66	0.28	- 9
Moundou	1465	1228	793	42	555	455	731	208	5.9	3.5	0.84	0.45	0.60	0.37	+ 6
Kaduna	1793	1298	1037	52	542	442	804	202	6.4	4.0	0.72	0.42	0.62	0.34	- 5

Mean annual water budget parameters and coefficients of the 35 reference stations arrayed in increasing order of mean annual rainfall. All the amounts listed on the right are in millimetres of water. WD, WS, EL, RO and EP are worked out on a monthly basis. From amongst the coefficients on the left, it is seen that P/M+S and EP/M+S are fairly constant. EP/P, the rainfall efficiency index, is highest around 600 mm mean annual rainfall. The moisture index is derived from Thornthwaite's formula, 60WD+100WS/E_T, but using E_T values obtained by Penman's method.

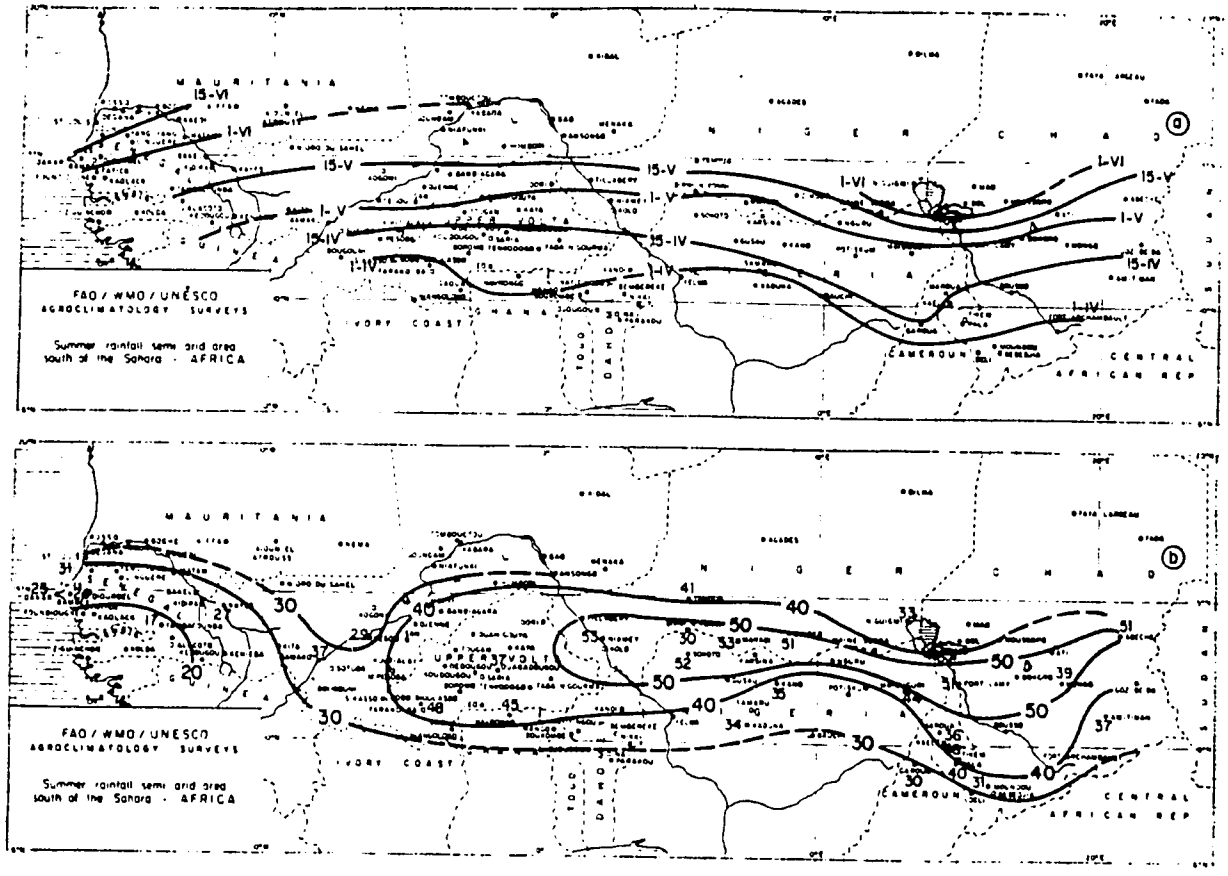

Figure 41 -- (a) Isochrones of mean date of beginning of period; (b) mean duration in days.

2.5.2 The humid period

The humid period is one of active growth and development, when actual evapotranspiration matches potential values. It is worth noting that during the period E_T has dropped to amounts around 4 mm a day, well within the water conduction means of the crops.

It is also the best time for crops to flower. Those with terminal inflorescences, such as cereals, give the best yields when flowering occurs shortly before the end of the period, and for those with axial flowering, such as groundnut, useful flowering — that is production of flowers of which the fruits will be gathered — should take place entirely during it.

In the Area, the humid period varies in length from zero in the north to 140 days in the south. The spatial distribution of this length is shown in Figure 42 (c) where it is seen to be zonal, in unison with rainfall. In the same diagram, the distribution of the beginning and end of the period is also illustrated by means of fortnightly isochrones. It is equally zonal in both cases, with slight retardation in Senegal, but not as important as that affecting the preparatory period.

It is of course during the humid period that surplus and runoff occur at the monthly scale, and absence of actual drainage away from the surface might be an adverse climatic factor, giving waterlogging.

Isochrones of the beginning and end of the humid period are shown in Figure 42 (a) and (b), stretching from first of June in the south and first of August in the north, to first of October in the south and first of September in the north.

2.5.3 The intermediate periods

Both intermediate periods are, on the average, of fairly constant duration throughout the Area: 25 days for the pre-humid and 15 for the post-humid. They are the periods during which rainfall is most variable and critical, for vegetative growth in the first case and ripening of fruit in the second.

The beginning of the first intermediate period appears to be the best time for sowing (with the reservation made about sowing during the preparatory period) and, traditionally, it is the time when sowing most commonly takes place. The first intermediate and the humid period taken together therefore represent approximately the time from sowing to heading of cereals.

2.5.4 The moist period

The moist period, compounded of the humid and the intermediates, will therefore have a range of 40 to 180 days, which is extended to 55 to 200 if reserve is taken into account.

Isochrones of its beginning and end, without and with reserves, are shown in Figure 43, together with the surface distribution of its duration in ten-day periods. It is the climatic parameter most directly comparable with the growing cycle of crops from seed to seed when the extra days for water stored in the ground are included. Examples of this close relationship will be given in Part III.

2.5.5 Conclusions

In the semiarid Areas the main adaptation of crops to their environment seems to be a matching of the growing cycle and its main biological events to the moist period with reserve and its main climatic events. The unfolding of the various periods over the Area is summarized diagrammatically in Figure 44, where the 35 reference stations are arrayed in order of magnitude of mean annual rainfall. The relative symmetry of the availability-of-water periods throughout the Area is well illustrated: the constancy of the intermediate periods and the gradual increase in the humid. The main departure from this position is the lag shown by stations in the extreme west.

2.6 Variability

A sample study of the departures from the average length of availability-of-water periods at Zinder, in Niger, for the period 1931-1960, was carried out. Rainfall for ten-day periods was compared with mean potential evaporation which, being the more conservative element, was taken to be constant. An example of the thirty-yearly diagrams is shown in Figure 45.

The frequency of occurrence of the beginning of the moist and humid period estimated to the nearest ten days is shown in Table 15. The beginning of the moist season is spread over two months and fairly normally distributed around a mean date of 6 July. This date is brought forward, close to 25 June, obtained with the smoothed monthly mean histograms, if the false starts (presently to be discussed) are taken into account.

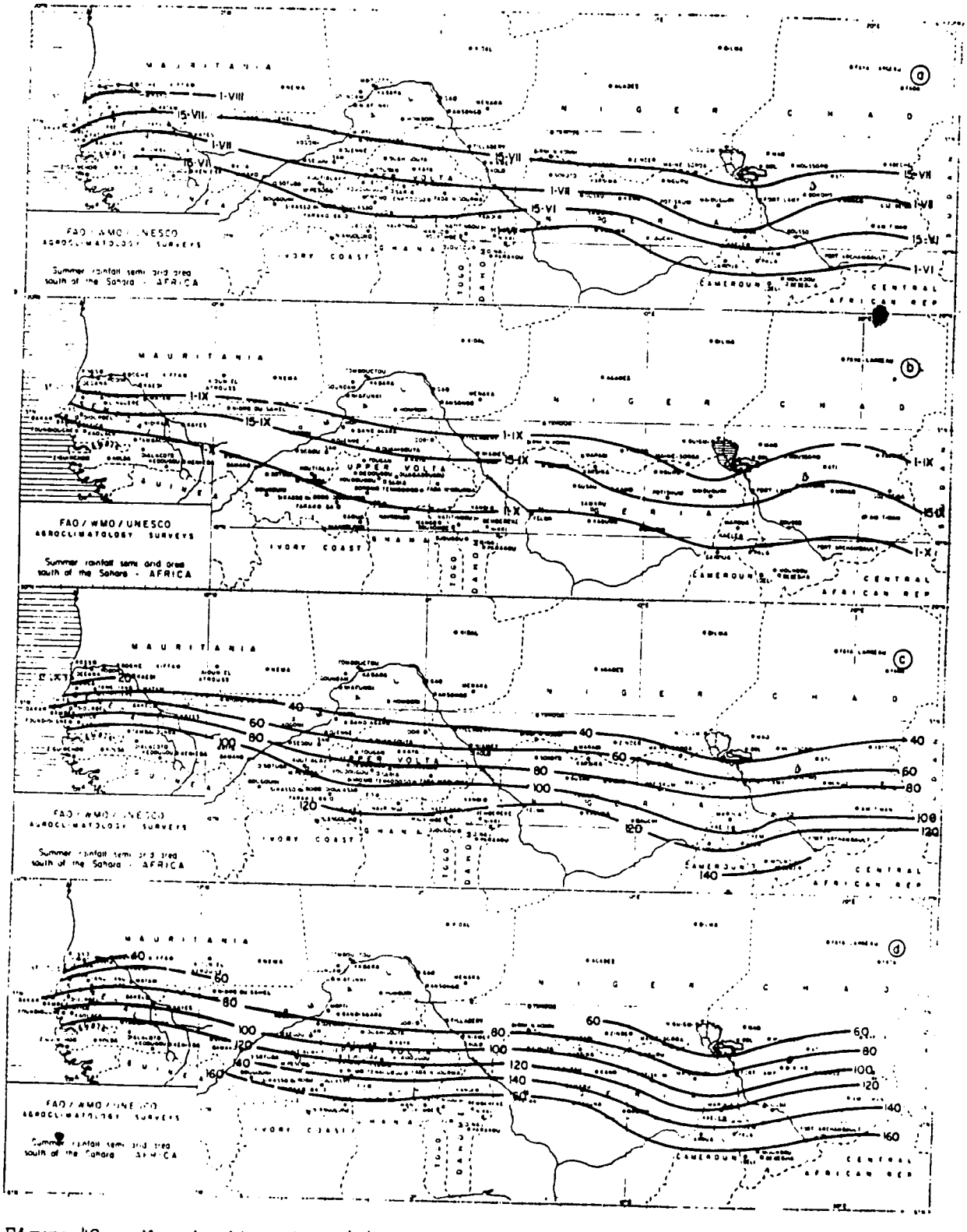

Figure 42 -- Mean humid period. (a) isochrones of the beginning; (b) isochrones of the end; (c) duration; (d) duration of the first intermediate plus humid period.

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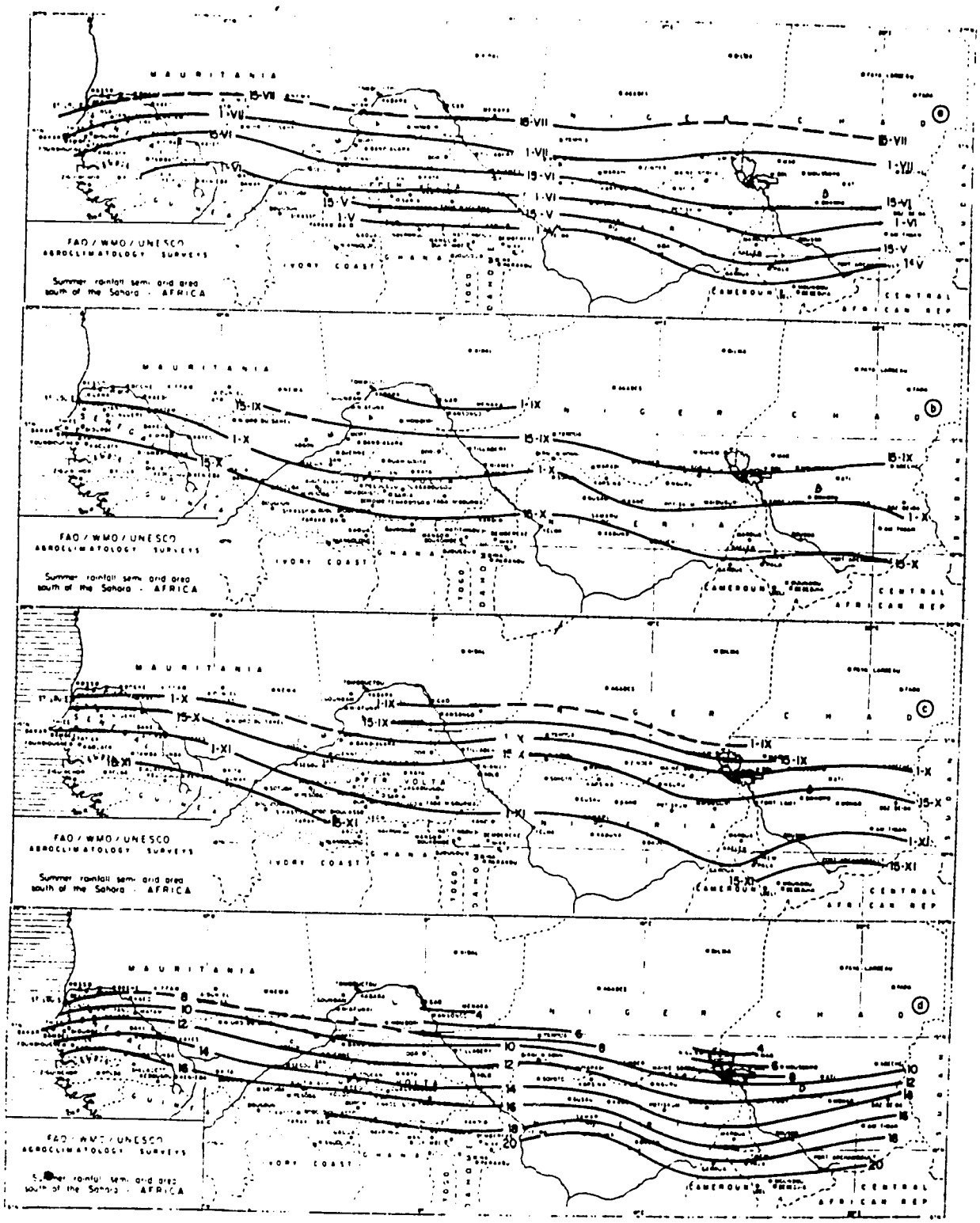

Figure 43 -- Mean moist period. (a) isochrones of the beginning; (b) isochrones of the end; (c) isochrones of the end taking ground reserve into consideration; (d) duration.

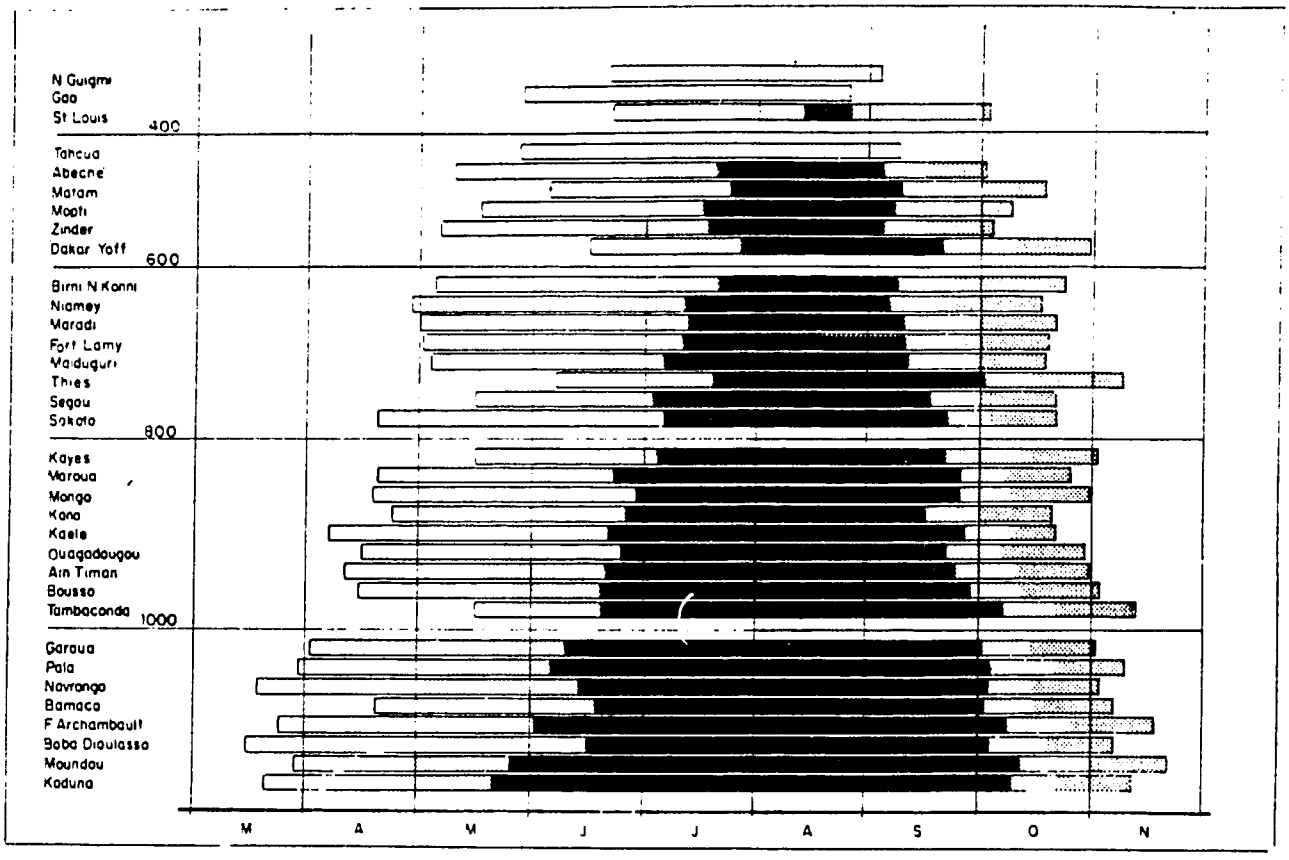

Figure 44 -- Diagrammatic summary of availability of water periods in the Area. From left to right: preparatory, intermediate, humid (darkest), intermediate, intermediate with storage. Notice the lag of Thies and other stations in the west.

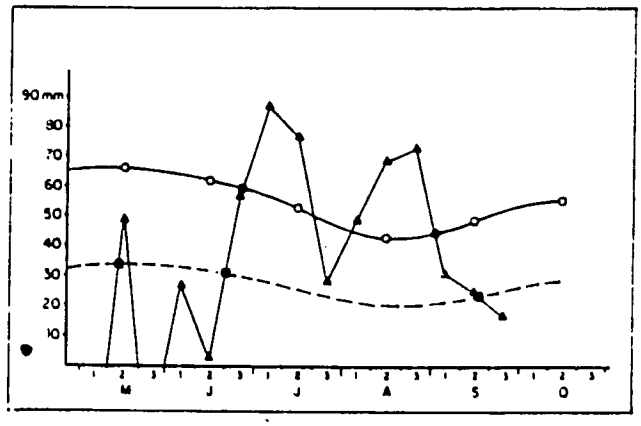

Figure 45 -- Comparison of mean E_T and $E_T/2$ (curved lines) for the period 1952-63 with ten-day rainfall for the year 1960. Black squares mark beginning and end of moist period and a white square the beginning of a false start. Black circles indicate the beginning and end of humid period.

The beginnings of the humid periods are more closely and normally distributed and their mean date, 15 July, is practically the same as that obtained with the smoothed monthly histograms. Empirically, it may be stated the humid period will begin in July three years out of four.

2.6.1 False starts

A false start was deemed to have occurred when the water balance reverted to less than preparatory values.

Such false starts to the moist period occurred 14 years out of 30. However, there were only four in June and one during its last decade. This suggests that false starts to the moist period are mainly the result of an early beginning of the rains. Indeed, since no false starts occurred after the mean date of beginning of the moist season, it can be said empirically that, when the moist season begins after its mean date, it is totally safe for sowing. There were no false starts to the humid period.

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HEAT AND LIGHT

1. RADIATION

1.1 General considerations

Solar radiation is of interest to us since it is the source of the different forms of energy used by crops for their metabolic processes and, eventually, dry matter production.

The various transformations of the energy radiated by the sun and, in its turn, by the earth, have been discussed in detail by physicists of many disciplines, and diagrammatic representations of the energy apportioning may be found in the works of Geiger (1965, 4th ed. tr.) and, more recently, of Angus (1959).

Here we are more particularly interested in the global radiation at crop level, of which a small part (2-4 per cent) controls photosynthesis, and in the net energy available at the surface of the earth to warm it and the air near it, and also to evaporate water.

1.2 Incoming radiation at the top of the atmosphere

Incoming radiation may be looked upon as the gross energy input and will be discussed first. Its supply to the Area is consistently high. Figures tabulated in Table 16 were taken from the Smithsonian Tables (1951). Annual amounts, which increase slightly from north to south over the Area, are 1/6 higher than those over the Mediterranean, and 1/3 higher than for north-west Europe.

TABLE 15

FREQUENCY OF TEN-DAY PERIOD OF FIRST INTERMEDIATE OR MOIST, AND HUMID PERIOD IN TERMS OF TEN-DAY RAINFALL AND TEN-YEAR AVERAGE POTENTIAL EVAPOTRANSPIRATION

Z I N D E R, Niger, 1931-1960

Month	May			June			July			August	Mean dates
Ten-day period	1	2	3	1	2	3	1	2	3	1	of beginning
Intermediate				3	5	3	10	8	1		21 June
Intermediate false start	2	5	3	1	2	1					
Humid					2	4	8	9	5	2	15 July

TABLE 16

SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE

kcal. cm^{-2}

Lat. °N	5°	10°	15°	40°	50°
Year	311.6	307.3	301.9	246.1	213.0
Summer half-year	160.9	164.9	167.7	164.6	156.0
Winter half-year	149.6	142.4	134.2	81.5	57.0

Note to Table 16:

40° may be taken as representing the Mediterranean area and 50° temperate latitudes. Note uniformity in summer and differences in winter.

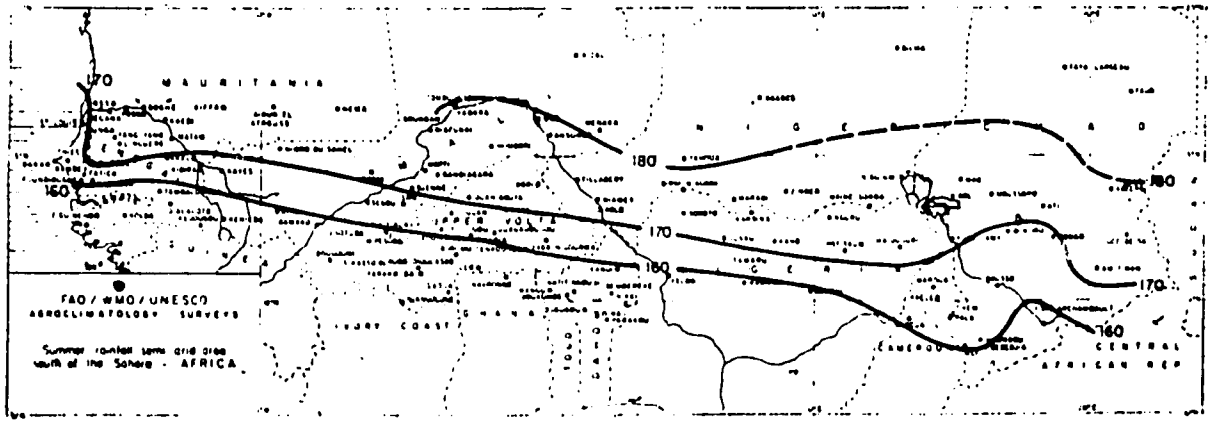

Figure 46 -- Mean annual global radiation in kcal.cm^{-2}.

The summer half-year amounts, which characterize the growing seasons in the Area (and also, to a large extent, in the other two areas) are about the same for the three areas.

Indeed, during the longest days of summer, about one-tenth more energy is received at the top of the atmosphere daily in western Europe than over the Area.

In the winter, however, whereas the supply to the Area is only decreased by about 15 per cent, the reduction is about 50 per cent in the Mediterranean basin and 70 per cent in southern England.

1.3 Global radiation

Global radiation is taken as meaning the solar energy, direct or scattered, reaching a horizontal surface at ground level, and consequently affecting the crops.

Hardly any direct measurements of global radiation were available from the Area. Recourse had to be made to an empirical formula based on the radiation incident outside the atmosphere and the proportion between observed and maximum possible sunshine.

The actual formula used is part of Penman's E_T formula, the estimates thus serving a dual purpose. They are based on ten years' data. Where sunshine duration was not available for the whole period, its relation with cloud amounts in octas observed simultaneously was worked out and used.

The annual amounts thus estimated vary between 160 and 180 kcal.cm^{-2} corresponding to mean daily values of 440 and 500 cal.cm^{-2} approximately, and are distributed zonally as shown in Figure 46, with the higher values in the north, unlike the gross input, owing to the more prolonged monsoon cloudiness in the south.

Departures thought to be significant were a minimum along the coast of Senegal, another in south Chad, the latter adjacent to a maximum in northern Cameroon. Besides these, it was difficult to decide how much importance to ascribe to two anomalies in the estimates: high values at Navrongo in Ghana and a reversed meridional gradient between Mopti and Segou in Mali, both on the Niger river.

The seasonal variation is relatively small in the Area. For monthly averages the range is 550 to 390 cal.cm^{-2}. day^{-1} at Kayes in Mali as opposed to 450 and less than 100 for Paris, France. Like E_T, global radiation shows two maxima, one before and one after the rains and one in winter.

1.4 Net radiation

The net radiation or energy balance at the surface of the earth was also determined by using the empirical formula incorporated in Penman's E_T formula.

The spatial variation of annual amounts shows only small variations between 100 and 110 kcal.cm^{-2}, except on the coast of Senegal, when values in excess of 120 kcal.cm^{-2} were calculated. There is a marked meridional gradient in August, at the height of the rainy season, with the highest values in the north. This gradient is reversed in winter.

Net radiation everywhere in the Area also showns two maxima and two minima, but the reduction during the rains is less marked, as the increased cloudiness and humidity reduce loss of energy radiated by the earth to outer space.

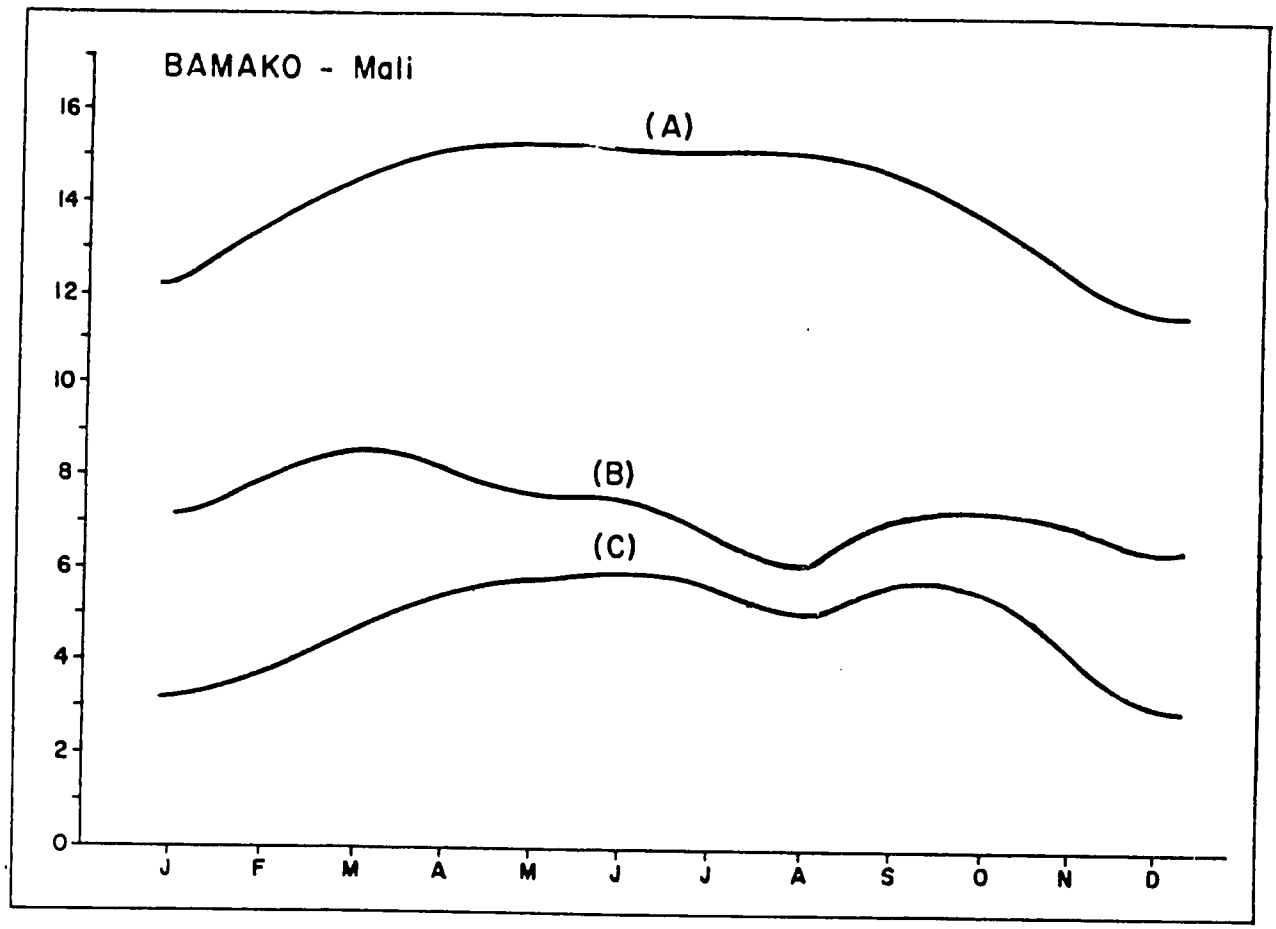

Figure 47 -- Seasonal variation in monthly mean radiations in the Area expressed in mm of evaporable water: (A) incident outside the atmosphere; (B) global; (C) net.

The relative seasonal variation at a place in the Area of the three forms of energy discussed is illustrated in Figure 47. Bamako is at Lat. 13½° N and the gross input shows two slight maxima as the earth position of the sun at its zenith crosses it.

2. TEMPERATURES

2.1 General considerations

Temperatures have been considered with respect to their effects on crops, both qualitatively and quantitatively: Qualitatively, for the occurrence of temperature thresholds likely to affect growth and development. (Development here means the succession of qualitative stages from seed to seed.) Quantitatively, as representing sums of energy to which total growth and also the occurrence of development stages may be related.

2.2 Surface distribution and seasonal variation of temperatures

As a result of the radiation régime which has been described, temperatures are consistently high in the Area. Some indications of the surface and seasonal distribution of

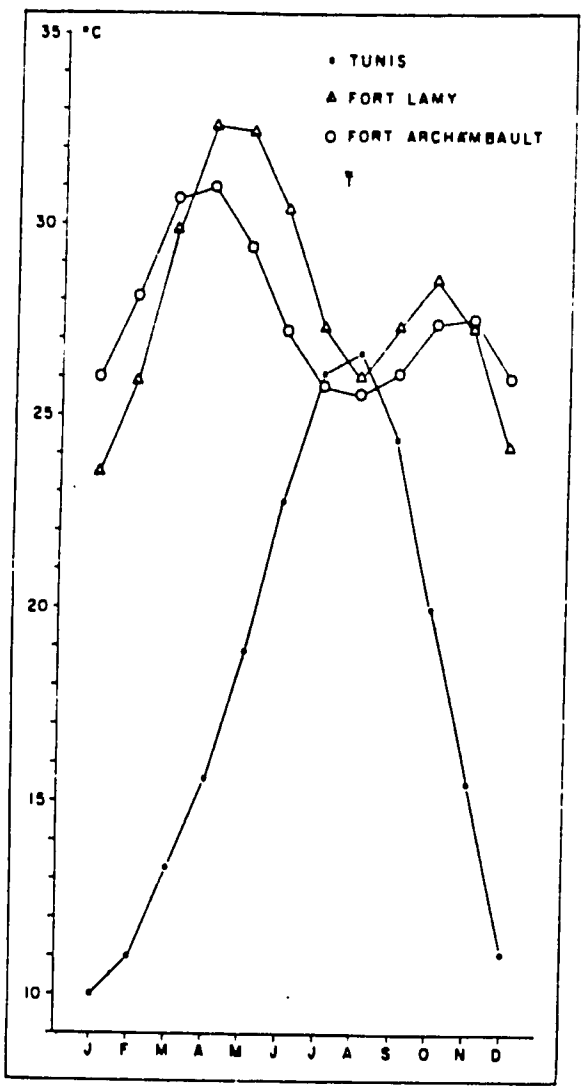

Figure 48 -- Monthly mean temperatures in the semiarid Area and in Tunisia on the north side of the anticyclonic belt. Cooling by the summer rains lowers the temperatures of the Area to the level of the dry Mediterranean summer.

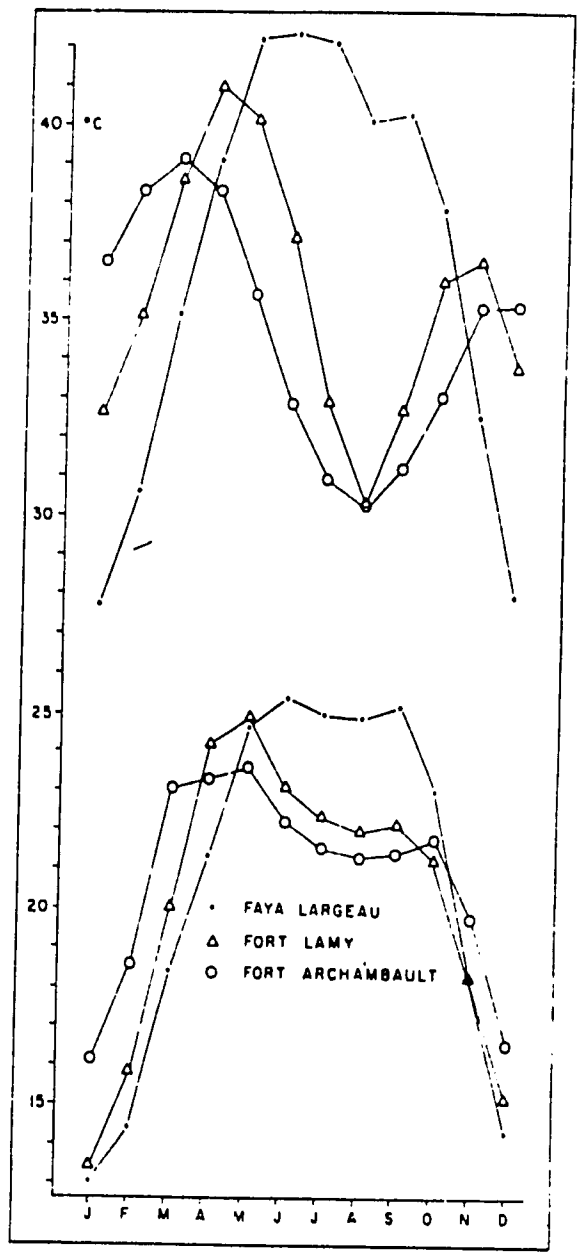

Figure 49 -- Seasonal variation of monthly mean extreme temperatures at three stations in Chad.

monthly mean temperatures have already been given, when the variables in the E_T formula were discussed. To these may be added monthly mean curves at two stations in Chad, in the north and south of the area (Figure 48) which show the familiar pattern, with two maxima and two minima, already met in connexion with radiation and evapotranspiration estimates.

These curves are contrasted with a similar representation of monthly mean temperatures for a station on the north side of the subtropical anticyclone in North Africa. There the northern winter is felt, all the more so since the rainy season coincides with it; whereas, during the dry summer, under the influence of the subtropical anticyclone, the temperatures rise to the level of those of the Area, depressed at the time by the summer rains.

The monthly mean extremes for the same two stations in the Area plotted in Figure 49 show the characteristic double-wave curve, but the summer reduction of the minima is comparatively small, because of the reduction in night cooling. Consequently, the daily range of temperatures, which is about 20°C in winter, with intensive night cooling, drops to less than 10°C in summer, as shown in Figure 50, for the same two stations.

Temperature characteristics for Faya Largeau, in the desert, in north Chad, were also plotted in Figures 49 and 50 to show the contrast with an arid and more northerly station with no depression of the temperatures by the rains in summer, a cooler winter, and little variation in temperature range.

In general, the lower the latitude in the Area, the longer the interruption of summer heating by the monsoon and, in consequence, the earlier the occurrence of the hottest temperatures of the year before the rains, and the lower these temperatures are.

2.3 Qualitative effect of temperatures on the crops

In the Area, the duration of the growing season is not likely to be controlled by the occurrence of temperatures below the vegetative zero of crops. 15°C may be looked upon as the highest of these growth-limiting temperatures, and even this is characteristic only of certain tropical crops such as cotton.

From Table 17, where some possible thresholds have been tabulated, together with information on their occurrence during availability-of-water periods, it will be seen that minimum temperatures of less than 15°C do occur in the north of the Area, but only during the three winter months, and they would not therefore affect dry farming, with which we are concerned in this survey.

The effect of these lower winter temperatures on summer rains crops grown outside their usual tolerances may be considerable, as will be seen in the section on sorghum.

High temperatures, on the other hand, may have a controlling effect, but available biological and agronomic information did not make this clear. Maximum temperatures well above 40°C do occur. Table 17 shows their occurrence as monthly means. The table also shows that no monthly mean maximum temperatures in excess of 40°C are reported from the Area during the humid or even the moist period.

Variability of temperatures, discussed in a later paragraph, shows that departures from the mean in the Area are of the order of a few degrees only; ±5°C from the monthly mean extremes would cover most occasions.

Maximum and minimum temperatures affect plants for only a short time. Monthly mean temperatures representative of the hours of daylight and darkness were also considered. Temperatures situated half-way between effective day and night temperatures respectively were computed for the 55 reference stations, and published as isotherms elsewhere (Cochemé, 1966).

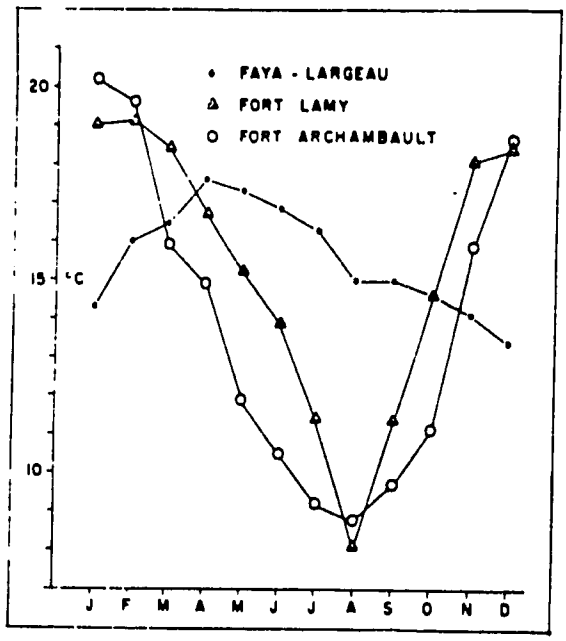

Figure 50

Seasonal variation of monthly mean diurnal temperature range in the Area and in the desert further north.

Effective day temperatures in excess of 37°C, tabulated in Table 17, occur only during the preparatory period in May and June at a small number of stations.

High night temperatures are more likely to be a hazard. The mechanisms which lead to their occurrence during the summer rains are increased cloud cover and atmospheric humidity, which prevent loss of energy by radiation from the earth at night.

From Table 17 it will be seen that effective night temperatures of 26°C (suggested as a threshold) occur commonly in the Area during the moist, and sometimes during the humid, periods. Effective night temperatures as high as 28°C also occur during the moist period, although none are reported to occur during the humid period. During the pre-humid intermediate period, high temperatures would be expected during reversals to harmattan conditions, especially after early or false starts of the period.

2.4 Sums of temperatures

It is suggested that, for some of the crops in the Area at least, and at certain times of the year, specific sums of accumulated temperatures in degree-days are necessary for the achievement of certain stages of development, such as flower initiation. This will be discussed again in Part III in connexion with specific crops. To establish the occurrence and surface distribution of these sums in the Area presupposes a knowledge of the dates of biological events, such as sowing and heading, which is not directly available. However, it has been shown that these biological events can be associated with climatological events such as the beginning and end of availability-of-water periods, of which the mean dates are known.

Consequently, temperatures above selected levels were accumulated for these periods. In Figure 51 are shown the surface distributions of two such sums: one corresponding to the growing season and the other to the season up to flowering. Again, the distribution is zonal,

TABLE 17

OCCURRENCE OF POSSIBLE THRESHOLD TEMPERATURES IN THE AREA

(Numbers 1-12 in heads represent months of the year)

	Effect day 37° Maximum >40°C							Minim <15°C				Effective night > 26°C							Effective night >28°C					
	4	5	6	3	4	5	6	1	2	12	3	4	5	6	7	8	9	10	3	4	5	6	7	9
Accaes			O		O		O	O	O	O		O	O	O	O	O	O				O	O		
N'Guigmi								O	O	O			O	+O	+O+									
Gao		+O	+O		O	O	O	O	O	O		O	+O	+O	+O	+O+	O	O			+O	+O	+O	O
St Louis																								
Tanoua					O	+O						O	+O	+O						O	+O	+O		
Abeche					O	+O					O	O	+O	+O+						O	+O	+O+		
Matam		+O			+O	+O		O					+O	+O+	[O]+	[O]+	O+				+O	+O+		
Mopti					O	+O		O				O	+O	+O+							+O	+O+		
Zinder					O			O					+O	+O+						O	+O			
Dakar Yoff																								
Birni N' Konni					O	+O					O	O	+O	+O+						O	+O	+O+		
Niamey		+O			+O						O	+O	+O	+O+				O+		+O	+O			
Maradi					+O			O	O	O		+O	+O	+O+							+O			
Fort Lamy					O	+O		O				O	+O	+O+							O			
Maiduguri					O			O	O	O		O	+O	+O+						O	+O			
Thies																								
Segou													+O	+O+							+O			
Sokoto												+O	+O	+O+						+O	+O			
Kayes	O	+O			O	+O					O	O	+O	+O+	[O]+					O	+O	+O+		
Maroua											O	+O	+O+							+O				
Mongo	+O			O	+O						O	+O	+O						O	+O	+O			
Kano								O	O	O		+O	+O+							+O				
Kaele											O	+O	+O+							+O				
Ouagadougou											O	+O	+O+											
Am Timan								O		O		+O	+O+									+O+		
Bousso											O	+O	+O+											
Tambacounda					O							O	+O	+O+					O		+O			
Garoua											O	+O	+O+							+O				
Pala											+O	+O	+O+							+O				
Navrongo											+O	+O	+O+							+O				
Bamako											O	+O	+O+	[O]+						+O	+O+			
F Archambault											+O	+O	+O+											
Boto Dioulasso												+O												
Moundou												+O+												
Kaduna																								

+O part preparatory O+ part moist [O]+ part humid

+O preparatory O+ moist [O] humid

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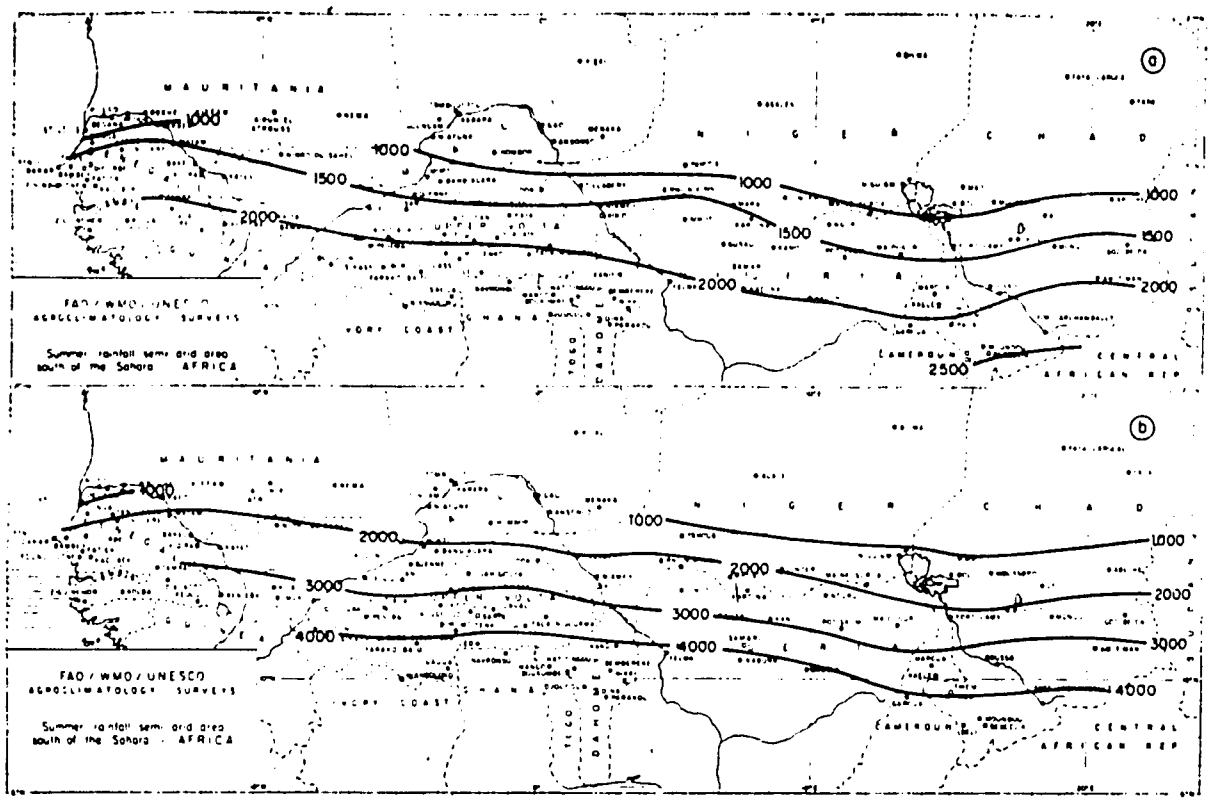

Figure 51 -- Sums of accumulated temperatures in degree-days during (a) moist period with reserve starting from 15°C; (b) first intermediate and humid periods starting from 0°C.

the smaller sums corresponding to the shorter periods, but not in an exactly inverse manner since, during the growing season, the temperatures are higher in the north, thus compensating to a limited extent for the shorter seasons. In some cases, as will be seen in Part III, when sorghum is discussed, it was found that the sums of night temperatures played a significant part in development.

2.5 Variability of temperatures

Sample studies of the interannual variability of maximum temperatures at Fort Lamy in Chad for periods of five days in June and August yielded coefficients of variability of 0.07 and 0.08, suggesting that temperatures 5°C warmer than the mean would only be expected to occur once in more than 20 years approximately.

For daily mean temperatures, a coefficient of 0.05 was calculated, putting 96 per cent of occasions within a range of a little more than 5°C.

3. LIGHT

3.1 General considerations

Two main aspects of the characteristics of light supply to the Area were studied: the duration of daylight or photoperiod, and the effect of light intensity in association with temperatures on net photosynthesis or dry matter production.

TABLE 18

MONTHLY MEAN LENGTH OF DAY IN HOURS AND HUNDREDTHS IN TERMS OF LATITUDE

Lat.	J	F	M	A	M	J	J	A	S	O	N	D
6°	11.82	11.93	12.09	12.25	12.39	12.46	12.43	12.31	12.15	11.99	11.86	11.79
7°	11.76	11.90	12.08	12.28	12.4	12.52	12.48	12.34	12.16	11.97	11.81	11.73
8°	11.72	11.87	12.08	12.30	12.49	12.58	12.54	12.38	12.17	11.95	11.77	11.67
9°	11.66	11.84	12.08	12.33	12.53	12.64	12.59	12.41	12.17	11.93	11.72	11.62
10°	11.61	11.80	12.08	12.35	12.58	12.70	12.65	12.45	12.18	11.91	11.68	11.56
11°	11.56	11.77	12.07	12.38	12.63	12.76	12.70	12.48	12.19	11.88	11.63	11.50
12°	11.51	11.74	12.07	12.40	12.68	12.82	12.75	12.51	12.19	11.86	11.58	11.44
13°	11.45	11.71	12.06	12.43	12.73	12.88	12.81	12.55	12.20	11.84	11.54	11.38
14°	11.40	11.67	12.06	12.45	12.78	12.94	12.87	12.59	12.21	11.82	11.49	11.32
15°	11.35	11.64	12.05	12.48	12.83	13.01	12.93	12.62	12.22	11.80	11.44	11.26
16°	11.29	11.61	12.05	12.51	12.88	13.07	12.98	12.66	12.22	11.78	11.39	11.20
17°	11.24	11.58	12.05	12.53	12.93	13.13	13.04	12.69	12.23	11.76	11.35	11.14

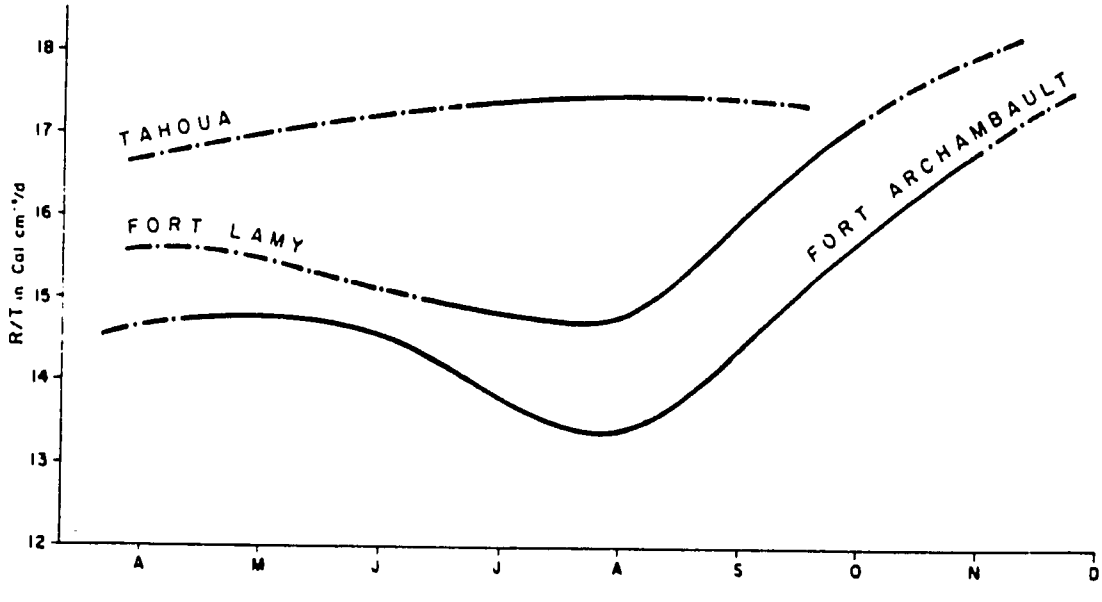

Figure 52 -- Seasonal variation of ratio Rg/C. The plain lines indicate the growing season. Tahoua is virtually outside the Area.

3.2 Photoperiodism

Little seasonal variation in duration of daylight occurs in the Area, the annual range being 1½ hours in the north and ½ hour in the south. Actual monthly mean values tabulated in terms of latitude are given in Table 18. Although the differences are small, they affect significantly the occurrence of flowering in many of the cultivated varieties grown.

Since, at all latitudes in the Area, the dry farming growing season is spread over the longest days of the year, plants adapted to it flower in days of decreasing length and, photoperiodically, must be short-day varieties (or neutral, if they are early varieties confined to short growing cycles), and this is actually what is observed.

Between the two extremes, varieties showing varying degrees of short-day photoperiodism are found.

Thus the necessity for a cereal to make the most of the growing season, and to flower shortly before the end of the humid period, in order to produce optimum yields, appears to be met by two different adaptations:

(1) A growth adaptation which, it is suggested, causes flower initiation to occur at an optimum interval from germination. It is also suggested that this period may in certain cases be more accurately expressed in degree-days than in days;

(2) A photoperiodic adaptation which will cause flower induction to occur when increasing nights reach a certain length.

For a cereal well adapted to a given region, with characteristic length of the growing season and its components, these two adaptations are in phase. But this synchronization may not obtain at other places of apparently similar climate within the Area. Although the annual rainfall may be the same, its timing may be different: we have already seen that the march of the monsoon is retarded in the extreme west of the Area. This would cause the end of the humid period to occur at a later date relative to length of day.

Furthermore, the dipping southwards of the isohyets would also cause small changes in the relation of the end of the humid period of a given duration to length of day.

A cereal sown in a location or at a time such that there is maladjustment will react diversely with respect to length of cycle and time of flowering according to its innate characteristics, but almost invariably the yield will suffer. Concrete examples of these relations will be given in Part III.

3.3 Dry matter production

It is known that, other things being equal, dry matter production or net photosynthesis reflects a balance between day and night temperatures. Temperature affects the rate both of photosynthesis and of the breaking down of its product by respiration. At night, the breaking down goes on uninterrupted, and thus relatively high night temperature will adversely affect productivity.

In the Area, the daily range of temperatures of 20°C drops by about half during the rains, because, as already explained, the reduction in maximum temperatures is not matched by a similar drop in the minima.

Consequently, there is a possibility of excessive reduction in dry matter production.

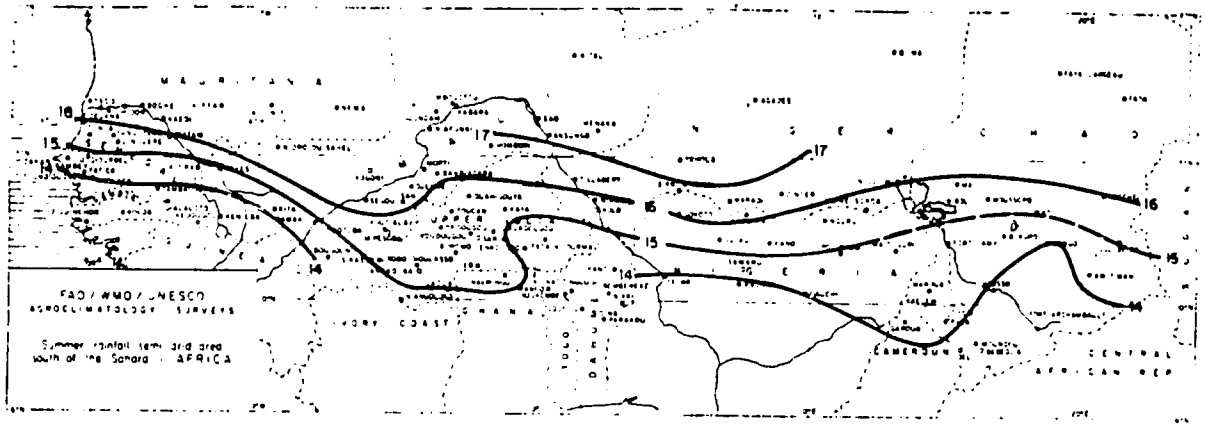

Figure 53 -- Mean surface distribution of coefficient Rg/C in August.

It is also known that the rate and the total extent of photosynthesis depend on the intensity and amount of light available, not only by itself, but also relative to the ambient temperatures regulating general metabolic rates. For a given set of such conditions, there appears, moreover, to be an optimum leaf area index, or ratio of leaf to soil area, for maximum production by a given crop.

A simple way of comparing accumulated temperatures and light proposed by Geslin (1944) is the ratio of the daily global radiation in $cal.cm^{-2}$ to the daily mean temperature in degrees Celsius. In France, this heliothermic index varies between 40 in late spring and 20 in the autumn. In the Area, this index is lower during the growing season since, as has been shown, the temperatures are higher but the global radiation is about the same as in western Europe. Values between 13 and 18 were obtained, with a reduction in the middle of the season, as shown in Figure 52.

Figure 53 shows the surface distribution of this parameter in August. It is again zonally distributed, with the higher values in the north.

From these figures and considerations it may be deduced that light intensity and duration characteristics in the Area, in association with prevailing high temperatures, may be limiting dry matter production by dense crops, especially in the south.

3.4 Summary and conclusions

The high temperatures of the Area, consequent on the radiation régime, are reduced to values more acceptable to crops during the summer rains.

Crops in the Area are photoperiodically short-day or neutral. The physical characteristics of the pre-flowering growth duration, and the photoperiodic characteristics of flowering, do not vary in unison over the Area.

Dry matter production may be limited by relatively high night temperatures and relatively insufficient light, especially in the south of the Area.

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PART III

THE CROPS

GENERAL CONSIDERATIONS

In Part III, the adaptation of selected annual crops to the climate of the Area is discussed in an attempt to define their climatic needs and tolerances.

The importance of these climatic requisites will vary according to whether the crops are subsistence or cash crops. The tolerances of plants grown for essential food may, in marginal areas, be pushed to the limit, whilst to produce economic yields an approximation to optimum climatic needs is required. It is realized that a crop such as groundnut can be grown for subsistence in one location and for export in another. However, in general, subsistence cultivations in the Area tend to be more extensive and parcelled, whilst cash crops tend to be more concentrated over the ground; which may give rise to differences in climatic requirements for light and water.

In the Area, subsistence crops are mainly grains of gramineous or leguminous origin. South of the Area, roots and tubers predominate, while north of it the population is increasingly dependent on animal products.

The subsistence crops of the Area selected for discussion are millet, sorghum, maize and cowpea.

The cash crops selected are groundnut and cotton.

Dry farming alone will be taken into account, flood plain and irrigation cultivations being mentioned only incidentally. Pasture and fodder crops will, however, be discussed.

The reactions of domestic animals to the physical conditions of the atmospheric environment is also an important part of agroclimatology.

Whilst this is recognized, the almost complete absence of biological and physiological data from the Area made it impossible to include a discussion of this specialized branch of agroclimatology in this report. Nevertheless, it is thought that some of the parameters tabulated in Part II in connexion with radiation, temperature, humidity and wind speed are of potential use for comparison with biological data such as heat load.

A preliminary consideration suggests that animals have greater plasticity, with productivity the price of adaptation. More easily perhaps than with plants, an economic balance may be found between this reduction of productivity and the cost of such localized "climate modifications" as air-conditioned sheds. The first step in any study of these problems, the working out of the spatial and seasonal distribution of specific climate parameters, has already, to a large extent, been taken; but the necessary complement of biological data is still lagging behind.

To determine the limits of tolerance of a crop, the actual geographical distribution of its cultivation must be known, for comparison with the distribution of climatic factors, independently estimated, due account being taken of interannual variability. To assess needs for optimum production, yield and production data must be available for comparison with concurrent weather and climate.

A consideration of the growth and development processes of crops is also required, and this must be based on observational data of the timing of biological events, such as flowering, in order that, by comparison with climatic data, phenological information may be obtained.

Neither yield nor production data nor phenological information is plentiful in the Area. However, examples of the different types of analysis enumerated above will be given.

In brief, the most important adaptations seem to be a matching of the length of growing cycle, a biological characteristic, to the duration of availability-of-water periods, which is a climatic characteristic.

Crops in the Area, and more particularly those which are indigenous to it, show a multitude of forms adapted severally to the whole range of its climatic conditions. A comprehensive agroclimatic analysis must subdivide these crops into ecotypes with a narrower range of climatic requirements which can then be defined with sufficient accuracy for the needs of planning. An example of this more detailed agroclimatic analysis will be given in the case of the cotton variety almost exclusively grown in the Area.

MAIN CROPS OF THE AREA

SORGHUM

1. DISTRIBUTION

Sorghum cultivated in the Area belongs to several species of the genus Sorghum. It is an extremely plastic crop and, using the possibilities offered by flood plains, separately from the rains or in combination with them, sorghum is grown somewhere in the Area at all times of the year.

Under dry farming conditions alone, sorghum is found over most of the Area, with the exception of the extreme north.

Rain-fed sorghum is in fact found in localities where mean annual rainfall is as little as 400 mm. This is partly explained by the fact that sorghum grows well on very fine-textured soils, able to store more than 100 mm of water and thus to prolong the moist season.

2. CYCLES AND AVAILABILITY-OF-WATER PERIODS

The extensive distribution of sorghum in the Area covers a wide range of growth cycles. Tentative tabulations of the lengths observed within the main cultural group show great diversity within the groups themselves (Table 19).

The very late cycles given in Table 19 can be extended to 250 days. The mean rainfall amounts corresponding to moist periods of 80 and 250 days, according to the general relation, $P = M \times 5.5$ (where P is mean annual rainfall in mm, and M is moist period in days) proposed in Part II, are 440 mm and 1,375 mm, covering the Area, with the exception of the extreme north, and extending well beyond its southern limits.

Since the length of the moist period is distributed zonally, the longer its cycle is, the further south will sorghum need to be grown. In practice, mixtures covering a range of cycle lengths are sown to ward against interannual variation. A knowledge of rainfall probabilities can help in deciding the range of cycles to be sown at a given place.

TABLE 19

OCCURRENCE OF GROWTH CYCLES OF VARIOUS LENGTHS WITHIN THE VARIOUS GROUPS OF SORGHUM

Number of days	Early 80-110	Semi-early 110-130	Semi-late 130-150	Late 150-180	Very late Over 180
Caudatum	+	+	+	+	+
Guineense	+	+	+	+	
Margaritiferum		+	+	+	
Gambicum		+	+	+	
Notabile			+	+	
Elegans				+	
Membranaceum				+	
Exsertum				+	
Cernuum					+

Short-cycle, or early varieties, are also grown in the south, using part of the growing season only, as catch crops, for subsistence, in combination with a cash crop such as cotton.

3. HEAT AND LIGHT

3.1 Temperatures

Qualitatively, the fact that sorghum can be grown at all times of the year implies an ability to withstand the high temperatures and also, incidentally, the high evapotranspiration rates which prevail in late spring, before the rains.

There are indications that some of the varieties of the Area, at least, are adversely affected by the low temperatures of the winter in the north.

The quantitative effect of heat or accumulated temperatures on growth and development is thought to be important, even in the relatively uniform régime of the Area, and is discussed at length in a subsequent section.

3.2 Light

The late varieties of sorghum are photoperiodically sensitive, heading time being accurately controlled by shortening days. This is also discussed at length in the following section.

4. PHENOLOGICAL ANALYSIS

An analysis by Bezot (1963) of detailed phenological observations on varieties of sorghum of different growth cycles, sown at monthly intervals at Deli, near Moundou, in Chad, substantiates remarks made in Part II, Heat and Light, 3.2, on the interaction of heliothermic and availability-of-water characteristics in the adaptation of cereals to the climate of the Area.

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TABLE 20

PHENOLOGICAL DATA ON STAGGERED MONTHLY SOWINGS OF SORGHUM AT DELI, 1962/63, TAKEN IN PART FROM BEZOT (1963)

		April	May	June	July	Aug.	Sept.	Oct.	Nov	Dec.	Jan.	Feb.	Mar.
A.	1...	69	71	64	60	58	54	53	(59)	67	96	92	71
	2...	7/6	10/7	2/8	29/8	26/9	23/10	22/11	26/12	5/2	5/4	2/5	10/5
	3...	2020	1960	1695	1530	1455	1395	1445	1580	1700	2685	2710	2105
	4...	2425	2340	2010	1800	1705	1660	1765	2050	2350	3565	3445	2380
	5...	1615	1580	1380	1260	1205	1130	1125	1110	1050	1805	1975	1860
	6...	12.43	12.54	12.59	12.48	12.30	12.09	11.86	11.70	11.68	11.90	12.08	12.23
	7...	9.5	8.6	9.0	7.2	5.6	5.5	5.8	-	-	9.9	10.5	11.6
	8...	6.6	6.2	6.2	4.6	2.5	2.0	1.8	3.0	-	5.1	4.9	5.8
	9...	324	336	348	284	244	166	155	96	-	224	277	327
B.	1...	189	163	136	110	92	78	82	94				
	2...	5/10	10/10	13/10	18/10	30/10	16/11	21/12	1/2				
	3...	5095	4295	3515	2815	2355	2070	2205	2455				
	4...	6055	5085	4150	3220	2790	2485	2580	3285				
	5...	4140	3505	2875	2305	1925	1645	1635	1630				
	6...	12.42	12.42	12.39	12.31	12.17	12.00	11.80	11.69				
	7...	25.1	21.3	18.0	14.5	10.6	8.2	7.6	6.5				
	8...	8.0	6.4	4.9	4.1	3.3	-	3.2	4.0		4.9	5.8	
	9...	475	400	350	345	270	-	145	105				
	10...	915	840	680	385	60							
C.	1...	191	161	131	108	84	67	(68)	77	(93)	113		
	2...	7/10	8/10	8/10	16/10	22/10	5/11	7/12	15/1	3/3	22/4		
	3...	5145	4240	3380	2770	2135	1755	1850	1915	2460	3195		
	4...	6115	5020	3990	3150	2525	2100	2300	2365	3350	4190		
	5...	4180	3465	2770	2265	1750	1415	1400	1260	1570	2200		
	6...	12.42	12.42	12.40	12.31	12.19	12.04	11.63	11.69	11.98	12.38		
	9...	460	415	310	-	-	-	110	80	-	255	320	

NOTE: Sowings took place at the beginning of the months indicated. Data are given for A, an early variety, No. 528; B, a batch of nine late varieties; and C, a late variety, No. 956. The numbers in the second column from the left correspond to the following measurements (where available):

1. Number of days from sowing to heading. 2. Heading date. 3,4,5. Sums of accumulated mean, maximum and minimum temperatures from sowing to heading. 6. Mean duration of daylight in hours and hundredths. 7. Number of internodes. 8. Number of functional leaves. 9. Leaf area in cm^2. 10. Number of grains per panicle.

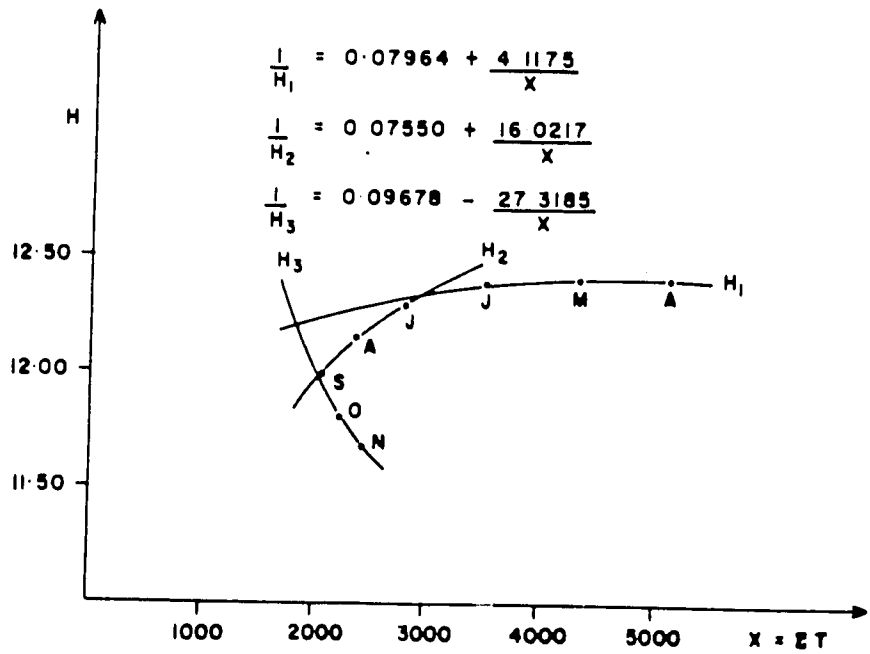

Figure 54 (a) -- Accumulated temperatures in degree-days v. mean photoperiod in hours and hundredths. Three hyperbolic relations are discernible according to the mean length of the photoperiod; above, around and below 1200 hours.

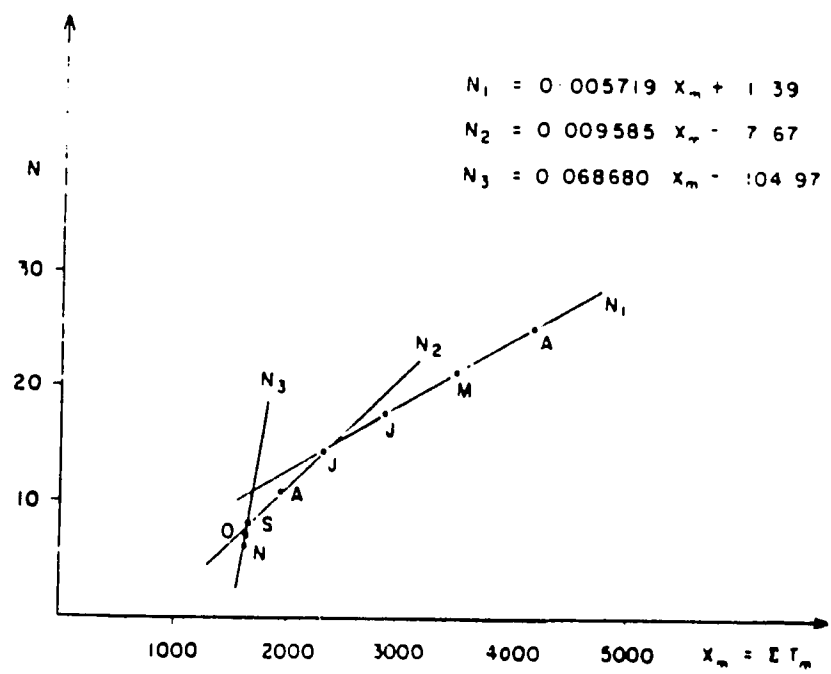

Figure 54 (b) -- Product of minimal temperatures by the number of days v. mean number of nodes, N. The three photoperiod classes lie along straight lines.

Data obtained from Bezot's paper, to which have been added sums of mean, maximum and minimum temperatures, accumulated from sowing to heading, and mean daylight duration during that period, are listed in Table 20.

The table shows three varietal entries: an early variety, No. 528; averages for nine late varieties; and a late variety, No. 956.

4.1 Photoperiodic control of heading time

Considering the batch of nine late or long-cycle varieties, it will be seen that sowings from April to August all headed in October in shortening days, so that the length of the growth cycle was progressively reduced. This demonstrates photoperiodic control of flowering. Shorter cycles, however, slightly delayed heading, and Bezot obtained an accurate relation to determine the date of heading in terms of the interval between 30 March and actual sowing date.

For sowings in September, October and November, the length of sowing-to-heading cycle increased rapidly, but the growth was stunted and unproductive. For sowings between December and February the results did not appear to have warranted comprehensive recording, and it can only be concluded that the resultant growth was even more negligible.

4.2 Cycle-length control of growth and yield

Using the length of the stem and the number of internodes and leaves as criteria, Bezot showed that vegetative growth is positively related with the length of the sowing-to-heading interval for the April to September sowings. This sowing-to-heading interval was also shown to be related positively to the number of grains per panicle. For sowings in September onwards, the yield is negligible or non-existent.

4.3 Neutral varieties

Bezot also found that the short-cycle variety was little affected by photoperiodism and managed to flower after a fairly constant interval, whatever time of the year it was sown.

5. FURTHER ANALYSIS

In the present study an attempt was made to estimate more specifically and quantitatively the part played by heat and light in these processes.

5.1 Effect of mean length of photoperiod

The cycles of the late variety sowings which led to heading in October and an appreciable production of grain had a mean photoperiod of more than 12 hours.

5.2 Sums of temperature of sowing-to-heading cycle

The sum of accumulated temperatures was well related to mean photoperiod subdivided into three classes: (i) more than 12 hours; (ii) about 12 hours; (iii) less than 12 hours. This is illustrated in Figure 54 (a). Within these three classes, the sums of temperatures were also well related to the number of nodes (particularly the product of minimum temperatures by the number of days, here called by analogy "sums of minimum temperatures").

The sums of daily mean temperatures in degree-days, from date of sowing to heading, were found to be related to the number of grains per panicle in the late varieties (section B, Table 20). This relationship takes the form of a parabola (Figure 55). The crops planted in April (with an accumulation at heading of 5,095 degree-days) had the highest average number of grains (915).

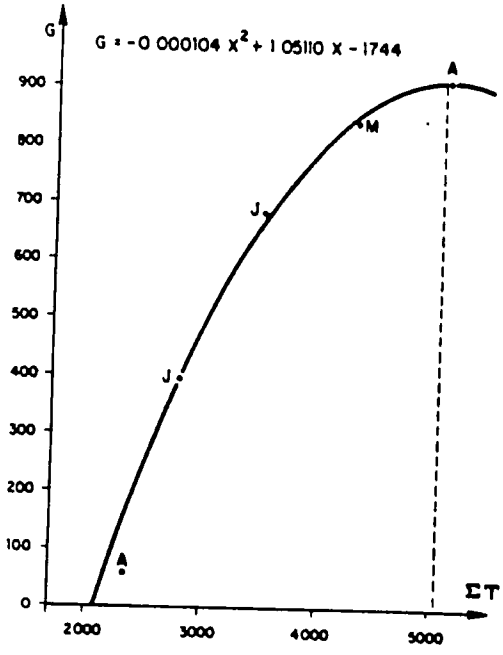

Figure 55 - Number of grains per panicle, G, v. sums of accumulated temperatures, ΣT, from sowing to heading. The relation takes the form of a parabola with a maximum. The letters A, M, J, J, A, are the initials of months of the year, from April to August, in which the crop was planted.

TABLE 21

DWARF AMERICAN VARIETIES

1	2	3	4
- 21/9	9/11	49	1030°
- 6/10	22/11	47	1010°
- 22/10	13/12	52	1030°
- 6/11	1/1	56	1015°

1. Sowing date. 2. Heading date.
3. Number of days sowing to heading.
4. Product of minimal temperatures by number of days.

TABLE 22

1	2	3	4
30/8 - 23/10	54	1138	1271
30/9 - 23/11	53	1096	1282
30/10- 28/12	59	1096	1336
30/11- 5/2	67	1054	1376

1. Sowing and heading dates. 2. Number of days. 3. Products of minima by number of days. 4. Sum of night effective temperatures in half degree-days.

TABLE 23

COMPARISON OF AVERAGE AVAILABILITY-OF-WATER AND HEAT PARAMETERS AT MOUNDOU WITH BEZOT'S OBSERVATIONS AT DELI

MOUNDOU		DELI		
Agroclimatic parameters		Earliest sowing giving high yield		Next monthly sowing
Beginning of moist period	27 April	Sowing	30 March	30 April
End of humid period	11 October	Heading	5 October	10 October
Length of prehumid and humid	167 days	Sowing to heading	189 days	163 days
Degree-days above 0°C for period	4400	Degree-days for cycle	5095	4295
		Mean number of grains	915	840

5.3 Constant sums of sowing-to-heading minimum temperatures

For the late varieties sown in September, October and November, it was found that the product of the minimum temperatures by the number of days remained constant, as shown in Table 20 and Figure 54 (b).

It was suggested that during such short-day cycles the photoperiodic requisites for flower induction are available early in the life of the plant and that accumulated temperatures then determine flower initiation.

A similarly constant sum of minimum temperatures was obtained in the case of the early variety, 528, for sowings at the beginning of September to December, and also for the dwarf American varieties reputed to be photoperiodically neutral (Table 21). These constant sums appear to be a varietal characteristic.

Although these products do not represent degree-days, they must be looked upon as the number of times a certain daily cycle of temperatures is repeated.

However, if the control action involved is of the kind associated with sums of temperatures, the minima may be taken to represent night temperatures and an expression in half degree-days or degree-hours could be calculated using mean night temperatures.

Sums of effective night temperatures in half degree-days at Moundou were calculated in the case of the variety No. 328 and compared with the minima-days product for the same period. Both were calculated carefully on the basis of short intervals. The values obtained are shown in Table 22. Both estimates are fairly constant but the minima-days product shows the narrower range.

In conclusion, it can be said that Bezot's data, and similar information obtained from other sources, demonstrate the importance of the photoperiodic control of the cycle of late varieties of sorghum in the Area and the dependence of yield on the length of cycle expressed in time or in amounts of energy.

6. ADAPTATION OF THE NINE LATE VARIETIES TO MOUNDOU CLIMATE

Agroclimatic parameters for Moundou (see Part II) were compared with those derived from Bezot's experiment. Both sets are shown in Table 23.

This would imply that these late varieties were reasonably well adapted to the rainfall régime of Moundou and yet able to react favourably to a somewhat more ample water supply.

It is seen that the characteristics for a sowing at the end of April agree well with the average agroclimatic parameters. However, sowing a month earlier appears to be a little more productive. Characteristics corresponding to this earlier sowing would be obtained on years of more than average rainfall expected to occur once in three or four years.

The question of the effect of length of cycle on yield is discussed further in connexion with millet.

REFERENCE

Bezot, P. (1963). L'amélioration des cultures céréalières au Tchad. Agron. Trop. 18 (1), 1963.

MILLET

1. DISTRIBUTION

Millet, another gramineous subsistence crop showing great plasticity, occupies an even larger portion of the Area than sorghum.

It is grown as far north as the northern boundary of the Area and as far south as the southern one. This wide coverage is due mostly to adaptation to climatic restrictions.

It is realized that factors other than climate also control the distribution of crops and, for millet, information was available to demonstrate this: the northern limit of millet cultivation in West Africa was obtained from an official French map of cultivations (1954) and has been plotted on the map of Figure 56 together with mean annual isohyets. It can be seen that, although there is broad agreement between rainfall and limits of cultivation, these are also some important departures; but these can all be explained, though they are due to factors other than climate.

Cultivation follows the course of the rivers Senegal and Niger into areas of poor mean annual rainfall. The bulge into Mauritania at Moudjeria is due to a vast depression into which water drains. It would be more accurate to surround this region by a circle, and have another boundary further south. In the instances mentioned above, flooding rivers and drainage basins can provide more water than is implied by the isohyets and can influence the distribution of cultivation.

The limit drops to nearly 500 mm along the Mali-Mauritania border where the soils are heavy, and the populations nomadic. Demographic factors intervene again further east, where two bulges in the limits of cultivation, one to the south and one to the north, occur side by side. The first, reaching down to the 500 mm isohyet, is within the territory of pastoral people, the Fulani and the even more nomadic Touareg; the second, extending towards the 200 mm line, is occupied by an agrarian people, the Hausa.

Thus modified by these extraneous factors, the northern limit of cultivation oscillates between 500 and 220 mm mean annual rainfall approximately.

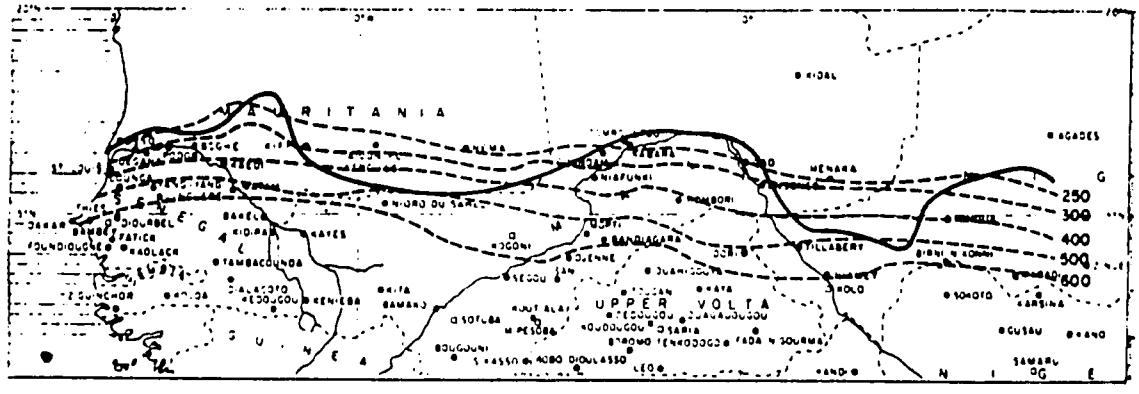

Figure 56 -- Mean annual isohyets (broken lines) and northern limit of millet cultivation (plain line).

2. CYCLE LENGTHS AND AVAILABILITY OF WATER

The length of growth cycle of millet varies in the Area between approximately 60 and 200 days. Resistance of the seedlings to drought permits early sowing, thus lengthening the effective moist period. Thus 10 days may be subtracted from the 60 to obtain the corresponding minimum availability-of-water period. Using the 5.5 mm approximation already mentioned, this would make the lower limits correspond to 275 mm mean annual rainfall and the upper one to 1,100 mm.

The 75 mm difference between the lower limit and the information given by the map is explained by the fact that in the extreme north cultivation will only take place in privileged positions where rain-water has accumulated by drainage.

Furthermore, profuse tillering allows millet to survive the dry spells of the pre-humid period, which are all the more likely to occur when sowing is brought forward.

3. SOIL TEXTURE

Millet, especially the early varieties, will also grow on soils of coarser texture than sorghum.

In most of the territories of the Area a zone is reached, around 700 mm mean annual rainfall, when millet replaces sorghum as the predominant cereal crop. This transition may also be due to a change in the texture of the soil, that is in the proportions of sand and clay, itself to some extent dependent on the climate.

Nevertheless, millet and sorghum can be found growing on the same soils, sometimes simultaneously.

Lastly, it may be mentioned that millet, unlike sorghum, does not lend itself to extensive flood plain cultivation, due to the fact that it does not readily accommodate fine-textured soils.

4. HEAT AND LIGHT

It can be deduced from its distribution in the Area, its ability to withstand drought and the fact that it can be sown in advance of the rains that millet can resist high temperatures.

Although no phenological data were available for millet, comparable with those for sorghum analysed in the previous section, there is every reason to believe that its reactions to photoperiod and sums of temperatures are the same as those of sorghum.

5. ANALYSIS OF EFFECT ON YIELD OF CLIMATIC FACTORS

No phenology data comparable to those discussed in connexion with sorghum were available for millet. However, an eleven-year yield series of all the millet grown at the research station at Bambey in Senegal had been published in a paper by Vidal (1963), in a detailed investigation of the respective importance of water and nitrogen supplies on yield.

His assessment of the water requirements of millet at various stages of growth and development is a model of the type of consideration which needs to be given to specific crop requirements in terms of biological events, when passing from a survey of the characteristics of atmospheric climate to more localized studies.

He recognizes eight distinct requisites for a high yield, which are listed here:

(i) As early a start as possible;

(ii) For the first 20 days: abundant rains to promote early tillering;

(iii) During the next 10 days: water supply reduced to the needs of existing plants and tillers, to stop further tillering;

(iv) Until stem extension: water supply plentiful to promote stem growth in width;

(v) During stem extension: water supply limited to the needs of the crops and ground charging;

(vi) During heading: water supply limited to the needs of the plants but sufficient to achieve ground charge;

(vii) From heading to harvest: water supply not exceeding evaporation losses in order to avoid loss of nutrients by deep drainage;

(viii) Altogether, for the duration of the growing cycle, rainfall should correspond to the sum of optimum evapotranspiration and maximum capacity ground charge.

It will be seen that although early and abundant rains are thought desirable at first, thereafter excessive amounts are considered to have an adverse effect at almost every stage in the growth cycle.

Expressing these ideas by means of indices and grouping them into a compounded index, he obtains between the latter and yield a correlation coefficient of 0.93. However, his conception of the optimum rainfall régime does not accommodate the fact that, at the rainfall level in Bambey, surplus generally occurs in amounts exceeding ground recharge.

Vidal's climatic requisites are based on biological events for which no dates of occurrence are available. This makes it impossible to define quantitatively corresponding climatic parameters.

6. FURTHER ANALYSIS

6.1 The variables

In the following analysis, the climatic variables compared with yield were based on the parameters described in Part II, but chosen to correspond as much as possible to Vidal's specifications. The budget used was a combination of E_T values obtained at Thies with Bambey rainfall figures. They are as follows:

X_1 Duration of the humid period

X_2 Rainfall during October

X_3 Rainfall during post-humid intermediate period

X_4 Water surplus

X_5 Interval between heading and the end of the humid period

X_6 Rainfall during pre-humid intermediate period.

These climatic variables are shown, together with the figures for yield, in Table 24.

TABLE 24

VALUES OF YIELD, RAINFALL, AND THE CLIMATIC VARIABLES

	kg/ha	mm	X_1	X_2	X_3	X_4	X_5	X_6
1950	670	1270	9.5	148	-	896	30	40
1951	790	940	10.0	227	10	470	40	107
1952	1440	885	9.0	101	24	413	25	95
1953	1330	755	9.0	62	5	305	20	82
1954	1230	745	7.5	2	58	360	0	51
1955	1770	780	8.5	15	16	380	10	58
1956	1060	640	6.0	47	54	170	15	155
1957	1100	670	7.0	77	6	284	20	124
1958	1220	820	6.5	39	46	492	5	61
1959	910	460	5.5	-	13	150	5	101
1960	1040	790	8.0	14	14	380	15	73
	1141.8	796	7.8	66.5	21.5	390.9	16.8	86.1

TABLE 25

b_1	b_2	b_3	b_4	b_5	b_6	r	r^2	R	R^2
0,00015						0.003	-		
	-0.109					-0.48	0.23		
		0.027				0.38	0.14		
			-0.208			-0.32	0.10		
				- 0.016		-0.41	0.17		
					-0.017	-0.15	0.02		
131.908	-4.057							0.66	0.44
137.755				-23.332				0.61	0.37
131.016	-3.673	3.383						0.70	0.49
170.955	-3.687		-0.605					0.73	0.53
138.148	-3.289			- 5.284				0.66	0.44
200.325	-5.268				3.317			0.72	0.52
130.066		1.874		-20.937				0.62	0.38
28.762		5.593			1.034			0.37	0.14
169.694	-3.310	3.350	-0.600					0.76	0.58
121.880	-4.364	4.004		5.730				0.70	0.49
187.358	-4.513	2.073			2.711			0.73	0.54
120.614	-1.131	4.058	-1.236		-4.452			0.78	0.60

NOTE: b_1 - b_6, regression coefficients; r, R, correlation coefficients.

6.2 Regression and correlation coefficients

First, linear regressions and correlation coefficients, simple and multiple, were worked out. The results are shown in Table 25. None of the correlations are statistically significant. The short length of the series makes it difficult to form a firm opinion, but it is thought that these indifferent coefficients are due to the curvilinear nature of the relation between yield and climate in this semiarid environment, discussed in the following paragraphs.

Some of the simple coefficients, though not significant, give indications, notably an adverse effect of rainfall during October on yield, which agreed with Vidal's requisite (vii); no excess water from heading to harvest.

To Vidal's explanation that water surplus in October leaches away useful nitrogen compounds may be added the increased risk of washing away pollen, and parasitic action.

6.3 Curvilinear nature of the regressions

Further consideration of X_5, the interval between heading and the end of the humid period -- a parameter of which the importance has already been discussed extensively -- suggests that there is an optimum date for heading and therefore that the relation between yield and X_5 is curvilinear. This is illustrated in Figure 57 where a curve drawn freehand represents a curvilinear relation with yield, with an optimum value for yield corresponding to an interval of 10 days between heading and the end of the humid period, a method explained by Ezekiel and Fox (1959).

It is, in fact, logical to think that if the millet grown in these trials is well adapted in terms of its cycle and main biological events to the climate of the Bambey region, it will react adversely to an excess as well as a deficit of most of the availability-of-water parameters characteristic of the region. Wherever this is the case, linear regressions cannot give significant results since low yields occur at both extremes of the climatic variables.

Figure 58 shows dot diagrams of four climatic variables plotted versus yield, namely: precipitation P, duration of the humid period X_1, water surplus X_4, and rainfall in October X_2.

The values of each variable, arrayed in order of magnitude, have been separated into three classes and averaged, and the mean values plotted, together with corresponding mean yields. Inspection of these diagrams strongly suggests curvilinear regressions with optimum values close to the over-all means of which the positions are given by dotted lines. This is least obvious in the case of X_2, rainfall in October, which gave the highest linear correlation with yield, partly because of the very high yield figure of 1955.

To test this further, correlations were worked out between yields and departures from the mean values of the same climatic variables -- mean values being provisionally looked upon as optimum values. In all cases, even with X_2, higher coefficients were obtained than with direct comparisons of yield with climatic factors. The correlation was highly significant in the case of water surplus, in agreement with Vidal's work. Results are shown in Table 26.

Determination of correlation ratios and working out of curvilinear regressions would give more formal expression to these relations and lead to estimates of optimum values. However, further elaboration was considered unnecessary for the purpose of this survey. It was thought that enough had already been done to confirm that the regressions between the

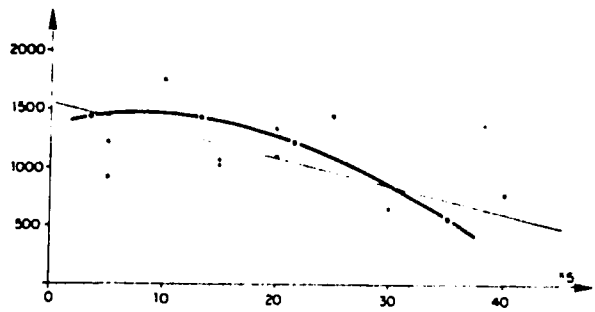

Figure 57 -- Scatter diagram of yield in $kg.ha^{-1}$ and length of interval in days between heading and the end of the humid period. The thin line is a linear regression. The thick line is a first approximation to a curvilinear regression.

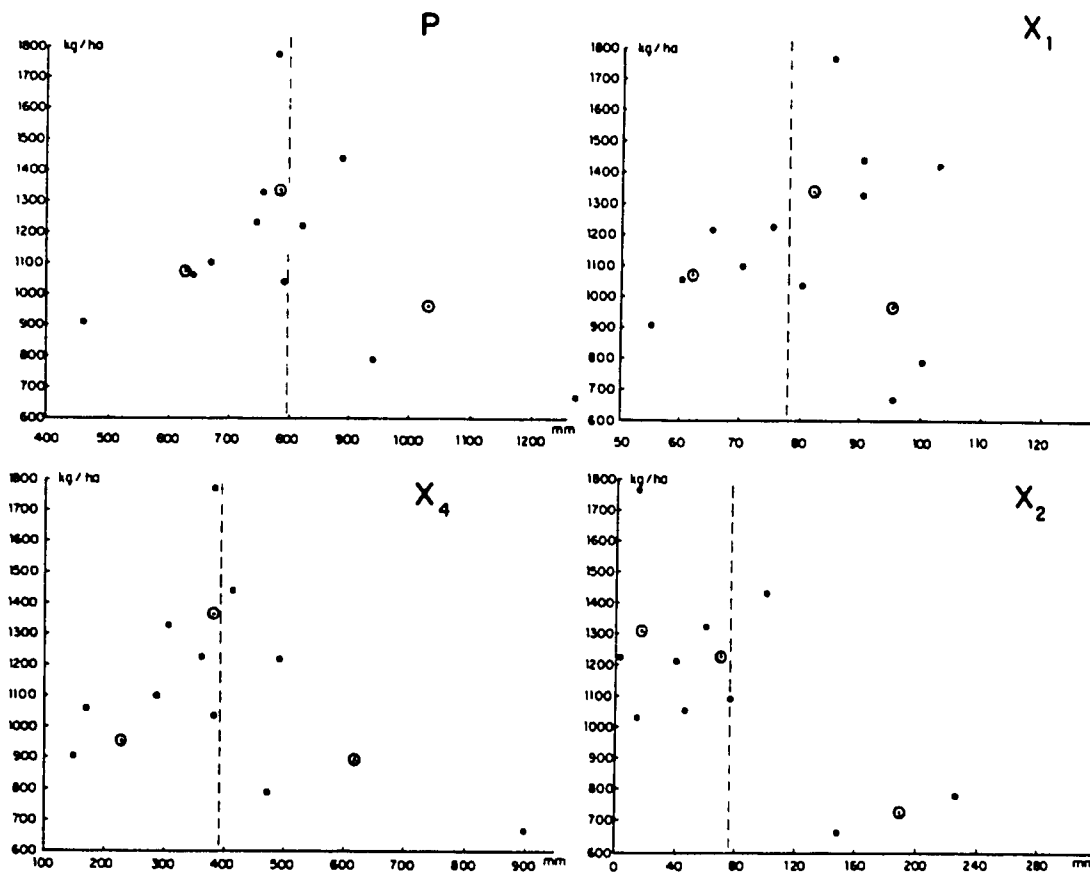

Figure 58 -- Scatter diagrams of yield versus rainfall P, duration of the humid period X_1, rainfall in October X_2, and water surplus X_4. The large ringed dots show the mean position of classes of the independent variables. A curvilinear regression with maximum close to the mean is indicated in the case of P, X_1 and X_4.

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TABLE 26

CORRELATION BETWEEN YIELD AND DEPARTURE FROM MEAN VALUES OF CLIMATIC VARIABLES

	r	t	Significance
Mean annual rainfall 796 mm	- 0.80	4.0	Significant
Mean humid period, X_1 78 days	- 0.67	2.8	Probably significant
Mean rainfall during Oct., X_2 66 mm	- 0.58	2.0	Not significant
Mean water surplus, X_4 391 mm	- 0.99	5.3	Highly significant

NOTE: "r" is correlation coefficient; "t" is Student's significance parameter.

yield and the climatic parameters discussed were curvilinear in nature, showing that, even in a semiarid environment, adapted crops can have too much water, or water for too long, to give best yields.

In conclusion, it is suggested that in the case of millet at Bambey -- and probably of all the cereals in the Area -- a year with more abundant rainfall than average is not necessarily a more productive year than average. It is realized, however, that good agricultural practice and measures such as mixed sowings will extend the range of optimum climatic conditions.

7. DESYNCHRONIZATION OF ADAPTATION MECHANISMS

It has already been suggested that the main climatic needs of millet, and also of sorghum varieties, are an optimum moist period to match their inherent cycle length limited on the long as well as on the short side, and, with late varieties, an optimum date of the end of the humid period to match a photoperiodically controlled date of heading. The analyses of the last two sections have supported these views.

It has also been stated that these two conditions do not necessarily vary in unison from one part of the Area to another. This disparity may now be discussed in more detail. At Thies, near Bambey, the mean humid period lasts 72 days and ends on 1 October. From amongst the 35 reference stations those with humid periods most comparable in length are

Maiduguri, 66 days, and Segou, 75 days. However, they end on 11 and 1[illegible] September respectively, 3 and 2 weeks earlier than at Thies, because of the lag in the arrival of the monsoon, characteristic of west Senegal. Thus, a late variety successfully adapted to the climate of Bambey would find at these other two places the right length of growing season, but the humid period would end too soon relative to its photoperiodically fixed date of flowering. This discordance would be aggravated by a few more days because these two places are on lower latitudes than Thies. It might therefore be mistaken to predict that this variety would do equally well at Segou and Maiduguri. The desynchronization of the two climatic adaptation mechanisms might cause disappointing yields.

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COTTON

1. SINGLE COTTON VARIETY GROWN IN THE AREA

Although different varieties and different cultivation systems for cotton fibre production are in common use south of the semiarid Area, within the Area itself commercial production is exclusively due to a Gossypum hirsutum var. Allen, which is thought to have originated in Uganda and reached the Area via the U.S.A. It is this variety which will be discussed here.

2. DISTRIBUTION AND YIELD

Rain-fed cotton is found throughout the Area, south of the 600 mm isohyets, wherever other controlling factors, such as soil and organized production, permit it to grow.

Amongst the main producing regions the following may be mentioned:

(i) The north-east of northern Nigeria (Sokoto, Katsina, and north Zaria, mainly along the Zaria-Gusau railway . The research station at Samaru is on the eastern edge of this region, which produces a mean yield of 500 $kg.ha^{-1}$.)

(ii) The south of Chad: mean yield 300 kg.ha

(iii) North Cameroon, which has the best mean yield: 600 $kg.ha^{-1}$

(iv) Smaller amounts are produced in southern Mali, southern Niger, Upper Volta and Senegal (where cotton has to compete with groundnut).

3. PRODUCTION

Lint production figures from the Area (taken from the FAO Production Yearbook and other sources) for 1965 are as follows:

	Metric tons produced	Amt. exported value, US$
Mali	7 000	1 390 000
Upper Volta	5 000	320 000
Niger	6 000	24 000
Nigeria	44 000	26 640 000
Chad	36 000	17 470 000
N. Cameroon	16 000	9 280 000

To these may be added small quantities from Senegal and northern Ghana, Togo and Dahomey.

4. CLIMATIC NEEDS AND TOLERANCES

Unlike sorghum and millet, the forms of cotton grown in the Area constitute an ecotype with a fairly narrow range of climatic needs.

4.1 Availability of water

4.1.1 Growing cycle

Average length of cycle is about 165 days made up as follows: 55 to 65 days from sowing to the beginning of flowering, 60 days for flowering and 55 to 45 for the boll maturing and opening.

4.1.2 Flowering

With cotton there is no terminal inflorescence to the main stem as in the case of the cereals discussed so far. The flowers are produced on side branches for a period which should end with the humid period. A short humid period tends to curtail production by reducing the number of flowers which will give rise to bolls. An unduly long humid period might affect fertility by washing away the pollen.

4.1.3 Boll maturing and opening

Forty-five days appear necessary for proper maturing of a boll or capsule and less than 30 days will not yield fibres worth picking. During maturing too much moisture has an adverse effect, partly through parasitism.

4.2 Heliothermic complex

4.2.1 Qualitative effect of temperatures

A temperature of 15° Celsius is suggested as the vegetative zero below which the growth of cotton is hindered. Such temperatures would only be felt in the winter in the extreme north of the Area. In the rest of it, cotton production is assumed to be free from this climatic control. No other direct qualitative effects of temperature have come to light during this survey.

4.2.2 Quantitative effects of temperature

The length of the vegetative period, from sowing to the appearance of the first flower, appears to be controlled by a sum of temperatures of 1,650 degree-days above 0°C in the case of the variety discussed. This means 55 days at a mean temperature of 30°C, or 65 at 25°C.

From the maps in Figure 30 (Part II) it will be seen that average temperatures of 30°C in the north of the cotton-growing area and 28° in the south are expected to prevail during the vegetative period. Temperatures will also affect the rate at which flowers are produced and their ultimate number. This is discussed in detail in the technical report. Typical temperatures during flowering would be those of the month of August in Figure 30.

4.2.3 Photoperiodism

The date of appearance of the first flower does not seem to be photoperiodically controlled. The cotton cultivated in the Area is probably neutral in this respect.

5. GROWING CYCLES AND CLIMATIC ZONES

5.1 Typical cycles

In Figure 59, above a time scale in days, is represented an idealized sequence of the three main stages in cotton production in the Area.

Above it, and at the same time scale, the availability-of-water periods at three places in the Area have been shown. Maroua appears to give the best approximation to the suggested optimum cycle, especially with respect to the timing of the end of the humid period. It also returns the best yields of the three places. At Garoua a large proportion of the bolls would open during the humid period, making them more susceptible to parasitic action. At Maradi, on the other hand, the shortness of the humid period would curtail flower production.

5.2 Cotton climatic zones

On the assumption that the climatic needs for optimum production of *G. hirsutum var. Allen* at present grown in the Area are those represented in Figure 59, climatic zones for this rain-fed cotton can be sketched as shown in Figure 60. These zones indicate climate resources only, and it is realized that other environmental factors may intervene to prevent the realization of the climatic potentials. It is also assumed that in the central and northern zones sowing takes place as early as possible, that is, at the beginning of the moist period.

5.2.1 Optimal zone

The central zone where, on the score of climate alone, optimum yields would be expected, is bounded by the 170- and 150-day isolines of duration of the moist period, with reserve. It should probably be stopped short of the coastal district of Senegal where, in any case, cotton cannot compete with groundnut.

5.2.2 Northern zone

To the north, extending as far as the 600 mm isohyet, is a zone where careful cultivation allied with soils capable of storing much water would raise the amount of effective rainfall sufficiently to produce economically interesting yields. These were the findings of an investigation of the potentialities of cotton production in the Republic of the Niger (unpublished).

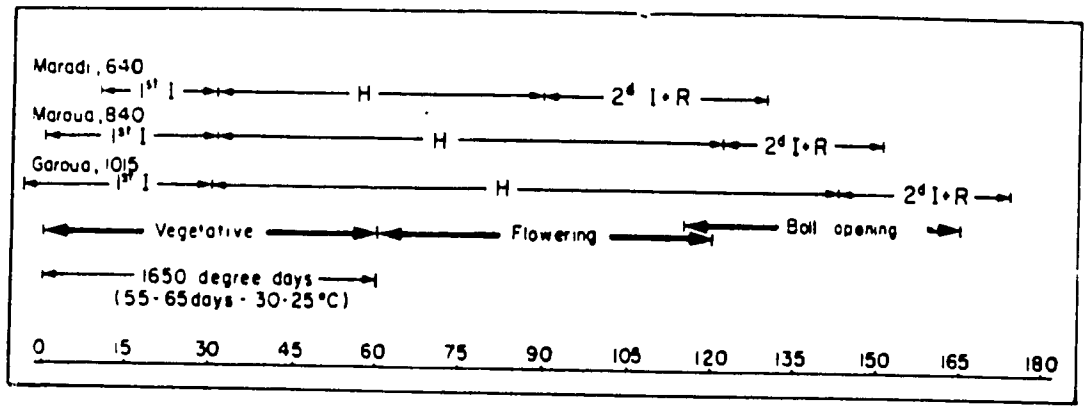

Figure 59 -- 165-day growing period of cotton in Area and availability-of-water periods at three localities. Maroua is only slightly shorter and represents the central zone of optimum production. Garoua is longer, and sowing there might be delayed. Maradi is shorter and requires sowing as early as possible and good water storage to lengthen 2nd I + R period.

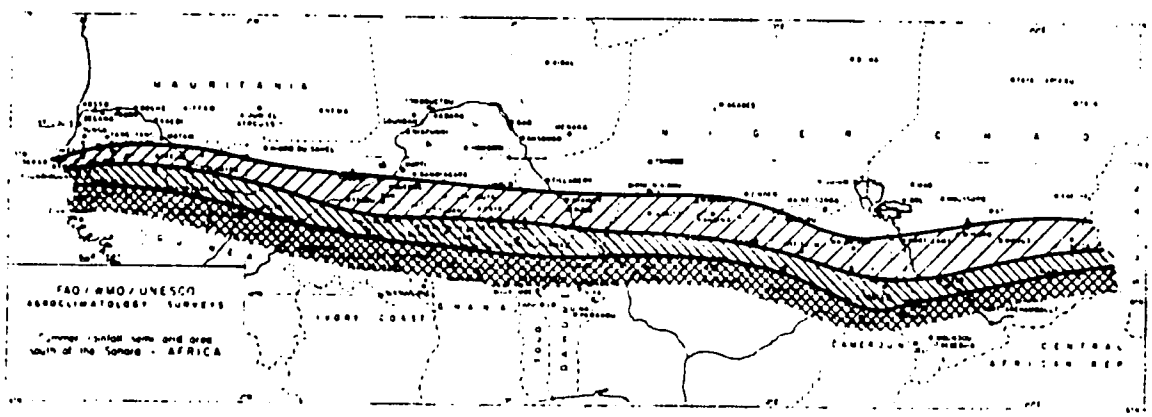

Figure 60 -- Climatic zones of rain-fed G. hirsutum var. Allen. Boundaries from north to south correspond to 600 mm annual rainfall and to 150 days and 170 days moist period with reserve.

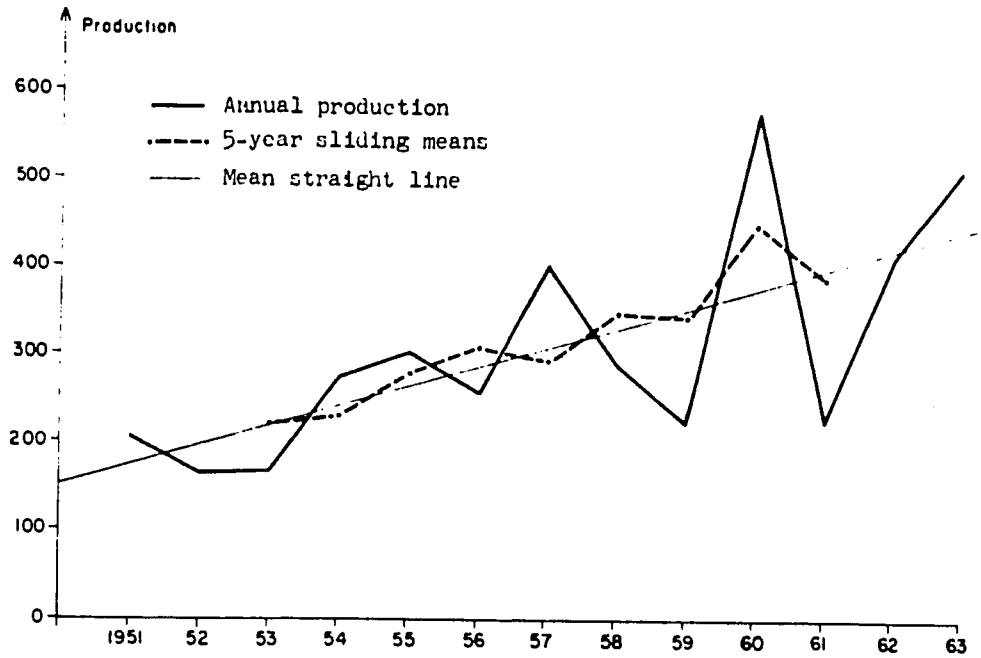

Figure 61 -- Cotton production in kg. ha^{-1} in the Fort Archambault district, and long-trend correction to isolate climatic fluctuation.

5.2.3 Southern zone

To the south of the optimal zone lies another to which no southern boundary has been allocated, where the availability-of-water periods appear too long for this particular ecotype. It is, of course, realized that breeding is in progress to produce forms able to react satisfactorily to a greater range of conditions; and that constant progress in cultivation techniques tends to minimize the adverse effects of climate.

6. AN ANALYSIS OF THE CLIMATIC CONTROL OF FLUCTUATIONS IN PRODUCTION

Annual production data from the Fort Archambault district, in Chad, for the period 1951 to 1963, were selected for an analysis of the effects of climate.

6.1 Long-trend correction

These data were first of all corrected by subtracting a long-term improvement obtained by fitting a straight line through plots of the production values, as shown in Figure 61. This improvement is due mainly to an increase in cultivation areas and a general development of cultivation techniques. It is thought that a better correction would be obtained by using five-year sliding means (represented by a broken line in Figure 61). This would have the disadvantage of shortening at both ends an already very short series of annual data.

6.2 Climatic variables

The climatic variables analysed were derived from a comparison of ten-day rainfall amounts and monthly E_T estimates at Fort Archambault itself, taken to be representative of the whole district. Mean dates to the nearest ten days for the availability-of-water periods were estimated as follows:

beginning of moist,	1 May;
beginning of humid,	1 June;
end of humid,	10 October.

Sowing was assumed to take place on 1 July -- a consequence of the relatively long duration of the availability-of-water periods on the southern border of the Area.

Fourteen climatic variables, listed below, were selected. Their yearly values are tabulated in Table 27 together with real (Pr) and corrected (Pc) production figures.

X_1	Rainfall in April and May
X_2	Rainfall in June
X_3	Rainfall in July
X_4	Rainfall in August
X_5	Rainfall in September
X_6	Rainfall in October and November
X_7	Duration of humid period in decades
X_8	Number of decades from the end of August to the end of the humid period
X_9	Number of decades from the beginning of the humid period to the beginning of August
X_{10}	Rainfall during the humid period
X_{11}	Rainfall per decade of the humid period, X_{14}/X_7
X_{12}	Rainfall during post-humid period
X_{13}	Rainfall during pre-humid period
X_{14}	Total rainfall

6.3 Regressions and correlations

Regression coefficients (b) and correlation coefficients, simple (r) and multiple (R), for the first seven variables are shown in Table 28.

6.3.1 Simple correlations

None of the simple coefficients were statistically significant. This may be due to the curvilinear nature of the regressions -- as was demonstrated in the case of millet. However, adaptations of the crop to the rainfall régime appear to be much looser in the Fort Archambault district in the south of the Area, since sowing takes place during the moist period and all the available water is not used. This poor correlation may also be due to the difficulty in assessing corrected production data, as discussed above. The best simple coefficient, 0.45, was obtained with X_7, length of the humid period.

TABLE 27

REAL (P_r) AND CORRECTED (P_c) PRODUCTION FIGURES IN THE FORT ARCHAMBAULT DISTRICT

Year	P_r	P_c	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
1951	203	205	137	110	251	318	178	163	14	6	5	957	68	62	152	1171
1952	162	142	37	106	150	389	315	125	11	3	5	935	85	44	145	1128
1953	166	123	112	155	104	241	175	69	13	6	4	675	52	70	136	881
1954	275	209	107	168	285	423	103	107	14	6	5	1075	77	11	107	1193
1955	300	211	256	125	196	234	266	121	17	9	5	1112	65	3	82	1197
1956	254	142	65	135	185	312	253	19	11	5	3	811	68	19	152	993
1957	402	267	250	116	215	328	116	65	14	9	2	911	65	99	80	1091
1958	290	133	140	110	189	257	308	28	12	5	4	801	67	28	205	1034
1959	223	43	219	131	316	250	118	67	14	8	3	978	70	67	148	1101
1960	575	373	157	146	199	325	156	139	14	6	5	886	63	78	159	1124
1961	226	-	170	229	347	251	106	72	12	6	3	933	78	72	190	1194
1962	414	165	124	95	140	240	226	59	12	5	4	736	61	23	137	898
1963	515	244	285	169	249	277	134	53	16	10	3	1078	67	53	36	1181
	308	174	158	138	217	296	189	83.5	13.4	6.5	3.9	914	68.2	48.4	133	1116

NOTE: X_1 to X_{14} are climatic parameters, defined in the text. X_1 to X_6 are calendar parameters in terms of monthly rainfall, and X_7 to X_{14} are related to availability-of-water estimates.

TABLE 28

REGRESSION (b) AND CORRELATION COEFFICIENTS SIMPLE (r) AND MULTIPLE (R) OF YIELD ON VARIABLES X_1 TO X_6, BASED ON MEAN RAINFALL DURING CALENDAR MONTHS OR GROUPS OF MONTHS; ALSO X_7, DURATION OF THE HUMID PERIOD IN DECADES

b_1	b_2	b_3	b_4	b_5	b_6	b_7	r	r^2	R	R^2
0.39							0.22	0.05		
	-0.75						-0.28	0.08		
		-0.40					-0.29	0.08		
			0.59				0.38	0.14		
				-0.06			-0.05			
					0.90		0.40	0.16		
						25.31	0.45	0.20		
0.35	-0.88								0.39	0.15
0.50		-0.61							0.46	0.22
0.59			0.91						0.56	0.31
0.31				0.07					0.23	0.05
0.31					0.93				0.46	0.22
-0.47						41.27			0.51	0.26
	-0.45	-0.27							0.33	0.10
	-0.70		0.57						0.45	0.20
	-1.35			-0.46					0.40	0.16
	-0.65				0.84				0.46	0.22
	-0.87					27.01			0.59	0.35
		-0.44	0.63						0.49	0.24
		-0.76		-0.52					0.43	0.18
		-0.45			0.95				0.52	0.27
		-0.57				30.65			0.61	0.37
			0.60	-0.10					0.38	0.14
			0.40		0.67				0.46	0.21
			0.72			29.21			0.63	0.40
				-0.03	0.89				0.40	0.16
				-0.05		27.23			0.46	0.22
					0.66	20.65			0.54	0.29
0.49	-0.37	-0.49							0.48	0.23
0.67	-0.92		0.92						0.65	0.43
-0.37	-0.79					39.40			0.59	0.35
1.03		-0.91	1.23						0.81	0.65
-0.20		-0.53				37.11			0.62	0.38
-0.01			0.72			29.41			0.64	0.41
	-0.30	-0.35	0.61						0.50	0.25
	-0.36	-0.46				30.31			0.62	0.39
	-0.83		0.70			30.77			0.71	0.50
		-0.66	0.81			35.85			0.79	0.62
1.03	0.02	-0.92	1.23						0.81	0.65
0.67		-0.84	1.10			16.44			0.83	0.68
0.99		-0.91	1.05		0.53				0.84	0.70
0.94		-1.17	1.24	-0.43					0.85	0.72
0.91		-1.15	1.08	-0.40	0.48				0.87	0.76
0.60		-1.10	1.12	-0.41		12.26			0.86	0.74
0.81		-0.87	1.02		0.43	8.21			0.84	0.70

NOTE: From top to bottom: simple coefficients, and multiple coefficients with two, three, four and five variables.

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6.3.2 Multiple corrélation

However, some of the multiple correlation coefficients were significant, notably: X_1-X_3+X_4, X_1-X_3+X_4-X_5, where X_5 is rainfall at the height of the flowering period when excess might cause washing away of the pollen, and X_1-X_3+X_4-X_5+X_6, where X_6 represents the rains of the post-humid period. All these multiple coefficients have a chance occurrence level of less than 1 in 100, and the last combination of five variables accounts for 76 per cent of the fluctuation in corrected production assumed to be due to climate.

6.3.3 Factors X_7 to X_{14}

Table 29 shows the coefficients obtained by comparing production with variables X_7 to X_{14} which take into consideration availability-of-water periods.

TABLE 29

REGRESSION (b) AND CORRELATION COEFFICIENTS SIMPLE (r) AND MULTIPLE (R) OF YIELD ON THE VARIABLES X_7 TO X_{14} BASED ON CONSIDERATIONS OF THE AVAILABILITY-OF-WATER PERIODS

b_7	b_8	b_9	b_{10}	b_{11}	b_{12}	b_{13}	b_{14}	r	r^2	R	R^2
25.31	12.45	27.00	0.14	-3.36	0.27	-0.96	0.14	0.45 0.26 0.29 0.19 -0.29 0.08 -0.46 0.16	0.20 0.07 0.08 0.03 0.08 - 0.21 0.03		
41.89	22.48 -19.20 21.81 31.42 19.97 21.89 4.65	45.15 3.76 45.17 56.02 44.99 54.48 37.50	-0.18	-2,65	0.79	-0.95				0.51 0.51 0.51 0.55 0.56 0.56 0.60	0.26 0.26 0.26 0.30 0.31 0.31 0.36
	41.17	86.15	-0.70	6.30	0.78	-1.24				0.67	0.45

Again, none of the coefficients of simple correlation were significant, but higher values were yielded by multiple correlations, although none reach a 1 in 20 chance occurrence level. The highest, 0.67, is obtained with X_8, X_9, X_{10}, X_{11}, X_{12} and X_{13}, and accounts for nearly 45 per cent of the assumed climatic fluctuation. The weaknesses inherent in coefficients of multiple correlation are realized.

6.3.4 Position of humid period

Since cotton is photopheriodically neutral, the position of the humid period with respect to flowering does not have the same importance as in the case of sorghum. However, the fluctuations of the extensions of this period preceding and following August, its central

month, (X_8 and X_9) were found to account for a greater part of the production variation than the fluctuations of the mere length of the period (X_7).

7. YIELD VARIATION IN SPACE

7.1 The data

Data for the period 1952-1963 from eight cotton-producing districts from north Cameroon obtained from the Compagnie Française pour le Développement des Textiles (CFDT) made it possible to carry out an analysis of the yield variation in space due mainly to climate, but also to soils and the technical level of cultivation.

7.2 Factors considered

The factors considered were mean annual rainfall for the 12 years (X_1), mean yield for the first 3 years (X_2), and latitude (X_3). The values of these factors in each district are listed in Table 30, together with mean yield for the 12 years (R^t) and mean rate of improvement in yield during the period (z).

The yield at the beginning of the period, X_2, was considered to be an index of soil fertility.

TABLE 30

DATA ON DISTRICT COTTON PRODUCTION IN NORTH CAMEROON

REGION	R^t	X_1	X_2	X_3	X_4	z
REY-BOUBA	260	1160	280	8°6	1005	3
GAROUA	330	955	355	9°3	925	6
GUIDER	495	985	505	9°9	1125	14
KAELE	430	895	440	10°1	975	8
YAGOUA	250	880	245	10°3	1085	7
MAROUA	500	790	385	10°5	790	30
MOKOLO	560	920	370	10°7	1000	44
MORA	675	840	420	11°0	790	67
Average	437	928	375	10°0	962	22.4

NOTE: R^t, mean yield in $kg.ha^{-1}$. X_1, mean annual rainfall in mm. X_2, mean yield during the first three years. X_3, latitude of district headquarters. X_4, mean annual rainfall during the first three years. z, mean slope of yield improvement in $kg.ha^{-1}$. $Year^{-1}$.

7.3 Regressions and correlations

Coefficients of regressions and correlations, simple and multiple, between yield and the factor considered were calculated, and are listed in Table 31. They show that mean yield increases with decreasing rainfall, and with latitude. The correlation coefficient of mean yield with latitude itself, significant at the 0.05 level, is not completely accounted for by rainfall alone. Sunshine and higher temperatures probably also play a part in the higher productivity of the north. However, no other climatic factors besides rainfall were

TABLE 31

REGRESSION (b) AND CORRELATION COEFFICIENTS, SIMPLE (r) AND MULTIPLE (R) OF YIELD AND INCREASE IN YIELD DURING THE PERIOD ON VARIABLES X_1, X_2 AND X_3

	b_1	b_2	b_3	r	r^2	R	R^2
YIELD	-0.70			-0.53	0.28		
		1.23		0.69	0.48		
			143.81	0.75	0.56		
	-0.51	1.06				0.78	0.61
	0.63		221.93			0.79	0.62
		0.90	112.84			0.89	0.79
	0.56	0.91	185.12			0.92	0.85
PERIOD : z	-0.11			-0.52	0.27		
		0.08		0.30	0.09		
			22.66	0.77	0.59		
	-0.10	0.05				0.55	0.30
	0.12		37.34			0.83	0.68
		0.02	22.06			0.77	0.60
	0.12	0.01	36.73			0.83	0.68

analysed, partly owing to lack of data. The adverse effect of rainfall is thought to be partly due to increased parasitism.

The initial yield appeared to be poorly correlated with latitude, and with rainfall during the first three years.

The slope of the mean improvement in yield was found to increase steeply with latitude, as shown by the graph in Figure 62, on which the increases in yield at Mora and Kaele are compared.

7.4 Map analysis

In Figure 63, three maps of the Area show, in the first place, the relative locations of the places which gave their names to the districts. In map (a) lines of equal mean yield and annual rainfall for the period have been plotted. They show a yield gradient towards the north-west and an inverse rainfall gradient towards the north-east; so that both yield and rainfall are related with latitude.

Map (b) shows initial fertility, sloping away from Guider in the centre of the region but hardly reduced at all in a northerly direction and falling off sharply to the east and south. Map (c) illustrates the very strong gradient in the rate of improvement from Guider to Mora, from south to north.

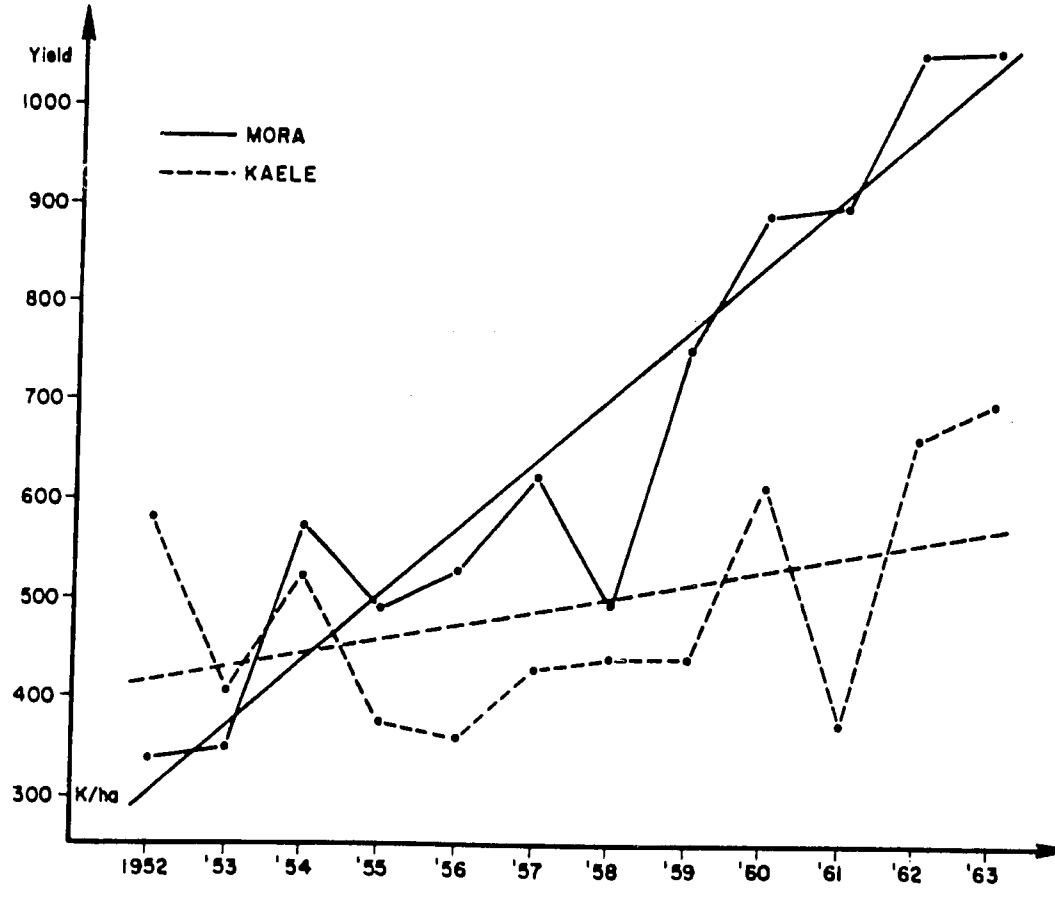

Figure 62 -- Annual yield variation at Mora and Kaele. The straight lines represent improvement trends.

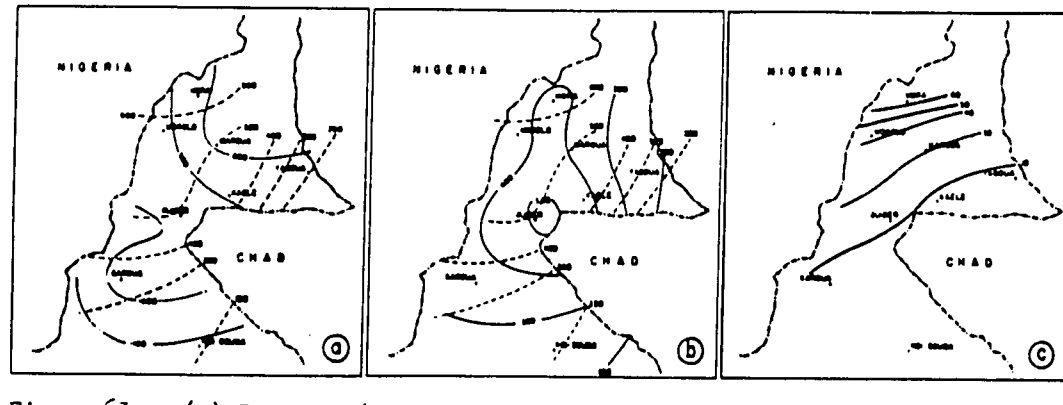

Figure 63 -- (a) Isohyets (plain lines) and mean yield for the period (broken lines), showing north-north-east inverse rainfall gradient and north-west productivity gradient. (b) Average yield over the first three years (initial yield) (plain lines), with a maximum around Guider and a steep decrease to the west-south-west and again mean yield for the period (broken lines). (c) Lines of equal improvement in yield with an increasingly steep gradient towards the north.

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7.5 Discussion of results

Mean annual rainfall amounts in the north are close to the range (750-850 mm) assured to be the best for the cotton variety grown in the Area. The fact that the mean yield gradient is at an angle to the inverse rainfall gradient suggests there is also a soil and initial fertility gradient towards the west or north-west.

Two features remain unexplained: firstly, the fertility gradient was not reflected in the initial yield data shown in Figure 63 (b); secondly, the very rapid improvement in the north, assuming that the technical level had been uniform.

7.6 Expert information from the region

Two private communications from cotton specialists in the region provided satisfactory explanations. The first (from Tourancheau) expressed general agreement with the form and findings of the analysis, stating that in north Cameroon "dry years gave good yields". It confirmed that the varieties grown were better adapted to the conditions found in the northern districts.

It also stated that there was a soil fertility gradient from south to north and added that yields were also conditioned by a parasitism gradient increasing eastwards.

Further, it pointed out that the districts used in the analysis -- the ones for which yield figures were published -- were in fact administrative districts rather than natural cotton-producing regions. It suggested a more appropriate subdivision which appears in the Technical Report.

The second (from Guillard) explained that the initial fertility pattern was biased by the fact that cultivations had started and at first concentrated on the central districts, in the assumption that they were the best. Later, a realization of the higher potentials of the northern districts led to their fuller exploitation.

This illustrates well the diversity of factors which must be taken into consideration in such an analysis. Climate, however, seems to be connected with most of them.

GROUNDNUT

1. DISTRIBUTION

Groundnut grown as a subsistence or a cash crop is found south of the 400 mm mean annual rainfall line where soil and other factors permit its cultivation, as shown in Figure 64. Soils must be of a texture and compaction such that they can be penetrated by the fruit-bearing stems and will not later retain the nuts when the plant is uprooted.

Important groundnut-producing regions are found in all the countries of the Area, notably in northern Nigeria, Senegal (see map in Figure 9 in Part I), and in southern Nigeria and Chad.

2. PRODUCTION AND YIELDS

Production in 1965 according to FAO was as follows:

	Green shelled, metric tons	Value US $
Senegal	204 400	35 343 000
Mali	29 790	4 149 000
Upper Volta	3 190	411 000
Niger	85 620	13 038 000
Nigeria	624 000	102 463 000
Chad	1 770	210 000

3. CLIMATIC NEEDS AND TOLERANCES

The cycle may be broken into three parts: vegetative period, flowering, maturing. An example of relative duration will be given presently.

3.1 Growth cycles

Cycles vary from 85 days (corresponding to about 450 mm mean annual rainfall) to 160 days (960 mm). However, groundnut is found in areas of as much as 1,200 mm rainfall growing as a catch crop, for which purpose the short-cycle varieties are often used although, other things being equal, longer-cycle varieties will return a higher yield.

3.2 Seasonal water need

Although the early varieties grown in the north show good resistance to drought, especially during the vegetative period, groundnut has been found to need water at most stages of its growth and development but more particularly during the period of useful flowering.

Flowering is axial, as in the case of cotton, but as there is a single harvest -- uprooting -- the flowering corresponding to the fruits harvested should constitute a more compact grouping. Ripe nuts left in humid ground will tend to germinate whilst nuts maturing long after the rains when the ground has hardened might not be possible to harvest.

3.3 Temperature

Temperatures appear to affect the rate of development, notably that of flower production, even within the fairly uniform régime of the Area. This would allow short-cycle varieties grown in the north to produce a sufficient number of flowers in a short time.

3.4 Photoperiodism

Though groundnut is generally held to be photoperiodically neutral, variation in the cycle length of some late varieties when sown at different dates suggests short-day reactions.

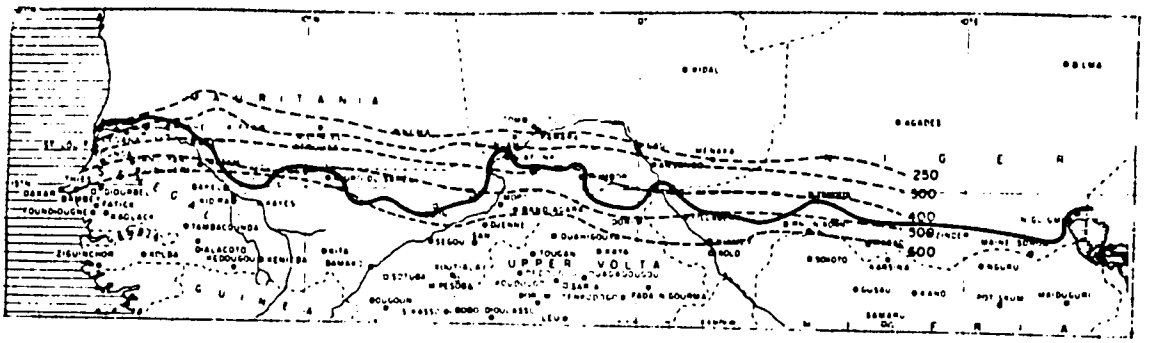

Figure 64 -- Northern limit of cultivation of groundnut, with isohyets. Disregarding flood-plain and irrigation areas in the vicinity of the rivers Senegal and Niger and of Lake Chad, the limit seems to vary between 400 and 600 mm.

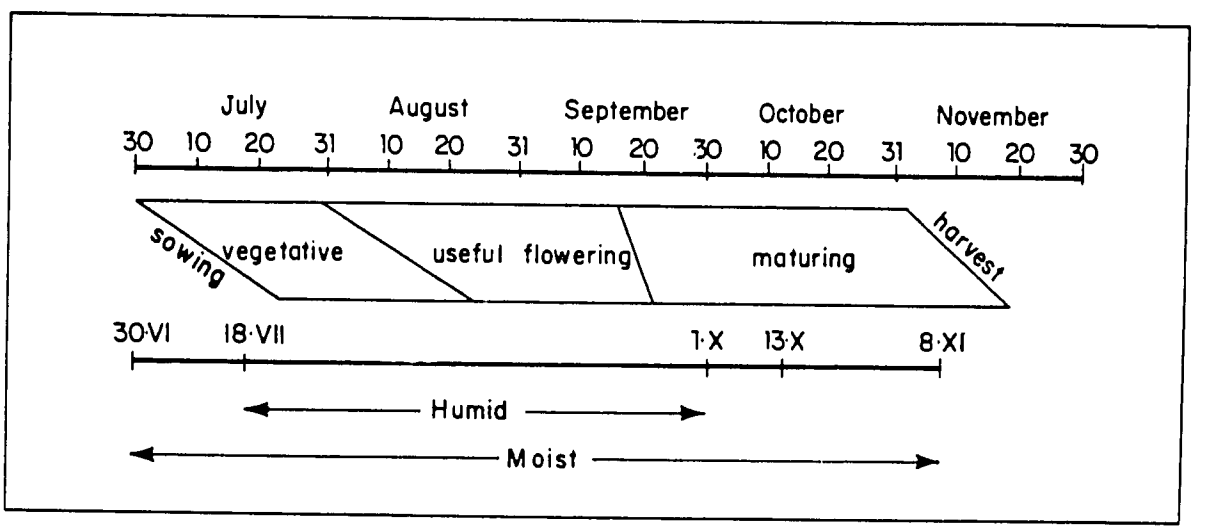

Figure 65 -- Below a time scale in days are shown the occurrence and range of the main biological events observed by Delolme in the Diourbel district; lower down appear the average dates of the availability-of-water periods at Thies.

4. MATCHING OF ECOTYPE TO CLIMATE

A paper by Delolme (1948) gives the actual range of cycles and main biological events for the groundnut varieties grown in the Diourbel district in Senegal. His graphical representation is shown in Figure 65 together with a diagram of the average timing of availability-of-water periods at Thies, nearby, drawn on the same time scale. Cycles and periods agree well. The total growth cycle corresponds to the moist period with reserve. Useful flowering occurs during the humid period within the range of sowing dates. Most of the maturing takes place after the humid period, thus minimizing the risk of germination. Harvest takes place as the soil is just drying out. This appears to be good adaptation of a crop to the climatic environment. It suggests that the availability-of-water periods are useful working agroclimatic parameters.

5. PARASITISM

Groundnut is sensitive to the rosette virus, which is carried by an aphid. The time of infection determines the extent of the damage. If it occurs earlier than the fortieth day, the crop may be totally destroyed.

The fact that the disease is more prevalent in the south suggests relatively high humidity as a climatic factor fostering aphid proliferation. It is thought possible that the aphids might be carried northwards from more humid source areas by the moist monsoon current. It might therefore be feasible to forecast the imminence of rosette infection; thereby attaining more concentrated, and hence more efficient and economical spraying, timed so as to provide maximum protection at the time of maximum exposure to the virus.

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MAIZE

1. COMPETITION WITH SORGHUM, AND DISTRIBUTION

If maize cultivation in the Area is increasing slightly at the expense of millet and sorghum, there are indications that it is also likely to give way to other more desirable cereals such as rice and wheat.

It is met as far north as sorghum and lends itself equally to flood cultivation, wherever its greater demands on soil fertility are satisfied. In the south of the Area it can be grown, like sorghum, either as a long-cycle crop or as a catch crop, and it is found everywhere.

Comparative figures are shown in the table below.

	Senegal	Mali	Upper Volta	Niger	Northern Nigeria	Chad
Maize	26 000	100 000	127 000	4 000	425 000	12 000
Millet and sorghum	463 000	800 000	1 266 000	1 328 000	6 423 000	850 000

(From FAO Production Yearbook 1965 and national sources.)

Yields in the Area are relatively poor. Maize is grown more successfully in many parts of the world -- notably in the "corn belt" of North America -- and is found as far as 58° north when warm and humid conditions are available.

2. WATER NEEDS

Available information on cycle length gives a range of 40 to 190 days. This means that in terms of this parameter it has access to the whole Area, using either the entire growing season, or, as mentioned above, only part of it.

In the maize plant, as compared to sorghum, the leaves have a thinner cuticle and less wax; its secondary root system is less extensive; its water content is higher and so is its transpiration in identical conditions. Also, it cannot compete with the tillering of sorghum.

Against this, very young maize seedlings have a special ability to resist and subsequently recover from dry spells, because of the way the leaves are rolled round the stem. This makes early sowing possible.

3. HEAT AND LIGHT

The minimum temperature requirements of maize are such that it would not be restricted on this score anywhere in the Area. It is possibly limited by excessive maximum temperatures although no precise data are available and the multiplicity of varieties and forms suggests that some might be resistant.

The short-cycle varieties appear not to be photoperiodically controlled, but those with a longer growth are short-day. This is an important characteristic which should be considered whenever new varieties of maize are to be introduced.

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THE CROPS

LEGUMINOUS PULSES

1. DISTRIBUTION

Besides groundnut, cowpea is another important source of vegetable proteins in the Area, throughout which its cultivation is spreading. The same cultivation applies to other types of leguminous pulses besides cowpea.

Production figures for 1965 (in metric tons) were as shown in the table below.

Senegal	Mali	Upper Volta	Niger	Northern Nigeria	Chad
21 000	30 000	85 000	80 000	680 000	-

(From FAO Production Yearbook for 1965 and national sources.)

2. WATER NEEDS

Cycle range extends from 45 days in the case of an early variety eaten green to 140 days. This gives it access to the whole of the Area and, in the south, to various sections of the growing season.

3. HEAT AND LIGHT

In common with other crops of the Area, varieties are short-day or neutral photoperiodically.

Long-day varieties from the winter rainfall areas of North Africa (such as Egypt) require early sowing; alternatively, they may constitute an interesting source of green fodder because of the prolonged pre-flowering growth which occurs when these varieties are grown during the second half of the year.

4. PARASITISM

An important controlling factor is insect-borne diseases. The vectors are sensitive to climate, becoming more numerous and active with the increasing humidity of the summer rains. Yields may be considerably reduced; however, early sowing, where it is possible, increases production.

PASTURES AND FODDER

In the agricultural system of the Area, land impoverished by cultivation is allowed to recuperate by lying fallow, sometimes for 10 years or more, and during that period livestock feed on plants growing on it as well as on the areas permanently set aside for grazing.

The maintenance of pastures and the production of fodder in the Area are therefore essentially connected with this system of fallows, and the two subjects will be discussed together.

1. AGROCLIMATIC FACTORS

Climate occupies an even more important part amongst the physical environmental factors in this section of agriculture than in those where human intervention is more direct and continuous.

1.1 Availability of water

The main agroclimatic problem, here as in the case of the crops already discussed, is one of adaptation to the duration of the availability- and non-availability-of-water periods, of the local or imported pastures and fodder plants available. The growth, or in the case of perennials, the active growth cycle, must fit the rainy season and the survival of perennial forage plants is controlled by the length of the dry season.

1.2 Water surplus

As already mentioned in Part II, water surplus occurs everywhere in the Area during the humid period and, where this surplus is excessive, it has a negative effect on the production of annual crops. It was suggested, on the other hand, that in the case of perennial forage plants with long roots, this surplus might determine, in privileged sites with deep soils, the permanent establishment of pastures. For similar mean annual rainfalls, water surplus may vary as shown in Table 32 extracted from Table 13.

TABLE 32

	P	WS	WS/p
Maiduguri	660	159	0.24
Thies	695	244	0.35
Mongo	860	367	0.43
Ouagadougou	880	247	0.28

NOTE: P, mean annual rainfall; WS, mean annual water surplus showing variation in relative amount of water surplus.

1.3 Flowering

The time of flowering, often induced by photoperiodism, and sometimes hastened by high temperatures, is also of importance, since it affects the possibility of finding the green and edible vegetative forms at various times of the year.

2. FALLOW IMPROVEMENT AND SUBSTITUTES

A number of steps can be taken to improve the quality and amount of the food available to livestock, depending on the conditions in which these animals are kept in the Area. These measures are discussed in increasing order of complexity.

2.1 Protected natural fallows

The simplest form of pastoral improvement consists of natural fallows surrounded by fences and guarded against grazing or fire, which may be subdivided into:

(i) Completely protected fallows, which are only justified when soil has become unproductive, not when soil fertility has merely to be maintained at a certain level. The effect of protecting fallows is to regenerate the soil. It does not in itself replace useful forage plants eliminated by cultivation. A first level of fertility is regained after two to four years in the south and three to

six years in the north. To regain full potential fertility, a much longer period is necessary, in order to establish the microclimate which natural vegetation, with its denser cover, provides. During cultivation, the increased aeration and temperature, and the reduced humidity, destroy organic matter.

(ii) Partially protected fallows, where some control on firing and grazing is maintained, especially at first. Firing is, in fact, not invariably negative in its effects. It can be one of the best and cheapest methods of encouraging the development of useful gramineous plants. The best time to fire is at the end of the dry season after the first good fall of rain. Tufts of useful perennials like Andropogon gayanus are then able to provide an excellent regrowth. (The seeds of annual grasses, incidentally, are not harmed, since they are protected by soil humidity.) Early firing at the beginning of the dry season, on the other hand, favours bushes and trees at the expense of grasses.

Besides these fallows, the land set aside or available for permanent pasturing, which increases very rapidly in extent towards the north of the Area, may also need controlled firing.

2.2 Seeded fallows

The next step is to foster by seeding the re-establishment of perennial species, which plowing has eliminated, and which cannot at first compete with the more rapidly developing annuals.

A knowledge of the climatic needs and tolerances of the desirable perennial varieties is of course essential in choosing which to grow in the zones of different rainfall régimes. The flowering time of these perennials is important, as it often marks the end of their green palatable phase and is followed by dessication of the parts above the ground. In all cases, the number of the desirable varieties available decreases from the south to the north of the Area.

The best local species available for seeding is Andropogon gayanus, of which there are many varieties. They cover a wide range of flowering dates: 50 days in a typical collection from northern Nigeria. The range of the dates of the end of the humid period between 1000 and 400 mm mean annual rainfall in the Area is 30 days.

A. gayanus is the species that is best known, most studied, and most experimented with. It has been used for much fallow reseeding in various parts of the Area. It is found naturally at least as far north as the 400 mm isohyet where the dry season lasts about 200 days. At Fort Lamy (650 mm) it is known to produce some green grass at the bottom of the tufts all the year round.

Leguminous plants are also used and some of them are more adaptable to conditions in the north of the Area. Much remains to be found out about their climatic tolerances.

Amongst the imported varieties suitable for reseeding, a leguminous plant, Stylosanthes gracilis, with a northern limit of about 900 mm, is thought to be important in the south of the Area.

Finally, it is of course also possible to grow certain annuals on these seeded pastures.

2.3 Temporary pastures

Temporary pastures are entirely sown and meant to exclude competition from local species growing spontaneously. Because these leys require more attention than improved fallows, a greater range of species can be grown. Most of those which have already been quoted can be grown, and A. gayanus is prominent amongst them. Buffel grass, reputed in Australia to accommodate low and variable rainfall, may also be mentioned. Amongst leguminous plants, S. gracilis may again be mentioned, and Dolichus lablab, one of the pulse-producing species, is interesting because of its long-day varieties which flower in April-May, so that they are available in the vegetative state during the dry season.

Finally, certain annuals may be used, notably A. pseudapricus and Pennisetum pedicellatum.

2.4 Annual fodder production

Annual forage production implies growing annual forage plants specially for feeding livestock. Short-cycle annuals can be used and this production is therefore possible right up to the northern boundary of the Area.

Amongst Graminae, sorghums, like Sudan grass, appear the most interesting. S. almum is developed at Bambey where the duration of the moist period with reserve can be estimated as 130 days.

From the Leguminosae, only producers of grains like cowpea and D. lablab appear to be interesting. They have relatively short growth cycles.

3. PRACTICABILITY AND INTENSITY OF THESE MEASURES

All these standard methods of intensifying pastures and fodder production are technically possible everywhere in the Area, to a degree depending on the climatic conditions discussed at the beginning of this chapter, and on the plants available to meet these conditions. But the extent to which this intensification is taken will depend in the last resort on socio-economic considerations.

PART IV

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

AGROCLIMATIC CHARACTERIZATION OF THE AREA

1. GENERAL CONSIDERATIONS

1.1 Introduction

As was indicated at the beginning of this report, the main purpose of the study is to make an inventory of the climatic resources of an area and, to that extent, of its food-producing potentials.

In the present world drive for intensification of agricultural production, it is essential to consider groups of several countries of similar physical environment and potentials of production. With this in view, the report describes the seasonal occurrence and spatial distribution of climatic factors, increasingly selected to characterize the needs and tolerances of important crops in an area showing much homogeneity of climate.

Because of the size of the Area, which covers eleven countries, this survey is of a general nature, although sometimes it quotes or presents more detailed studies. Some of its salient features are repeated below and, at the same time, the most useful way of presenting the basic information, which constitutes its main import, is discussed.

1.2 Characteristics of the summer rains

1.2.1 Dual nature of climate in the Area

It has been shown, in terms of the circulation of the atmosphere, how a moist and warm climate alternates each year with one that is dry and seasonally hot.

1.2.2 Milder conditions during summer rains

During the rainy season or monsoon, sunshine, air temperatures, saturation deficits and wind strength are such that, with the possible exception of night temperatures, they do not appear to have a limiting effect on the productivity of the crops in the Area. At the same time, daily mean rates of potential evapotranspiration are reduced to 4 mm or less, well within the water conducting capabilities of these crops (Table 33).

1.2.3 Daily rainfall amounts

In the Area, rainfall per day of rain is about 14 mm on an annual basis. Mean daily rainfall averaged over the whole of the growing season is about 5.5 mm, and mean daily effective rainfall during that time is about 4 mm. This uniformity in the relation between rainfall amounts and duration is characteristic of the simple rain-bearing mechanisms of the Area and would not apply to other parts of the world, even in the tropics.

TABLE 33

MONTHLY MEAN POTENTIAL EVAPOTRANSPIRATION IN MM PER DAY

	J	F	M	A	M	J	J	A	S	O	N	D
Agadès	4.45	5.75	6.16	6.75	7.03	6.81	6.53	5.74	5.66	5.45	4.84	4.19
N'Guigmi	3.83	4.59	5.20	5.72	5.95	5.98	5.43	4.71	4.88	4.83	4.21	3.57
Gao	4.56	5.88	6.87	7.32	7.93	7.63	6.80	5.71	6.11	5.86	4.91	4.54
St. Louis	4.22	4.59	5.49	5.17	4.75	4.70	4.69	4.52	4.60	4.54	4.24	4.06
Tahoua	5.90	6.65	6.83	7.47	7.72	7.58	6.00	4.89	5.47	6.11	6.19	5.13
Abéché	4.55	5.44	6.11	6.86	6.54	5.84	4.90	3.83	4.59	5.28	5.19	4.25
Matam	3.06	3.74	4.57	5.20	5.73	6.20	5.02	4.37	4.56	4.42	3.48	2.95
Mopti	4.72	5.82	6.78	7.43	6.80	6.29	4.99	4.48	4.53	4.76	4.50	4.17
Zinder	4.44	5.48	5.95	6.39	6.39	6.15	5.08	4.12	4.87	5.39	4.81	4.19
Dakar	4.59	4.78	5.16	5.76	5.36	5.51	5.14	4.55	4.75	4.81	4.96	4.88
Birni N'Konni	4.58	5.45	5.85	6.24	6.42	6.09	4.74	4.22	4.53	4.83	4.46	4.25
Niamey	5.20	5.98	6.68	6.96	7.08	6.76	5.04	4.23	4.58	5.52	5.06	4.61
Maradi	3.77	4.37	4.94	5.55	6.02	5.87	4.65	3.91	4.35	4.33	3.83	3.46
Fort Lamy	4.70	5.77	6.64	7.21	6.85	5.84	4.43	3.74	4.44	5.14	5.24	4.53
Maiduguri	4.66	5.68	6.48	6.95	6.70	5.74	4.34	3.64	4.32	5.04	4.96	4.27
Thies	4.31	5.22	6.16	6.39	5.79	5.14	4.39	3.71	3.99	4.16	3.92	3.59
Segou	4.44	5.30	5.93	6.05	6.31	5.70	4.53	3.96	4.25	4.59	4.42	4.14
Sokoto	4.17	4.81	5.43	6.03	5.90	5.41	4.18	3.62	4.14	4.70	4.42	3.90
Kayes	4.34	4.97	5.98	6.56	6.97	5.93	4.66	3.81	4.15	4.47	4.07	3.91
Maroua	4.21	5.41	5.96	5.97	5.80	4.71	3.94	3.38	3.71	4.53	4.47	4.16
Mongo	3.60	4.53	4.74	4.99	5.18	4.45	3.77	3.05	3.60	4.03	3.66	3.46
Kano	4.17	4.96	5.67	6.55	6.60	5.47	4.38	3.70	4.44	4.88	4.49	3.94
Kaele	4.89	5.81	6.23	6.33	5.97	5.91	4.04	3.56	3.80	4.39	4.87	4.70
Ouagadougou	4.56	5.34	6.09	6.39	6.08	4.92	4.29	3.60	3.96	4.77	4.45	4.23
Am Timan	3.82	4.20	4.79	5.30	5.15	4.28	3.49	3.21	3.62	3.97	3.76	3.38
Bousso	3.74	4.47	4.86	5.26	4.58	4.11	3.47	3.06	3.53	3.96	3.84	3.37
Tambacounda	4.02	4.76	5.54	5.86	6.23	4.87	3.67	3.43	3.54	3.84	3.72	3.67
Garoua	4.75	5.68	6.87	7.06	6.02	4.69	4.12	3.83	3.98	4.93	5.28	4.73
Pala	4.15	4.81	5.48	5.47	5.07	4.17	3.61	3.34	3.54	4.26	4.54	4.21
Navrongo	4.57	5.18	5.73	5.73	5.32	4.63	3.87	3.68	3.93	4.68	4.60	4.08
Bamako	4.85	5.80	6.59	6.62	5.96	5.05	4.00	3.58	3.95	4.36	4.29	4.35
F. Archambault	3.65	4.40	4.83	5.04	4.61	3.62	2.95	2.99	3.29	3.78	3.94	3.64
Bobo Dioulasso	4.76	5.62	6.07	5.69	5.26	4.35	3.94	3.79	3.88	4.43	4.28	4.39
Moundou	3.93	4.70	4.89	4.98	4.59	3.79	3.31	3.14	3.30	3.80	4.02	3.74
Kaduna	6.30	6.64	6.22	5.80	5.05	4.06	3.42	3.05	3.76	4.31	4.77	5.55

NOTE: The availability-of-water periods are underlined -- the humid period with a solid line and the intermediate periods with a broken line. During the humid period E_T values do not rise much above 4 mm per day. The highest monthly means occur just before and after the moist period, especially in the north, where it is short.

1.2.4 Drought risks

These amounts exceed the mean rates of potential evapotranspiration occurring during the milder climate of the summer rains shown in Table 33.

When rainfall occurrence during individual years is considered instead of averages, it is seen that it is only at the beginning of the rains that interruptions sufficientl prolonged to cause crop failure are likely to occur. Furthermore, in the greater part of the Area, these interruptions occur only when the beginning of the rains has been premature (as was shown in the case of Zinder -- Availability of Water, paragraph 2.6.1). There is, however, a risk of significant interruptions at any time in the extreme north and also, perhaps, in areas of greater rainfall irregularity such as west Senegal.

1.2.5 Length of the rainy season

Consequently it is, on the whole, the actual duration of the rains rather than the adequacy of the water supply during the rains, which is the most important agroclimatic limitation in the Area.

In order to define more specifically this duration in terms of agronomic productivity potentials, "availability-of-water" periods were used, based on a comparison of rainfall and evapotranspiration.

1.3 Zonation of agroclimate in the Area

The length of the "humid" period, during which rainfall exceeds potential evapotranspiration, varies with latitude fairly uniformly, increasing from north to south from nil to 140 days. All the other parameters derived from the water budget also vary along meridional gradients; positively from north to south like the availability-of-water parameters and sometimes negatively, as is the case with water surplus. Radiation outside the atmosphere, being zonal in distribution, also results in zonal characteristics through its interaction with the zonal cloud and atmospheric humidity pattern of the Area.

In several of the tabulations of the other climatic variables of the 35 reference stations, this common zonation has been represented by arraying the stations according to mean annual rainfall and separating classes every 200 mm. The agreement has been consistently good.

Thus, throughout the Area, the meridional gradients and latitudinal zones, briefly described in Part I, not only in terms of climate but also of vegetation and soils, were found to characterize equally well the more specialized parameters of Parts II and III, as can be seen from the various sets of isolines illustrating them. It must be borne in mind that these isolines are artificial boundaries and that the variations are mostly gradual and continuous.

2. AGROCLIMATIC SUBDIVISION OF THE AREA

2.1 Further subdivision

The question now arises whether the utility of this report would be improved by subdividing the Area further into agroclimatic regions and subregions based on the integration of different climatic variables.

2.1.1 Scale of survey

This question has to be viewed first in terms of the scale of the survey and of the number of reference points used.

Mapping was originally done at a scale of 1:6 000 000, which was further considerably reduced by the printing of the illustrations. (It is thought, however, that the final scale is in keeping with the accuracy of the estimates represented.)

2.1.2 Density of reference points

The number of reference points, 35, corresponding approximately to one station per 100 000 square kilometres, is not conducive to the drawing of detailed boundaries. Lines based on an insufficient number of points may do more harm than good if used to dictate agricultural policy. The need for wind speed, sunshine duration and cloud amounts reduced drastically the number of main reference stations but these elements are essential for evapotranspiration and radiation estimates.

2.1.3 Meridional boundaries

Another difficulty in the agroclimatic subdivision of the Area is the absence of marked meridional boundaries to break up the monotony of the zonation. The differences of a non-zonal nature apparent at the scale of the survey are few and slight and will be discussed briefly.

2.1.4 Wind speed

The wind speed, irrespective of direction, seems to be the only simple meteorological element not zonally distributed; with maxima in northern Mali and on the coast of Senegal and minima in southern Chad. Although this has an important bearing on evaporation rate, it is not thought sufficient to justify agroclimatic subdivision at this stage. The information on mean wind speed given in Part II, Figure 34, should suffice.

2.1.5 Chad and Cameroon

There is some contrast between southern Chad and adjacent northern Cameroon. Southern Chad is more humid, more cloudy and less windy. A result of these differences is seen in the evapotranspiration estimates and possibly reflected in the yields of cotton which are higher in northern Cameroon. These differences, no doubt of great importance in studies at a lesser scale (see Part III, section 7) are overshadowed by meridional gradients when considering the Area as a whole.

2.1.6 Sahelio-Canarian region

In the coastal districts of western Senegal, maritime influence, reinforced by the strong and constant northerly winds associated with the Azores anticyclone, delimits a region sometimes called "Sahelio-Canarian", where the onset of the rains is delayed and their irregularity is greater. The region is also characterized by occasional winter rains. Several of the maps in Part II show vertical lines in that coastal zone and, in the technical report, a map for the hottest month of the year singles out this region as the only one where this occurs after the summer rains. Another illustration shows the short penetration of the maritime influence. This is probably the only valid case for the drawing of a meridional agroclimatic boundary at the scale of this study.

2.2 Systems of climatic classification

Here the more general question of the usefulness of world-wide systems of agroclimatic classification might be discussed briefly in as far as it concerns surveys such as the present one. Such systems may also lead to defining territorial subdivisions on which agricultural policy might be based.

A number of partly independent climatic variables are taken into account and thresholds are chosen arbitrarily to subdivide the variation range into classes. If a large number of variables are considered simultaneously, the system becomes complicated and unwieldy. If only a few factors are retained for the sake of clarity the system is oversimplified (and its use limited to teaching or the very first approach to a problem). For such limited purpose, already existing systems such as that of Koeppen are sufficient.

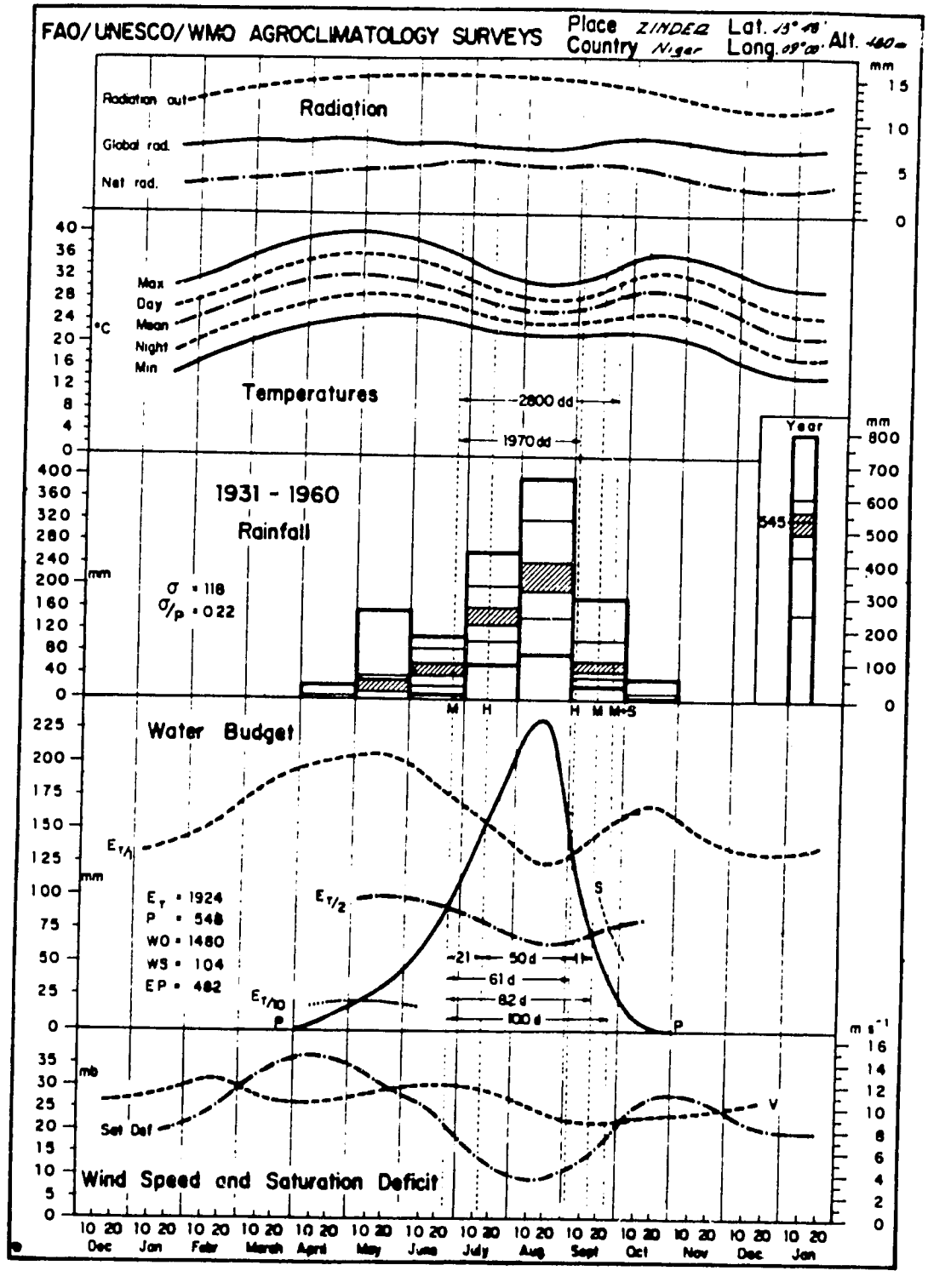

Figure 67 -- Specimen diagrammatic summary of the main agroclimatic characteristics of a reference station (Zinder).

Notes to Figure 67:

Radiation. From top to bottom: radiation incident outside the atmosphere; global and net radiation. All are expressed in millimetres of evaporable water per day.

Temperatures. Extremes and average, and also effective day and night temperatures. Below, sums of temperatures in degree-days accumulated during the moist period plus storage, and during the first intermediate plus humid period.

Rainfall. Monthly variability histogram (based on a 30-year series, 1931-1960), showing, from the bottom upwards, amounts equalled or exceeded 30, 24, 18, 12 and 6 times out of 30. The last value is the highest amount observed during the 30-year period. On the right, yearly amounts. (All heights are given in millimetres.)

Water budget. Comparison of rainfall and three levels of evapotranspiration, demarcating the lengths of the availability-of-water periods. The lengths of these periods are given in days. They are, from top to bottom: the humid between the two intermediate periods; the moist period plus storage; the moist -- and the sum of the first intermediate and the moist period.

Wind speed and saturation deficit. The wind speed, V (broken line) is in metres per second and represents the sum of three daily readings. The saturation deficit (broken line with dots) is in millibars, and is the mean of three daily readings.

In agroclimatology, for each crop variety, for each particular problem (such as the effect of climate on a certain disease affecting a given crop) a different system of classification, involving a different choice of climatic variables and different thresholds is required. Nowadays, the recordings of the variations of the climatic factors can be stored in machines and re-arranged into specialized systems to meet each new requirement as the need arises. (A limited example was given in the case of the cotton ecotype grown in the Area.)

2.3 Conclusion

It is therefore thought that no useful purpose at this stage could be served by subdividing the Area into subregions other than the latitudinal zonation traditionally associated with rainfall amounts, with the possible exception of the Sahelio-Canarian zone.

The main purpose of this survey should be to evolve specific parameters and define their spatial and seasonal variation so that they may be variously recombined as required or used in more detailed investigations.

3. AGROCLIMATIC DIAGRAM

It is on the other hand essential to try to describe as clearly and yet as comprehensively as possible the characteristics of the reference stations. Such description can be usefully summarized by the use of diagrams and thus, to a large extent, freed from the limitations of national language. (Diagrams have, in fact, been employed wherever possible throughout this report.)

An example is given in Figure 67, in the case of Zinder in Niger. The basis of the diagram is the P - E_T water budget comparison, since here it is water which limits the length of the growing season -- elsewhere it could be temperature. Besides this, rainfall, temperatures (including sums corresponding to some of the availability-of-water periods), radiation, wind and humidity characteristics are also depicted or quoted.

Additional climatic factors and parameters, specialized and compounded as needed, should also be listed or tabulated, together with the phenological information or crop calendar available for the main crops grown in the vicinity of the station, to form a comprehensive agroclimatic dossier.

DATA AND NETWORKS

The scope of an agroclimatic survey such as the present one depends on the availability of reliable data both on climate and crops, and these data, whenever possible, should be quantitative. Quantitative data are easier to obtain with a physical science such as meteorology than with agronomy and biology, and this causes a disparity to arise in the information available. Here the nature and origin of the most essential information is reviewed and recommendations thought to be realistic are made.

1. AGRONOMIC INFORMATION

Under this heading, data on yield and production, and biological data for phenology, are considered.

1.1 Yield and production data

Although a considerable effort was made to obtain from the Area yield and production data of a quality and coverage which would make fruitful comparison with climatic factors possible, only a few tractable series were found. Five different types of data found useful are listed below.

1.1.1 Yield data from agricultural trials

Information obtained from agricultural trials comes primarily from research stations, but useful data can also be obtained from trials performed outside.

Valuable data are derived from variety trials spread over several years, when it is relatively easy to separate fluctuations in yield due to climate from those due to improvement in stock and techniques, but yield from trials involving fertilisers, insecticides, or different cultivation techniques, are less easy to interpret.

Very useful yield data are obtainable from the mean yield of all the trials of a station (as was the case with millet at Bambey, discussed in Part III).

1.1.2 Seed production records

Yield data obtained from seed production records are probably superior to those from trials, for analyses of the effect of climate, because of the larger areas involved. There again, data both from inside and from outside agricultural stations are valuable.

1.1.3 Extension work at experimental farms

Data from such work have the great advantage of coming from agricultural operations closest to normal production. When available from reliable sources such data are by far the most useful for agroclimatic planning.

1.1.4 Published yield statistics

Published yield data usually apply to a sufficiently large area to cancel out variation due to soil. However, as the area increases from village to canton, market centre and district, it may reach such a size that the effects of local climate variation tend to be smoothed out by averaging.

1.1.5 Production statistics

The utility of production statistics depends on the information obtainable on the annual variation of the area cultivated. (If this area were known accurately, yields would of course be obtainable.) However, it is sometimes possible to assume a steady increase and correct accordingly, so that it becomes possible to assess the effect of climatic variation on yield from the information.

1.2 Biological data

Biological data for phenology were even scarcer than yield and production data and yet, as pointed out by the WMO Guide to Agricultural Meteorological Practices, paragraph 2.1.2 (1963), "it is only possible to make limited progress unless routine biological observations are made for comparison with routine meteorological observations". These observations are further subdivided according to the places where it is practicable to make them.

1.2.1 Simple biological events

During agricultural trials, seed production and extension work, phenological information of importance can be obtained if the dates of simple biological events such as sowing, heading, flowering and harvesting are observed. However, although sowing and harvesting dates are usually recorded, the dates of flowering in its various forms are often not recorded although it is an important event which, in annuals, marks the end of the vegetative stage.

1.2.2 More complex biological observations

Careful and detailed recording of selected biological events of a more complex nature for comparison with simultaneously recorded meteorological data provide very useful information on climatic control of the growth and development of crops. These observations should be carried out in small plots in the vicinity of a meteorological enclosure and, in the case of annuals, in connexion with staggered sowings.

The mean productivity of the plants can be assessed at the same time, by measuring vegetative growth parameters, such as the number of nodes, and counting and weighing fruits or grains. The work of Bezot (1963), discussed in Part III under Sorghum.4, is a good instance of this method.

1.3 Recommendations

1.3.1 Yield and production data

It is therefore suggested that agricultural services and stations should bear in mind the need for yield data of the kind detailed in 1.1 and make them easily accessible by publication. At the same time, records of simple biological events should be made and also published, bearing in mind the importance of the date of flowering.

It is essential that the more detailed observations discussed in 1.2.2 be also made at the agricultural research stations of the Area, and published or circulated. The meteorological observations with which they are to be compared should be made at the same spot. These requirements are discussed further in connexion with meteorological information.

1.4 Network of agricultural stations

It is clear that considerations of climate enter into the siting of the agricultural research stations of the Area and their regions of extension. But it is also realized that many other considerations, such as logistics, administration and the historical aspect of development are also of importance.

Although little benefit would be derived from suggesting a model network of agricultural stations based entirely on agroclimatic considerations, some remarks arising out of this study may appropriately be made here to provide some guidance in the choice of station sites and the determination of their area of extension.

1.4.1 Length and timing of the humid period

The most critical agroclimatic parameter in the Area is the length of the humid period --itself fairly constantly 60 days shorter than the period within which the total growth cycle of crops must be fitted. This criterion should be taken into account in extension work. For instance, a variety of groundnut resistant to the rosette virus, developed in the groundnut area of western Senegal would flower too soon in the south of Upper Volta.

This question has already been discussed in the case of cereals, and it has been shown that the timing as well as the length of the humid period is of importance (Part III, section 7), and in this connexion it has also been shown that western Senegal differs from the rest of the Area in that its rainy season is delayed and begins more abruptly.

1.4.2 Rainfall variability

The rainfall in western Senegal and in Chad was found to be more variable than in the rest of the Area. Places in southern Niger, like Maradi, on the other hand, are representative of a region of relatively low rainfall variability. Mere consideration of mean annual rainfall might lead to under-estimating productivity in the latter case, and over-estimating it in the areas first mentioned. Furthermore, to assume that variability simply increases with decreasing rainfall would be misleading.

2. METEOROLOGICAL INFORMATION

As already indicated, meteorological information is generally at an advantage compared with agronomic information, and this is clearly reflected in the Area surveyed. This advantage is due to the fact that the physical measurements of meteorology are easier to make and record than the largely biological measurements of agronomy. Furthermore, meteorology is by its nature a world-wide science, and it maintains world-wide standardization. There are, for instance, WMO Guides (1960, 1961, 1963) on instruments, on climatological and on agricultural meteorological practices agreed upon by all the countries of the Area, which provide much of the guidance needed for the development of agricultural meteorology.

2.1 Nature of the information

The WMO guides referred to above give details of the nature of the meteorological information required and of approved methods of obtaining it, and here only two limited aspects will be discussed.

2.1.1 Radiation

The almost complete absence of routine radiation measurements from the Area has already been stressed. These observations are important in agroclimatology for assessments of potential evapotranspiration and potential photosynthesis. In their absence, sunshine duration records were used, and when even those were not available, recourse was made to cloud cover observations. Sunshine duration records should be available from, at the very least, all synoptic meteorological stations in the Area. This requirement has probably been attained now, although the measurements do not extend sufficiently far back for the working out of averages.

Instruments measuring radiation are on the whole expensive and require careful calibration. However, in East Africa, satisfactory results have been obtained with water-filled Gunn Bellani radiometers (McCulloch and Wangati, 1967). A network of these inexpensive and rugged instruments would be very useful in the Area. The level of daily global radiation is consistently well above the instrument's distillation threshold and all-the-year-round performance is therefore ensured. Simple bimetallic actinographs can also give good service. In all cases careful calibration and regular inspection are necessary.

2.1.2 Wind climatic returns

Mean wind speed, a scalar measurement, is needed for the calculation of the advected energy term of potential evapotranspiration estimates. Practically the only form of surface wind return available from meteorological publications in the Area is a tabulation of occurrences of concurrent wind speed and direction within specified ranges, an aviation meteorology requirement.

2.1.3 Recommendations

It is recommended that every effort should be made to increase the volume of global radiation observations from the Area. Attention should also be paid to the increased practicability of obtaining direct measurements of net radiation also.

It is further recommended that mean wind speeds irrespective of direction at specified times of the day should be included in published meteorological summaries.

2.2 Meteorological network

2.2.1 Synoptic network

The network of synoptic meteorological observation stations forms a solid basis, in the Area, for studies at the macroclimatological scale. In this report the concepts "atmospheric climate" and "theoretical water budget" discussed in Part II are of such a scale.

The selection of synoptic stations is controlled by many factors besides the need to have a network regularly spaced and of optimum density. The network is reviewed at intervals, at national and at international levels (such as the meetings of WMO Regional Association I). It is not thought appropriate to make suggestions for the enlargement of the synoptic network in this report.

This is not to say that even at the macrometeorological scale the Area is perfectly covered. There are localities from which regular observations would be very informative, notably immediately to the north of Lake Chad.

2.2.2 Other observing stations

In this report, when mean evapotranspiration estimates were needed for the agricultural stations at Bambey and Deli, the data of the synoptic stations at Thies and Moundou, in both cases some distance away, had to be used.

It is thought that the most urgent need, and it is a need which could easily be met, is to ensure that regular observations, of at least sufficient elements to work out Penman evapotranspiration estimates (temperature, humidity, wind and sunshine and/or global radiation) should be made at agricultural research stations, and subsequently published.

This would correspond to the level of an "ordinary agricultural meteorological station" as described at 2.3.1 (b) in the WMO Guide to Agricultural Meteorological Practices. Useful as they are, more complicated observations for the direct measurements of crop water needs, using apparatus such as lysimeters, should never displace these basic minimum requirements.

2.3 Agricultural-meteorological liaison

To ensure the continuity and evenness of standard of meteorological observations at agricultural stations, it is thought essential that they should be carried out by specially trained technical officers, or technical assistants, whose main or even sole responsibility is to do this work. Any other arrangement, such as interested specialists from other disciplines making the observations, tends to cause interruptions in the series of data.

It is thought that observers can best be trained in the schools of the national meteorological services or, in some cases, the regional observer schools.

The World Meteorological Organization recommends /Resolution 16 (EC-XI)/ "that a special division, section or unit for agricultural meteorology should be established by each Member, and that this division should normally be within the national meteorological service." The responsibilities of these divisions are outlined in the Guide to Agricultural Meteorological Practices, paragraph 1.2.1.

Progress in this direction, which seems to be an essential step in the development of agrometeorology, is accelerating in the countries of the Area at the time this report is being written, but much still remains to be done.

It is thought that these agricultural meteorological units within the national services should be matched by similar units within national agricultural services. The employment of meteorologists in agricultural services, to give physical expression to the weather characteristics which have been found significant, is as essential as the presence of agronomists in meteorological services to call attention to the problems which deserve consideration. Further details on collaboration between meteorologists and agriculturists are also given in the WMO Guide already quoted, in section 1.3.

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AGROCLIMATOLOGY AND AGRICULTURAL DEVELOPMENT IN THE AREA

1. CEREAL YIELDS IN THE AREA

Cereal yields increase with growth cycle lengths, and the maximum length of cycle which can be exploited anywhere in the Area depends on the length of the humid period.

1.1 Sums of temperature

A more accurate relationship between yield and cycle length can be obtained, especially during the vegetative period, if sums of temperatures in degree days are used, rather than just numbers of days; although, in the Area, temperatures are so uniform that the maximum difference from north to south during the growing season would be at the most 3 per cent. (It is realized that, at the macroclimatic scale, such factors as exposure might cause more significant differences.)

1.2 Maximum productivity

In Part III some instances were given of studies to establish the relation between yield and climatic factors; and it was shown that the regression of yield on availability of water of a well adapted ecotype at a given station is curvilinear. No attempt has been made in this study to estimate the rate at which yield increases relative to mean growth cycle, but there is evidence that the former does not keep pace with the latter. In other words, a sorghum with a growth cycle of 200 days is not expected to yield twice as much as an early variety ready for harvest in 100 days. It would appear that, if the entire range of ecotypes were considered (assuming that in all cases their climatic requirements are ideally met) the relation between yield per day and length of growth cycle would also be curvilinear.

This would be due to the fact that, although the range which semiarid cereals like millet and sorghum can accommodate is fairly wide, they have a growth cycle of optimum efficiency shorter than the moist availability-of-water period found in the south of the Area. Thus, as the humid period increases southwards, the use of cereals which do not fill the whole of the growing season may be justifiable from the point of view of maximum productivity (as well as from motives of expediency) long before the interruption of the "little dry season" makes the consecutive growing of main annual crops the rule.

1.3 Climatic parameters

In the analysis of their relation with yield, the quantitative climatic parameters employed were based either on calendar subdivisions such as months, or on the timing of availability-of-water parameters. The latter, though apparently more specific, did not yield distinctly more significant relations. Much investigation has yet to be done in this field. More and more specific climatic factors must be used. They will be of a phenological nature (which is another reason for making the biological observations recommended under the heading Information and networks, 1.2). These factors may also be combined into complex parameters. However, it must be realized that the more specific these parameters are, the less suitable they become for extrapolation to other crops and to areas other than those for which they were devised.

1.4 Corrections of yield and production trends for climatic fluctuation

Annual yields of millet and cotton discussed in this report (Part III, Table 24 and Cotton, section 6.1) show considerable interannual variation, of which a large part must be attributed to climatic fluctuation.

It was shown how these climatic fluctuations could be eliminated, thus leaving a general trend due to improvement in materials and methods and, in the case of production, also due to an increase in the area sown -- provided, of course, that this increase is regular.

This general trend can be represented by a smooth curve drawn freehand or plotted from calculation of sliding averages.

Forecasts of future yields which are a hypothetical extension of this general trend line, should start from a point lying on it, and not from the value for a given year which may be exceptionally high or low, owing to climatic fluctuation.

2. MODELS

The concepts "atmospheric climate" and "theoretical water budget", as described in Part II, have provided a general or macroclimatological model of the availability of water to crops in the Area. The assumptions on which the model was based were broad enough to apply to all the crops. It is thought that, in all cases, this general macroclimatological model should first be worked out before proceeding to more detailed studies.

2.1 Methods for finer models

Finer models should then be constructed, depicting the behaviour of specific crops in specific environments. (Though, strictly speaking, this is outside the brief of this study it is pointed out that these finer models are particularly applicable to the more complex water budgets used when considering irrigation, total or supplementary, or flood plain cultivation.) For the construction of such models the following suggestions are made:

2.1.1 P-E_T models

(i) Consideration of actual conditions during a given number of years rather than average for the period, which also makes it possible to estimate interannual variability and the risks of crop failures. An example of this kind of work is given in Part II under the heading Availability of water, 2.6.

(ii) Analysis of periods shorter than one month. For this purpose, a convenient period to be considered is the longest one during which, starting from field capacity, storage can still not have been depleted to wilting point. Ten days or even a week are suggested. (The difficulties of obtaining averages for such short periods are no longer restrictive since one is no longer concerned with averages.)

(iii) Since potential evapotranspiration varies relatively little from year to year and since it requires multiple meteorological observations and relatively laborious calculation, long-term averages can be used, especially in a first approach. Furthermore, classes of average E_T rates in terms of broad weather types like "wet and cloudy" or "sunny and dry" will give more accurate results for short-term estimates.

(iv) Specifying the rates of water consumption (actual evapotranspiration) in terms of the stages of development of the crop, and the amount of water still stored in the ground as well as potential evapotranspiration. These rates are best expressed as a ratio of E_T. (In the macro-model it was assumed that actual consumption equalled rainfall during the prehumid period and potential evapotranspiration during the humid period.)

(v) Estimating more specifically the maximum amount of water storable in the ground. This has generally been taken to be 100 mm, but it varies with soil texture and structure. These estimates can be based on actual measurements or on analogy with known soils.

2.1.2 Other models

Other aspects of the water budget may also be expressed as analogue models if this method should prove useful in expressing probabilities. For instance, the effect of water surplus and run-off in association with privileged topography and soils, which has already been referred to in connexion with permanent pastures.

Among other climatic factors taken in a context other than the water budget, sunshine, which is probably the most important and may be very critical with some crops, requires detailed study in relation to the characteristics of yield and quality of produce which it controls.

3. HOMOLOGOUS AREAS

In all continents there are areas where the basic tropical circulation described in Part I has resulted in semiarid climates and agricultural exploitations comparable to those of the Area surveyed; though nowhere is there such a large expanse free from the influence of high ground and of the sea. Some of these areas will be mentioned under the heading of the continents in which they are found and the two most important will be discussed briefly.

These two homologous areas are: north-west India and the adjacent part of West Pakistan in the northern hemisphere, and the north of Australia in the southern hemisphere. Neither presents quite the same climatic latitudinal zonation as the Area and, for reasons apart from climate, their exploitation has so far been very different.

3.1 Africa

The conditions found in the Area extend beyond the border of Chad into the Sudan, and it is only in the extreme east of that country that the mountains of Ethiopia and the Red Sea distort the simple tropical atmosphere circulation which prevails to the west.

South of the Equator, climates homologous to that of the Area are also found, notably in Malawi, Rhodesia and further west.

3.2 North and South America

In North and South America homologous tropical summer-rains climates occur, but, with the possible exception of Brazil, in rather limited areas, because of the influence of both high ground and of seas.

3.3 North-west India and adjacent West Pakistan

This homologous area lies along the south-eastern edge of the Rajasthan and Sind Desert. It shows the same arid to semiarid zonation with summer rains as the Area. Its subsistence cereal crops are the same, but it is more densely populated. In fact its food production problems are not dissimilar, though probably more acute.

Important work on agroclimatology, with which the names of Ramdas (1960) and A. K. Mallik (1966) may be associated, has been done in this area. Much of this work is applicable to the west African area.

The zonation in the Indian semiarid area is aligned from south-west to north-east and, in the east especially, the annual south-north movement of the monsoon shows greater amplitude, reaching as far as 20° - 25°N. Consequently winter temperatures and energy potentials are lower in the northern parts of this area. The annual variation in the length of day is also greater, a characteristic to bear in mind when plant material is exchanged.

3.4 Northern Australia

The high-pressure belt of the southern hemisphere lies athwart the Australian continent and, to the north of it, there is a south-north arid to equatorial zonation with monsoonal summer rains, in many respects similar to that of the Area.

However, the population is far less dense, and there is practically no traditional system of subsistence agriculture comparable with that of the Area. Consequently, the approach, the surveys, and the agricultural exploitation are, in a sense, contemporary.

Since the pressure of subsistence agriculture is far less than in the Area, livestock raising has received more attention and ranching extends into regions of higher rainfall.

Much work capable of useful application in the area of the present survey has been done in Australia. Publications of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) are of special interest. Amongst them, those dealing with surveys, and some of the work of R.O. Slatyer (1960) may be mentioned.

3.5 Complementary rainfall areas

It is worth noting that there is a difference of half a year between the summer rains of the two hemispheres and that, to this extent, they are complementary, a fact which may prove of importance in future planning of integrated food production for large areas such as tropical and equatorial Africa.

The same complementary relation exists between the rainfall régimes of the Area, south of the Sahara Desert, and of North Africa on the other side of it.

4. AGRICULTURAL DEVELOPMENT

The traditional agriculture of the Area has been described as extensive and devoid of technical achievement.

Progress appears to lie in the development of an agriculture as intensive as economic conditions will allow. Work at agricultural stations in the Area has demonstrated that stable (non-itinerant) and adequate production is possible in the physical environment prevailing. The main intensification techniques involved include, besides advanced water economy, improvement of genetical stock, use of fertilisers, plant protection, mechanization and integration of crop and livestock production. In all cases the basic agroclimatic information of this study can be of use. Some examples will be given.

4.1 Fallows and livestock production

The various substitutes for natural fallows were discussed in Part III, where it was shown that the ability of pasture and fodder plants to accommodate increasingly shorter availability-of-water periods, and correspondingly longer dry periods, decided their distribution in the Area. As much needs to be known about the climatic needs and tolerances of these plants as about those of cash and subsistence crops.

It should be possible to identify specific climatic parameters related to the livestock holding capacity of pastures. A pilot study, using the simple ratio P/E_T is to be found in the Technical Report.

Though socio-economic considerations strongly influence the apportioning of the land between pastures and crop production, in the end climatic factors often have to be used to define actual grazing, or ranching, boundaries (especially when they are enforced by legislation, as is already done in some countries). So far mean annual rainfall has been the parameter used in such cases, but it should be clear from this survey that more accurate parameters, based on availability-of-water periods and water surplus, could with advantage be used in the Area.

4.2 Fertilizers

Manufactured fertilizers coming from more developed areas tend to bring with them techniques of application adapted to the needs of their country of origin. It was seen in the analysis of millet yield that much deep drainage of nitrates could be caused by a large water surplus during the humid period, resulting in reduced yield. The single rainy season of the Area, with its peak in August, demands special times of application, and special dosages.

4.3 Plant protection

Desert Locust swarms periodically infest the Area, sometimes with devastating results. It is now well established that these swarms move with the wind. In the north of the Area, in summer, invading swarms are concentrated along the ITCZ by the convergence of the monsoon and harmattan currents, and both climatic and actual day-to-day information on low level wind direction and speed are used in the strategy and tactics of swarm control. At the same time, the Desert Locust requirements for laying (a loose-texture soil carrying small amounts of available moisture at a depth of about 10 cm) are met in the north of the Area, in the same convergence zone, whenever more than about 10 cm of rain has fallen on sandy soil, and thus weather and climate can often provide the key to efficient control of newly hatched hoppers.

In the application of insecticides by methods such as air spraying, far from waiting for still conditions, advantage is now taken of atmospheric turbulence to deposit very small drops on vertical surfaces. For this technique, a knowledge of actual distribution with height of temperature and wind velocity is required.

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4.4 Mechanization

It was pointed out in Part II that, in Senegal, the preparatory period was much shorter than further east, and consequently the ground had to be prepared much more rapidly. Consequently where this operation is mechanized, a larger stock of machinery would be needed.

4.5 Conclusion

In conclusion it may be said that, although the actual degree of agricultural development in the Area will depend on socio-economic factors, agroclimatology is an essential part of its achievement.

5. WATER SUPPLY AND AGRICULTURAL DEVELOPMENT IN THE AREA

It seems that continuous food production is possible throughout the year in the Area, whenever water supply is not limiting, as the other climatic factors themselves are not limiting.

5.1 Winter season

Monthly mean global radiation amounts in December and January are not very different from August values, about 400 cal $cm^{-2}.day^{-1}$. The corresponding level of potential photosynthesis is sufficiently high for active production of vegetable matter.

The day temperatures do not appear to be depressed below the vegetative zero of the most warmth-demanding crop plants. However, in the north, different cereals, like wheat and rice, are grown with advantage in winter, where there is irrigation water, or in flood plains. The night temperatures are then at their lowest, which may be a desirable feature for dry matter production. During the winter season, the ratio of global radiation to temperatures is at its highest. This too may be an advantage with certain dense crops.

5.2 Extension of summer growing season

Irrigation during the dry season preceding the moist period and, to a lesser extent, during that following it, can, in the north of the Area, extend that period to match more productive crop growth cycles (say about 160 days).

Supplying this additional water does not however bring about the milder conditions of temperature and atmospheric humidity associated with the monsoon. Consequently, the potential evapotranspiration rates, then at their highest (as shown in Table 33), will remain relatively high (about 6 mm) and dry matter production per mass of water consumed will be at its lowest. Moreover, the dessicating action of the harmattan is then at its most intense, and it is in such weather that the protection afforded by shelter belts would be most useful.

5.3 Disease-free nature of the dry period

One advantage of the dry period, which spreads over the winter as well as the hot and dry autumn and spring months, is that, owing mainly to the low humidity of the air and sparse natural vegetation, there is a great reduction in the incidence of pests and of parasites and their insect vectors. It would seem either that they are in a dormant state or that they have migrated with the ITCZ.

5.4 Supplementary water needs

Using the estimates and suggestions of this study, it might be said tentatively that a summer "moist" period of about 160 days (which seems to be an optimum length of annual growing cycle in the Area) requires about 800 mm of well-spread rainfall. The amount of sup-

plementary irrigation water needed to provide such a season annually would range from about 500 in the north to nil in the south.

A winter growing season of about the same duration would require about 500 mm. In the south of the Area this is almost the extent of the water surplus, and with optimum means of storage and economy 1,200 mm of mean annual rainfall should suffice to ensure continuous cultivation over a large proportion of the arable land.

5.5 Water supply

About one million million cubic metres of water fall annually over the survey area, and the various ways in which it can be more aptly distributed, or made to circulate more rapidly from the surface of the ground to the crops and back into the atmosphere, are receiving attention.

Large dams and irrigation works have been or are being planned and built in connexion with the two main rivers and some of their larger tributaries. But these can only affect a relatively small percentage of the Area.

The amount of accessible water underground is being increasingly realized, and the exploitation of this water will no doubt increase the productivity of the Area.

Finally, it is thought that village-scale works for storing water (preferably underground) from artificial catchments, for use especially in the perimeters of settlements, which are richer in nitrates, represent another major potential, because the surfaces they could affect add up to an important fraction of the Area.

6. FOLLOW-UP ACTION

Agricultural meteorology in its present form is developing very rapidly, so that this report would soon be out of date, both with regard to methods and, more especially, information, if there were no follow-up action. The forms of action which are recommended will be briefly discussed.

(Recommendations concerning the observational network arising out of this study have already been made in another section of Part IV.)

6.1 Technical meeting

A technical meeting should be held in the Area some time after the publication of the reports to discuss their contents and gather the opinion of meteorologists and agronomists from the countries concerned, as to how this work can be extended and improved. A meeting of this kind was held in Beirut, as a follow-up to the first survey, with beneficial results (not the least being an improvement in collaboration between the meteorologists and the agronomists in the countries concerned).

6.2 Extension of number of reference stations and publication of their agroclimatic characteristics

As the data available improves with respect to diversity, quantity and serial length, it will be possible to increase the number of reference stations (here 35) in the Area and amplify the climatic and biological information characterizing each. It is suggested that this basic information should be published as a collection of agroclimatic characteristics independently from any other work of synthesis, interpretation or cartography. Each station would have its own dossier, illustrated by diagrams like Figure 67. For the exchange of plant stock it is thought that accurate descriptions of the agroclimate at a given spot are more valuable than the sketching out of agroclimatic regions.

6.3 Publication of lists of unpublished data

Some unpublished information (especially in the field of agronomy, as a result of the IRAT mission), was collected from the Area. Lists of this information, which in places is difficult of access, and in some cases perishable, should be published.

6.4 More detailed work

At the beginning of this report (and elsewhere in the text) it was pointed out that one of its most useful outcomes should be to touch off more detailed investigations at a national or subregional level. Some sample studies, especially of variability -- as opposed to those of average conditions used in this predominantly macroclimatological survey -- were included in the report, and it is hoped that they will suggest appropriate lines of investigation.

In addition, it is thought that some of this more detailed work should be undertaken by personnel from the interagency agroclimatology project itself to test further the applicability of the working concepts used in the surveys to the increase of agricultural production.

This could best be done in association with United Nations technical assistance programmes of the three agencies supporting the project, or of the Special Fund. An important aspect of such collaboration would be to appraise the extent to which the basic information presented by the surveys can be used by experts in the field.

Indeed, the main purpose of this survey is to provide these experts, native or expatriate, with basic agroclimatic information of an international character.

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AGROCLIMATOLOGY AND AGRICULTURAL DEVELOPMENT IN THE AREA

1. CEREAL YIELDS IN THE AREA

Cereal yields increase with growth cycle lengths, and the maximum length of cycle which can be exploited anywhere in the Area depends on the length of the humid period.

1.1 Sums of temperature

A more accurate relationship between yield and cycle length can be obtained, especially during the vegetative period, if sums of temperatures in degree days are used, rather than just numbers of days; although, in the Area, temperatures are so uniform that the maximum difference from north to south during the growing season would be at the most 3 per cent. (It is realized that, at the macroclimatic scale, such factors as exposure might cause more significant differences.)

1.2 Maximum productivity

In Part III some instances were given of studies to establish the relation between yield and climatic factors; and it was shown that the regression of yield on availability of water of a well adapted ecotype at a given station is curvilinear. No attempt has been made in this study to estimate the rate at which yield increases relative to mean growth cycle, but there is evidence that the former does not keep pace with the latter. In other words, a sorghum with a growth cycle of 200 days is not expected to yield twice as much as an early variety ready for harvest in 100 days. It would appear that, if the entire range of ecotypes were considered (assuming that in all cases their climatic requirements are ideally met) the relation between yield per day and length of growth cycle would also be curvilinear.

This would be due to the fact that, although the range which semiarid cereals like millet and sorghum can accommodate is fairly wide, they have a growth cycle of optimum efficiency shorter than the moist availability-of-water period found in the south of the Area. Thus, as the humid period increases southwards, the use of cereals which do not fill the whole of the growing season may be justifiable from the point of view of maximum productivity (as well as from motives of expediency) long before the interruption of the "little dry season" makes the consecutive growing of main annual crops the rule.

1.3 Climatic parameters

In the analysis of their relation with yield, the quantitative climatic parameters employed were based either on calendar subdivisions such as months, or on the timing of availability-of-water parameters. The latter, though apparently more specific, did not yield distinctly more significant relations. Much investigation has yet to be done in this field. More and more specific climatic factors must be used. They will be of a phenological nature (which is another reason for making the biological observations recommended under the heading Information and networks, 1.2). These factors may also be combined into complex parameters. However, it must be realized that the more specific these parameters are, the less suitable they become for extrapolation to other crops and to areas other than those for which they were devised.

1.4 Corrections of yield and production trends for climatic fluctuation

Annual yields of millet and cotton discussed in this report (Part III, Table 24 and Cotton, section 6.1) show considerable interannual variation, of which a large part must be attributed to climatic fluctuation.

It was shown how these climatic fluctuations could be eliminated, thus leaving a general trend due to improvement in materials and methods and, in the case of production, also due to an increase in the area sown -- provided, of course, that this increase is regular.

This general trend can be represented by a smooth curve drawn freehand or plotted from calculation of sliding averages.

Forecasts of future yields which are a hypothetical extension of this general trend line, should start from a point lying on it, and not from the value for a given year which may be exceptionally high or low, owing to climatic fluctuation.

2. MODELS

The concepts "atmospheric climate" and "theoretical water budget", as described in Part II, have provided a general or macroclimatological model of the availability of water to crops in the Area. The assumptions on which the model was based were broad enough to apply to all the crops. It is thought that, in all cases, this general macroclimatological model should first be worked out before proceeding to more detailed studies.

2.1 Methods for finer models

Finer models should then be constructed, depicting the behaviour of specific crops in specific environments. (Though, strictly speaking, this is outside the brief of this study it is pointed out that these finer models are particularly applicable to the more complex water budgets used when considering irrigation, total or supplementary, or flood plain cultivation.) For the construction of such models the following suggestions are made:

2.1.1 P-ET models

(i) Consideration of actual conditions during a given number of years rather than average for the period, which also makes it possible to estimate interannual variability and the risks of crop failures. An example of this kind of work is given in Part II under the heading Availability of water, 2.6.

(ii) Analysis of periods shorter than one month. For this purpose, a convenient period to be considered is the longest one during which, starting from field capacity, storage can still not have been depleted to wilting point. Ten days or even a week are suggested. (The difficulties of obtaining averages for such short periods are no longer restrictive since one is no longer concerned with averages.)

(iii) Since potential evapotranspiration varies relatively little from year to year and since it requires multiple meteorological observations and relatively laborious calculation, long-term averages can be used, especially in a first approach. Furthermore, classes of average E_T rates in terms of broad weather types like "wet and cloudy" or "sunny and dry" will give more accurate results for short-term estimates.

(iv) Specifying the rates of water consumption (actual evapotranspiration) in terms of the stages of development of the crop, and the amount of water still stored in the ground as well as potential evapotranspiration. These rates are best expressed as a ratio of E_T. (In the macro-model it was assumed that actual consumption equalled rainfall during the prehumid period and potential evapotranspiration during the humid period.)

(v) Estimating more specifically the maximum amount of water storable in the ground. This has generally been taken to be 100 mm, but it varies with soil texture and structure. These estimates can be based on actual measurements or on analogy with known soils.

2.1.2 Other models

Other aspects of the water budget may also be expressed as analogue models if this method should prove useful in expressing probabilities. For instance, the effect of water surplus and run-off in association with privileged topography and soils, which has already been referred to in connexion with permanent pastures.

Among other climatic factors taken in a context other than the water budget, sunshine, which is probably the most important and may be very critical with some crops, requires detailed study in relation to the characteristics of yield and quality of produce which it controls.

3. HOMOLOGOUS AREAS

In all continents there are areas where the basic tropical circulation described in Part I has resulted in semiarid climates and agricultural exploitations comparable to those of the Area surveyed; though nowhere is there such a large expanse free from the influence of high ground and of the sea. Some of these areas will be mentioned under the heading of the continents in which they are found and the two most important will be discussed briefly.

These two homologous areas are: north-west India and the adjacent part of West Pakistan in the northern hemisphere, and the north of Australia in the southern hemisphere. Neither presents quite the same climatic latitudinal zonation as the Area and, for reasons apart from climate, their exploitation has so far been very different.

3.1 Africa

The conditions found in the Area extend beyond the border of Chad into the Sudan, and it is only in the extreme east of that country that the mountains of Ethiopia and the Red Sea distort the simple tropical atmosphere circulation which prevails to the west.

South of the Equator, climates homologous to that of the Area are also found, notably in Malawi, Rhodesia and further west.

3.2 North and South America

In North and South America homologous tropical summer-rains climates occur, but, with the possible exception of Brazil, in rather limited areas, because of the influence of both high ground and of seas.

3.3 North-west India and adjacent West Pakistan

This homologous area lies along the south-eastern edge of the Rajasthan and Sind Desert. It shows the same arid to semiarid zonation with summer rains as the Area. Its subsistence cereal crops are the same, but it is more densely populated. In fact its food production problems are not dissimilar, though probably more acute.

Important work on agroclimatology, with which the names of Ramdas (1960) and A. K. Mallik (1966) may be associated, has been done in this area. Much of this work is applicable to the west African area.

The zonation in the Indian semiarid area is aligned from south-west to north-east and, in the east especially, the annual south-north movement of the monsoon shows greater amplitude, reaching as far as 20° - 25°N. Consequently winter temperatures and energy potentials are lower in the northern parts of this area. The annual variation in the length of day is also greater, a characteristic to bear in mind when plant material is exchanged.

3.4 Northern Australia

The high-pressure belt of the southern hemisphere lies athwart the Australian continent and, to the north of it, there is a south-north arid to equatorial zonation with monsoonal summer rains, in many respects similar to that of the Area.

However, the population is far less dense, and there is practically no traditional system of subsistence agriculture comparable with that of the Area. Consequently, the approach, the surveys, and the agricultural exploitation are, in a sense, contemporary.

Since the pressure of subsistence agriculture is far less than in the Area, livestock raising has received more attention and ranching extends into regions of higher rainfall.

Much work capable of useful application in the area of the present survey has been done in Australia. Publications of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) are of special interest. Amongst them, those dealing with surveys, and some of the work of R.O. Slatyer (1960) may be mentioned.

3.5 Complementary rainfall areas

It is worth noting that there is a difference of half a year between the summer rains of the two hemispheres and that, to this extent, they are complementary, a fact which may prove of importance in future planning of integrated food production for large areas such as tropical and equatorial Africa.

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Progress appears to lie in the development of an agriculture as intensive as economic conditions will allow. Work at agricultural stations in the Area has demonstrated that stable (non-itinerant) and adequate production is possible in the physical environment prevailing. The main intensification techniques involved include, besides advanced water economy, improvement of genetical stock, use of fertilisers, plant protection, mechanization and integration of crop and livestock production. In all cases the basic agroclimatic information of this study can be of use. Some examples will be given.

4.1 Fallows and livestock production

The various substitutes for natural fallows were discussed in Part III, where it was shown that the ability of pasture and fodder plants to accommodate increasingly shorter availability-of-water periods, and correspondingly longer dry periods, decided their distribution in the Area. As much needs to be known about the climatic needs and tolerances of these plants as about those of cash and subsistence crops.

It should be possible to identify specific climatic parameters related to the livestock holding capacity of pastures. A pilot study, using the simple ratio P/E_T is to be found in the Technical Report.

Though socio-economic considerations strongly influence the apportioning of the land between pastures and crop production, in the end climatic factors often have to be used to define actual grazing, or ranching, boundaries (especially when they are enforced by legislation, as is already done in some countries). So far mean annual rainfall has been the parameter used in such cases, but it should be clear from this survey that more accurate parameters, based on availability-of-water periods and water surplus, could with advantage be used in the Area.

4.2 Fertilizers

Manufactured fertilizers coming from more developed areas tend to bring with them techniques of application adapted to the needs of their country of origin. It was seen in the analysis of millet yield that much deep drainage of nitrates could be caused by a large water surplus during the humid period, resulting in reduced yield. The single rainy season of the Area, with its peak in August, demands special times of application, and special dosages.

4.3 Plant protection

Desert Locust swarms periodically infest the Area, sometimes with devastating results. It is now well established that these swarms move with the wind. In the north of the Area, in summer, invading swarms are concentrated along the ITCZ by the convergence of the monsoon and harmattan currents, and both climatic and actual day-to-day information on low level wind direction and speed are used in the strategy and tactics of swarm control. At the same time, the Desert Locust requirements for laying (a loose-texture soil carrying small amounts of available moisture at a depth of about 10 cm) are met in the north of the Area, in the same convergence zone, whenever more than about 10 cm of rain has fallen on sandy soil, and thus weather and climate can often provide the key to efficient control of newly hatched hoppers.

- In the application of insecticides by methods such as air spraying, far from waiting for still conditions, advantage is now taken of atmospheric turbulence to deposit very small drops on vertical surfaces. For this technique, a knowledge of actual distribution with height of temperature and wind velocity is required.

4.4 Mechanization

It was pointed out in Part II that, in Senegal, the preparatory period was much shorter than further east, and consequently the ground had to be prepared much more rapidly. Consequently where this operation is mechanized, a larger stock of machinery would be needed.

4.5 Conclusion

In conclusion it may be said that, although the actual degree of agricultural development in the Area will depend on socio-economic factors, agroclimatology is an essential part of its achievement.

5. WATER SUPPLY AND AGRICULTURAL DEVELOPMENT IN THE AREA

It seems that continuous food production is possible throughout the year in the Area, whenever water supply is not limiting, as the other climatic factors themselves are not limiting.

5.1 Winter season

Monthly mean global radiation amounts in December and January are not very different from August values, about 400 cal $cm^{-2}.day^{-1}$. The corresponding level of potential photosynthesis is sufficiently high for active production of vegetable matter.

The day temperatures do not appear to be depressed below the vegetative zero of the most warmth-demanding crop plants. However, in the north, different cereals, like wheat and rice, are grown with advantage in winter, where there is irrigation water, or in flood plains. The night temperatures are then at their lowest, which may be a desirable feature for dry matter production. During the winter season, the ratio of global radiation to temperatures is at its highest. This too may be an advantage with certain dense crops.

5.2 Extension of summer growing season

Irrigation during the dry season preceding the moist period and, to a lesser extent, during that following it, can, in the north of the Area, extend that period to match more productive crop growth cycles (say about 160 days).

Supplying this additional water does not however bring about the milder conditions of temperature and atmospheric humidity associated with the monsoon. Consequently, the potential evapotranspiration rates, then at their highest (as shown in Table 33), will remain relatively high (about 6 mm) and dry matter production per mass of water consumed will be at its lowest. Moreover, the dessicating action of the harmattan is then at its most intense, and it is in such weather that the protection afforded by shelter belts would be most useful.

5.3 Disease-free nature of the dry period

One advantage of the dry period, which spreads over the winter as well as the hot and dry autumn and spring months, is that, owing mainly to the low humidity of the air and sparse natural vegetation, there is a great reduction in the incidence of pests and of parasites and their insect vectors. It would seem either that they are in a dormant state or that they have migrated with the ITCZ.

5.4 Supplementary water needs

Using the estimates and suggestions of this study, it might be said tentatively that a summer "moist" period of about 160 days (which seems to be an optimum length of annual growing cycle in the Area) requires about 800 mm of well-spread rainfall. The amount of sup-

plementary irrigation water needed to provide such a season annually would range from about 500 in the north to nil in the south.

A winter growing season of about the same duration would require about 500 mm. In the south of the Area this is almost the extent of the water surplus, and with optimum means of storage and economy 1,200 mm of mean annual rainfall should suffice to ensure continuous cultivation over a large proportion of the arable land.

5.5 Water supply

About one million million cubic metres of water fall annually over the survey area, and the various ways in which it can be more aptly distributed, or made to circulate more rapidly from the surface of the ground to the crops and back into the atmosphere, are receiving attention.

Large dams and irrigation works have been or are being planned and built in connexion with the two main rivers and some of their larger tributaries. But these can only affect a relatively small percentage of the Area.

The amount of accessible water underground is being increasingly realized, and the exploitation of this water will no doubt increase the productivity of the Area.

Finally, it is thought that village-scale works for storing water (preferably underground) from artificial catchments, for use especially in the perimeters of settlements, which are richer in nitrates, represent another major potential, because the surfaces they could affect add up to an important fraction of the Area.

6. FOLLOW-UP ACTION

Agricultural meteorology in its present form is developing very rapidly, so that this report would soon be out of date, both with regard to methods and, more especially, information, if there were no follow-up action. The forms of action which are recommended will be briefly discussed.

(Recommendations concerning the observational network arising out of this study have already been made in another section of Part IV.)

6.1 Technical meeting

A technical meeting should be held in the Area some time after the publication of the reports to discuss their contents and gather the opinion of meteorologists and agronomists from the countries concerned, as to how this work can be extended and improved. A meeting of this kind was held in Beirut, as a follow-up to the first survey, with beneficial results (not the least being an improvement in collaboration between the meteorologists and the agronomists in the countries concerned).

6.2 Extension of number of reference stations and publication of their agroclimatic characteristics

As the data available improves with respect to diversity, quantity and serial length, it will be possible to increase the number of reference stations (here 35) in the Area and amplify the climatic and biological information characterizing each. It is suggested that this basic information should be published as a collection of agroclimatic characteristics independently from any other work of synthesis, interpretation or cartography. Each station would have its own dossier, illustrated by diagrams like Figure 67. For the exchange of plant stock it is thought that accurate descriptions of the agroclimate at a given spot are more valuable than the sketching out of agroclimatic regions.

6.3 Publication of lists of unpublished data

Some unpublished information (especially in the field of agronomy, as a result of the IRAT mission), was collected from the Area. Lists of this information, which in places is difficult of access, and in some cases perishable, should be published.

6.4 More detailed work

At the beginning of this report (and elsewhere in the text) it was pointed out that one of its most useful outcomes should be to touch off more detailed investigations at a national or subregional level. Some sample studies, especially of variability -- as opposed to those of average conditions used in this predominantly macroclimatological survey -- were included in the report, and it is hoped that they will suggest appropriate lines of investigation.

In addition, it is thought that some of this more detailed work should be undertaken by personnel from the interagency agroclimatology project itself to test further the applicability of the working concepts used in the surveys to the increase of agricultural production.

This could best be done in association with United Nations technical assistance programmes of the three agencies supporting the project, or of the Special Fund. An important aspect of such collaboration would be to appraise the extent to which the basic information presented by the surveys can be used by experts in the field.

Indeed, the main purpose of this survey is to provide these experts, native or expatriate, with basic agroclimatic information of an international character.

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