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SPACE SCIENCE, WEATHER, AND MAN IN TROPICAL AFRICA

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INTRODUCTION

Since the first weather satellite was launched in April 1960, observation from space of the earth's atmosphere and the weather systems embedded in it has developed rapidly in quality and quantity. Today every part of the globe can be viewed at frequent intervals from both orbiting and geostationary satellites. An advantage of geostationary satellite observation is the vast spatial domain served from the vantage point of outer space. There has never been an observational platform with a resolution to coverage ratio of $1:10^8$ as in the case of geostationary satellites. Five of these satellites can provide data on an almost global basis every half an hour. With the visual and infrared sensors on the satellites it is possible to provide coverage on an almost continuous day and night basis. A geostationary satellite is a satellite, the circular orbit of which lies in the plane of the earth's equator and which turns about the polar axis of the earth in the same direction and with the same period as those of the earth's rotation. The period of a geostationary satellite is about 1436.0683 minutes. Its norminal orbit is about 35,778.6657 km. An orbiting satellite on the other hand can have its orbit as near polar as possible. This is determined by the inclination angle necessary to induce a precession of one rotation of an orbital plane in the course of a year. This ensures that the satellite passes over the equator at a fixed solar time rather than a fixed sidereal time, every day. A perfectly polar orbit satellite will not precess. An orbiting satellite can be so placed such that a minimum possible period is only ninety minutes. An orbiting satellite provides full coverage of the earth twice a day from altitudes low enough to permit good ground resolution.

Remote sensing of the earth's atmosphere from space is particularly advantageous in the tropics which is 40% oceanic and whose land area is relatively sparsely populated. Large data lacunae and even conceptual gaps had imposed a fundamental limitation on research efforts into tropical weather systems. Hence the weather systems of the tropics are not as well understood as those of the extratropical areas. The use of satellite data in conjunction with the few ground based observations, has provided new perspectives for looking at the weather systems of the tropics. The prospects of new sources of data and the desire to understand the role of the tropics in the general circulation of the atmosphere had motivated special observational experiments over the tropical oceans in the last two decades. In the late sixties localized experiments in the tropics were mounted. Such experiments included the Line Island Experiment (LIE, 1967) located in the tropical Pacific Ocean, the Barbados Meteorological Experiment (BOMEX, 1969), the Venezuelan International Meteorological and Hydrological Experiment (VIMHEX, 1979) and TROPEX, a tropical field experiment organized by the Russians in 1972. The success of such experiments only underscored the need for more elaborate experiments. The Global Atmospheric Research Program was an international research endeavour which made, as one of its main objectives, the filling of tropical weather data gaps in order to provide means of estimating the effects of smaller scale tropical weather systems on the earth's large scale circulation and to facilitate numerical modelling and prediction by developing better models of tropical weather systems. More relevant to the present discussion is the GARP sub-programme called GATE, that is, GARP Atlantic Tropical Experiment executed during the Summer of 1974. During the experiment, data were collected from about one third of the earth's tropical belt between latitude 20 N and latitude 20 S. The experiment located over the East Atlantic Ocean Area involved seventy-two nations which provided 40 ships, 13 air crafts, a Synchronous Meteorological satellite and several U.S. and USSR orbiting satellites. The GATE experiment greatly stimulated tropical weather research. Since GATE, FGGE, (First GARP Global Experiment), MONEX, (Monsoon Experiment of the Indian Ocean), WAMEX, (West African monsoon Experiment) have also been executed.

It is not possible and perhaps even not appropriate to review the results of all these experiments in this paper. This paper discusses the role played by satellite-derived data in making it possible to observe some prominent features of the weather systems and climate over tropical Africa during the execution of some of these experiments and at other times.

Figure 1 shows the essential ingredients of the weather over Tropical Africa. The Sub-tropical High Pressure systems, the Tropical Easterly Jets (TEJ), the African Easterly Jets (AEJ), the African Easterly waves, the Monsoon systems, the Intertropical Discontinuity, the desert and ocean influences all contribute in varying ways to the weather and climate over the region. The extent to which observation from space-based platforms has helped to define the structure of these atmospheric systems and influences and the promise that satellite-derived data holds for the future in the understanding of the weather and climate of Tropical Africa are the focus of this input to the study week.

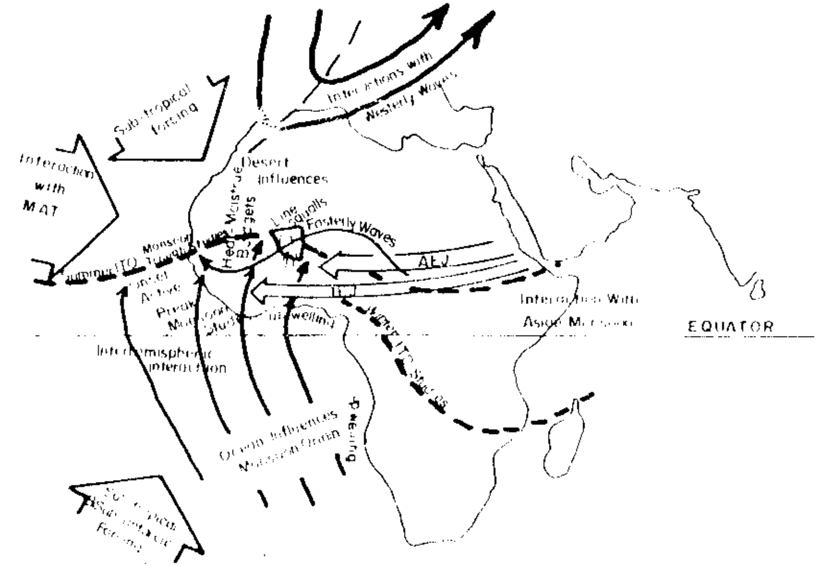


FIG. 1. Some atmospheric systems which influence weather events in Tropical Africa. (Adapted from GARP Publication series N° 21. World Meteorological Organization)

Meteorological Parameters Measurable from Space

The number of meteorological parameters measurable from space is only limited by the capability of the instrument that can be mounted on a satellite. Some of the weather and climate parameters that are derivable directly or indirectly from satellite-borne instruments are: cloud cover, atmospheric profiles of water vapour and temperature, surface albedo, rain areas and rain amounts, cloud drift winds, sea surface temperatures, estimates of other atmospheric constituents like ozone, dust etc., earth radiation budget and some other weather related information. The process of retrieving the various parameters can not be adequately covered in this paper. In subsequent sections summaries of the importance of these parameters in weather and climate analyses and the importance of the parameters to the understanding of the weather and climate of tropical Africa will be discussed.

Both active and passive systems aboard satellites are used in the measurement of weather parameters. Active systems, for example radar, send out signals which react with a target and after reaction are observed and measured qualitatively and quantitatively by the system. Satellite-borne active systems now feature prominently in the estimation of rainfall. Radars which perform as scatterometers and altimeters are also active sensors which image the oceans and land surfaces. Passive systems on the other hand observe and measure the natural emanations from the gas and aerosol constituents of the atmosphere or the scattered and reflected solar radiation from the earth and the atmosphere. Much of the early use of the satellite observation has been in the form of the visible and infrared imagery which were registered by passive instruments on satellites. Passive sensors can also detect radiation in the near infrared.

Most of the illustrations in the paper have been obtained from the synchronous meteorological satellite (SMS) which was available over the GATE area, the METEOSAT (the geostationary satellite of the European Space Agency), and from several orbiting satellites belonging to the United States of America and other countries. Special mention needs to be made of the METEOSAT because of its unique view of the African continent (from an altitude of 36000 km) with most of the continent being within 30° of the subpoint of the satellite and because most of the data presented in this paper was derived from its observations.

The principal pay load of the satellite was a multispectral radiometer which had two identical adjacent visible channels in the 0.4-1.1 μm spectral band, a thermal infrared channel in the 10.5-12.5 μm band and an infrared water vapour channel in the 5.7-7.1 μm band. The water vapour band is normally operated in place of one of the visible channels and because of that, two possible sets of images are available in any thirty-minute period: images with 2.5 km resolution in the visible channel and images with 5 km resolution in the infrared channels, or images with 5 km resolution in the visible channel and a 5 km resolution in the infrared channels. The latter set of images was used in the results presented in this paper. METEOSAT-I was also part of the global network of five geostationary meteorological satellites placed around the equator at intervals of approximately 70° longitude to generate cloud images during the First GARP Global Experiment (FGGE). Of interest in the preparation of this paper were observations from two of the other five satellites GOES-I and GOES-E in orbit over the Indian and the Atlantic oceans respectively. GOES-E was a replacement for the SMS.

Cloud Cover Over Tropical Africa

A striking feature of any satellite imagery of the Earth in the visible or infrared band is the presence of clouds. Satellite observed cloud cover of weather systems provided the first clues to the three-dimensional structure of the atmosphere. Clouds indicate weather processes. Configurations of cloud patterns often reflect the motion of air that carried them. Repeated occurrence of certain types of clouds often indicates the frequency of a specific set of atmospheric conditions that are responsible for the clouds. Apart from indicating weather processes, clouds also make impact on global weather in two important ways, through the albedo effect and the greenhouse effect. Because clouds are efficient scatterers of solar radiation (80% can be effectively reflected by clouds a few hundred meters thick) increased cloud cover means increased amount of the total solar radiation scattered and less energy to be absorbed by the earth's surface. This is the albedo effect. At thermal infrared wavelengths clouds are efficient absorbers and so infrared radiation from the earth surface is absorbed and reradiated downwards by the clouds so that the temperature of air near the earth surface increases. This is the greenhouse effect. There is a complex interplay between these two effects but recent investigations indicate that the cloud albedo effect is dominant.

Starting with observations from the early generation of satellites

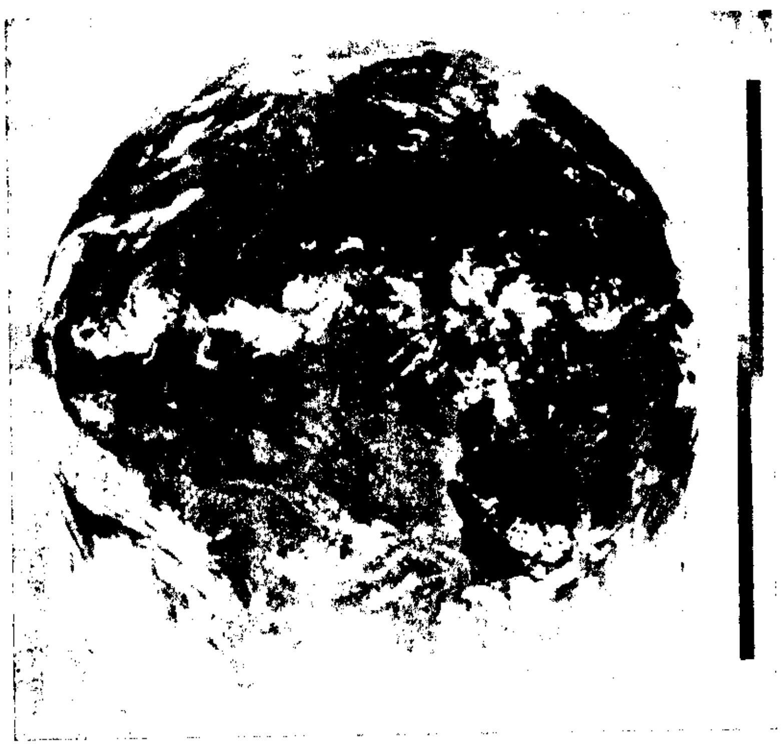


FIG. 2.

(e.g. TIROS series 1960-1966, ESSA series 1966-1969) researchers attempted to compute average cloud cover over the earth surface (Sadler, 1968; Taylor and Winston, 1970). With subsequent generation of satellites, it was possible to study the behaviour of large-scale disturbances in Tropical cloudiness (Balogun, 1972, 1975; Zangvil, 1975; Chang, 1970; Reynolds and Vander Haar, 1977; Yanai and Murakami, 1970; Wallace, 1971, Wallace and Chang, 1972; Martin and Schreiner, 1981 and others). Despite the unremitting research effort the nature of the large scale cloud fields over the tropics and its relationship with the large scale wave disturbances have not yet been clearly understood. Even spectral analysis of cloud fields only succeeded in giving approximate estimates of the space and time scales of these disturbances.

Figure 2 shows an infrared imagery of cloud organization over Africa

from METEOSAT 1. The band of cloudiness over tropical Africa is made up of cloud systems in different scales of organization. In the following subsections, a further discussion of the various scales of cloud organization over tropical Africa will be presented.

Mean Cloud Cover

The mean cloudiness map prepared by Sadler (1975) shows similar features to the map shown in figure 3 even though with less details, especially as it concerned the land area of West Africa. The mean cloud cover shown in the figure was for only 32 days at the peak of the monsoon rains over West Africa. The source of data is the METEOSAT and the method of estimating the cloud cover was that developed by the author (Balogun, 1977). The significant feature of the map is that there is a zone of maximum cloud cover some 500 km south of the surface position of the Intertropical Discontinuity (ITD). The surface of transition be-

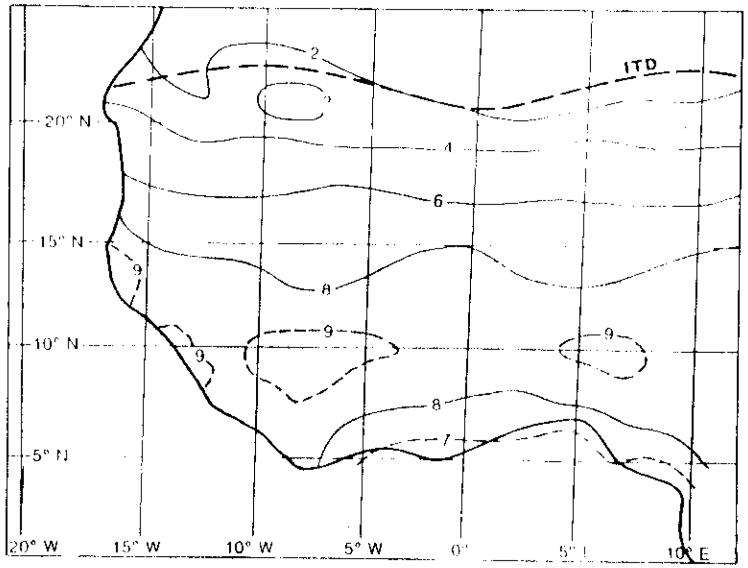


FIG. 3. Mean cloud cover in tenths for the period J[illegible] to August [illegible], 1979, using infrared imageries from the Meteosat.

tween the moist monsoon air stream and the dry air mass from the Sahara is known as the ITD surface. The intersection of this surface with the ground has a migrating position between Lat. 4°-6° N (in January) and Lat. 22°-25° N (in August). The northernmost position of the ITD is therefore observed around the middle of August and at that time, the slope of the ITD surface is about one in five hundred.

That the zone of maximum cloudiness is not closer to the surface position of the ITD than it is as revealed by the satellite is not difficult to explain. Near the ground position of the ITD, the depth of the moist layer is small and vertical development of clouds is inhibited by the dry Saharan air aloft. However, that the zone of cloudiness did not extend further south than it is, given the fact that the moisture layer is deeper to the south, cannot be easily explained. That this zone of cloudiness marches north and south is indicated schematically in Figure 4. Zone C in the figure corresponds to the zone of maximum cloudiness in Figure 3. Figure 4 was composed by the author from conventional data sources, (other earlier authors, notably Hamilton and Archibold, 1945; Walker, 1958; Adejokun, 1966, have identified similar zones), and it illustrates how the zone of maximum cloudiness shifts in the meridional direction during the course of the year over parts of West Africa.

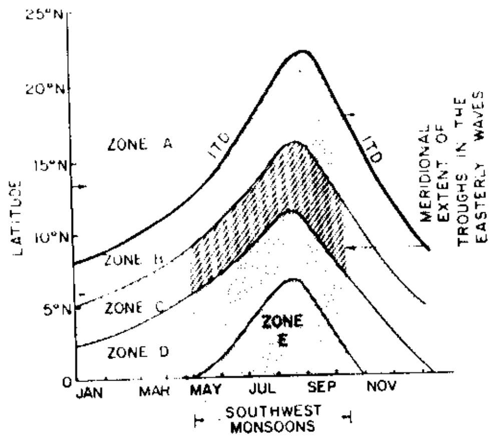


Fig. 4. Meridional variation of the ITD position at about longitude 7°E and the weather zones over Nigeria.

Cloud Clusters

The mean cloud cover over an area does not give an indication of the various cloud organizations that constitute it. Figure 5 shows the satellite imagery from the Defence Meteorological Satellite (DMS, United States Government). The picture shows various clouds assemble over East Africa. (Picture taken June 1, 1977). A cloud cluster is defined as a distinct persisting cloud mass (essentially of convective origin) containing very deep convection during some parts of its life. The average life time of these clusters has been found to be about 24 hours (Martin and Schreiner, 1981). With the help of satellite data it has been possible to study some characteristics of the cloud cluster. Their tracks, time of occurrence, their sizes have been studied and classified. To some extent their thermodynamic structure is known. What is still a mystery about these systems is the atmospheric mechanisms that trigger them off, and the mechanism for their dissipation. It is still not clear why some of these clusters move rather slowly and some, like the West African squall lines, move fast. Because of the importance of the West African squall lines as major rain-bearing systems over West Africa, they will be given special attention in a subsequent subsection.

Figure 6 shows the DMS picture of the same areas in Figure 5 for June 3, 1977. By that time the cloud clusters shown in Figure 5 had cleared with some new ones just developing. The figure also shows very clearly the East African lake systems. Figure 7 shows the frequency and the time of occurrence for cloud clusters as estimated from satellite (SMS-1) during GATE. More clusters are observed in the late afternoon than at any other time of the day over the West African land areas while a bimodal distribution is observed over the East Atlantic Ocean and at the coastal areas. Figure 8 shows a schematic diagram of the distribution of various types of clusters at 113000 on July 27, 1979, over West Africa. That convection can be organized on different scales and with different structures within the same air stream is a feature of the West African atmosphere that is still being investigated.

Figure 9 shows the vertical extent of the tops of samples of cloud clusters of different size categories over the West African region during July 14 to August 15, 1979. The diagram shows that the larger the cloud cluster, the more probable it is to find very tall cloud elements within it. The cloud heights and cloud areas were estimated from the METEOSAT observations with the aid of a computer.

Fig. 5. East Africa.

Fig. 6.

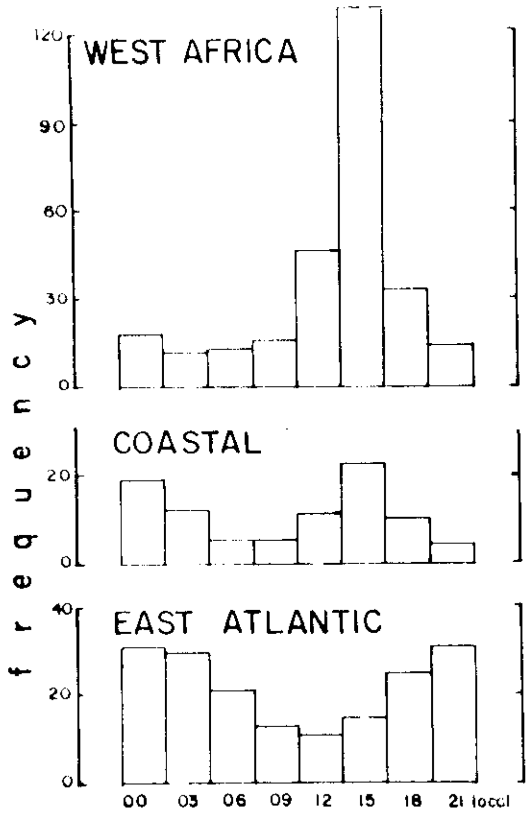


FIG. 7. Time of cloud cluster appearance and frequency (After Martin and Schreiner, 1981).

West African Squall Line

The squall line is an important rain-bearing system over West Africa. The system accounts for more than two-thirds of the rainfall over the Sahel and contributes substantially to the rainfall in other areas of West Africa. The importance of these systems to Agriculture and Water resources management over the region can not be over emphasized. Squall lines are different from other cloud clusters only in their propagation speeds and their vertical wind shears.

The West African Squall line system has been reported upon by merchants and by scholars centuries ago. Hubert (1926), Brooks (1932), and Regula (1936) have provided some information about these weather systems. The quest for the origin of the disturbances that eventually develop into hurricane and the revelations of satellite imageries motivated several publications on the disturbance over West Africa during the middle and late nineteen sixties. Publications by Arnold (1966, 1967), Carlson (1969, 1971), Frank (1963) and others focussed attention on the variety of systems over the land areas of West Africa and the adjacent oceans. More recent investigation by Olori-Togbe (1981), Balogun (1981), Burpee (1976, Dhonneur (1974), Tschirhart (1958), La Roux (1976), Latrasse (1972), Obasi (1974), Payne and McGarry (1977), Okulaja (1970), Aspliden *et al.* (1976), Houze (1977), Fortune (1980), Frank (1978), Tourre (1979), Bolton (1981) have produced a wealth of ideas about the squall line system over West Africa. Reports from special experiments like the Operation Niger ASECNA have also provided some information. Most

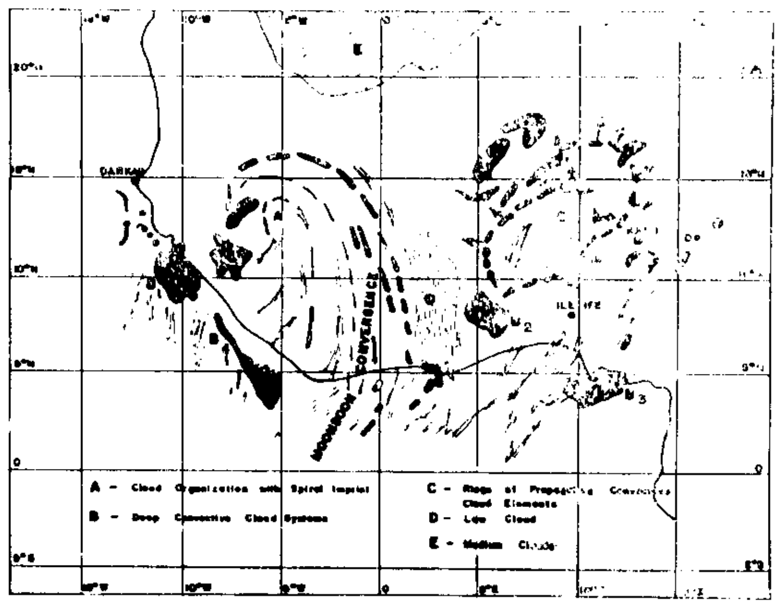


FIG. 8. Approximate schematic representation of cloud organization at 113000Z, July 27th, 1979 (day 208).

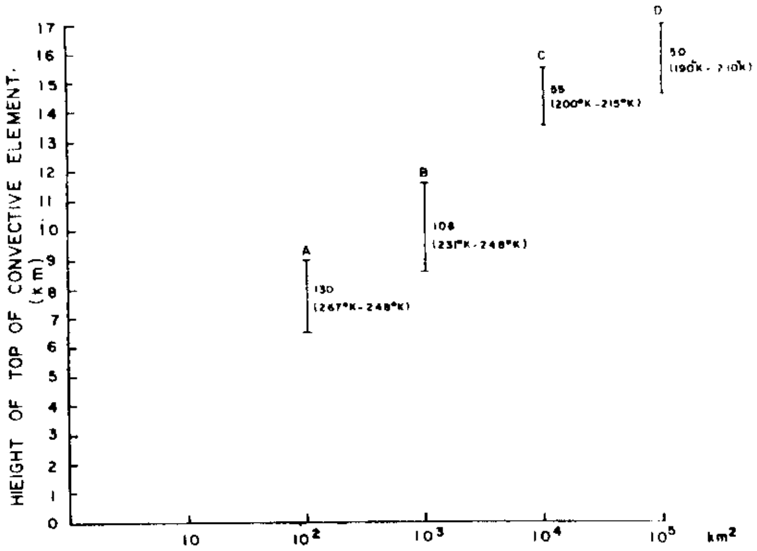


FIG. 9. Order of magnitude of cloud organization.

of the research efforts used satellite data in varying degrees. The following characteristics of the squall line have been established or confirmed by satellite data:

(a) They are identified in both infrared and visible images as distinct cloud masses characterized by explosive growth, and high brightness.

(b) They propagate generally from East to West. Most squalls move directly westwards rather than towards the Northwest or Southwest. The speed of propagation is between 15 ms^{-1} and 18 ms^{-1}.

(c) Their leading edges are usually arc shaped while their edges are generally rather indistinct and fibrous. Roll clouds are sometimes visible along the leading edge and sometimes detached from the main cloud system.

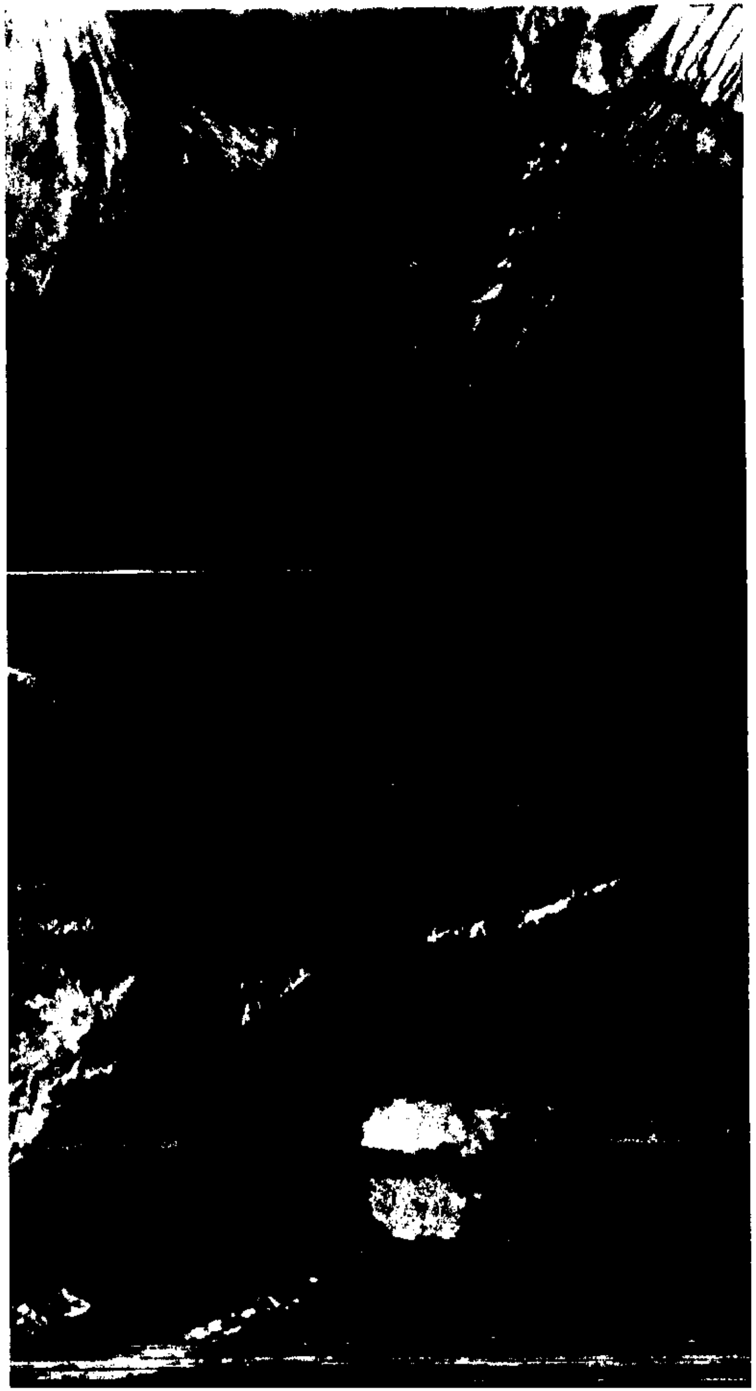
(d) Their cloud masses achieve areas about 1° square and have lifetimes of at least six hours. Cloud masses could achieve a length about 300-1000 km long and lying roughly North South over the West African region.

(e) Squall lines forming over the West African land mass often dissipate on arriving at the coast. Squall lines forming over the oceans often differ in their orientation and direction of motion from squall lines forming over land.

(f) Tops of cloud element within the squall line may grow up to 17 km.

Several classifications of squall lines as seen by satellites have been made by some authors. Latrasse (1972) classified squall lines into two main types depending on whether they are made up of one or two arcs. Gurka (1976) using both visible and enhanced infra-red images identified four types depending on the relationship of the arc front to the main cloud mass. Balogun (1984) using data from DMS and the METEOSAT concluded that only three independent types of squall line cloud structure could be isolated. Type one is gibbous-like in structure with a well-defined convex leading edge and fibrous at the rear. Figure 10 is representative of this type. Roll clouds may or may not be discernible in front of the convex leading edge. Sometimes the gibbous-like structure may exist as a doublet as shown in Figure 11. Type two is usually made up of a long line of cumulonimbus ensemble oriented mainly in the north-south direction. The leading edges are not so well-defined as in type one and roll clouds ahead of the leading edge may or may not be seen. The impression is given of a "beaded" well developed cumulonimbus cloud. Fibrous exudants are also visible to the rear of the system. Figure 12 shows a representative of this type of squall line. The third type often appears as a semicircular ring of cumulonimbus clouds in which clouds are not as well developed as in type two and in which the clouds are not strictly of north-south orientation as in type two. Near the left edge of figures 12 and 13 are rings of propagating convective clouds which belong to this class of squall line systems. It should be noted that convection is not of the same intensity around the rings. Figure 12 has been enhanced to show the convective cores of the cloud systems.

In spite of these research efforts, there are still many unanswered questions about the West African squall lines. The important factors which if present in the right order of magnitude and at the right time within the basic flow could trigger off the chain of convection in a squall line are not known. Although there have been good suggestions as to the relationship between squall lines and low level vortices, waves and the two jet systems (AEJ and TEJ), the precise relationships are still not yet known. The prediction and detection of potential areas of initiation



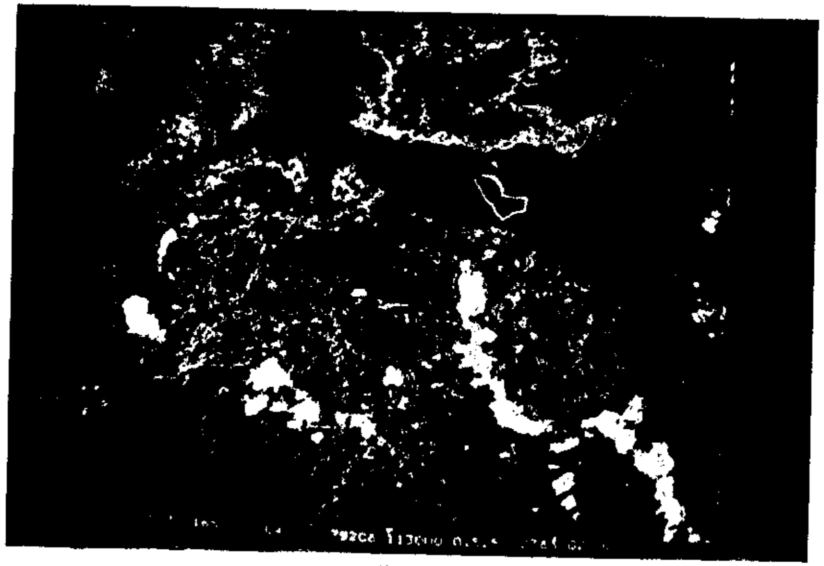


FIG. 12.

FIG. 13. Cloud rings on left-hand side.

and formation of squall lines are still difficult. Satellite data can still play a significant role in solving these problems. Rapid scan observation of the squall line system can be used effectively to detect the characteristics of the system during its formation stages. Use of such rapid scan products have so far not been reported in the study of West African squall line systems.

SATELLITE-DERIVED CLOUD DRIFT WINDS OVER TROPICAL AFRICA

Reports of wind measurement from conventional sources (radio sonde, pilot balloons etc.) are usually not of sufficient quantity or quality to carry out reliable wind analysis for weather forecasting purposes over tropical Africa at any given time. Weather forecasts can not be based on climatological wind maps which have been composed over long periods and from various sources (ships of opportunity, aircrafts etc.). That wind directions and strength remain the same for long periods over the tropics is a general statement that is not totally supported by recent experiments in the tropics. The great potential of satellite-derived windfields in the tropics and elsewhere lies in the improvement over conventional data sources in both temporal and spatial resolution. Even where radiosonde observations are abundant, such observations are normally available at 12 hour intervals which is too infrequent to describe the development in any meteorological phenomena particularly those occurring at subsynoptic scales. With an image frequency of one per half-hour from geostationary satellites it is possible to estimate wind flow reliably from a sequence of three images. It is now even possible to obtain an image frequency of one image in every 6 minutes from some of the existing satellites. Such rapid scan images permit computation of subsynoptic scale motions which characterize severe local weather events.

The philosophy behind estimating winds from cloud displacements from a sequence of images from geosynchronous satellites is predicated on the assumption that if cloud tracers are properly chosen, and tracked their motion will reflect the speed of the air in which they are imbedded. Several methods have been developed to estimate cloud motion from satellite imagery. These range from manual to fully automatic methods. The important steps in all procedures are: a properly aligned sequence of imageries, objective criteria for cloud selections, calculation of cloud displacement and altitude assignments of the displacements. The various methods, the assumptions usually made, and the problems associated with

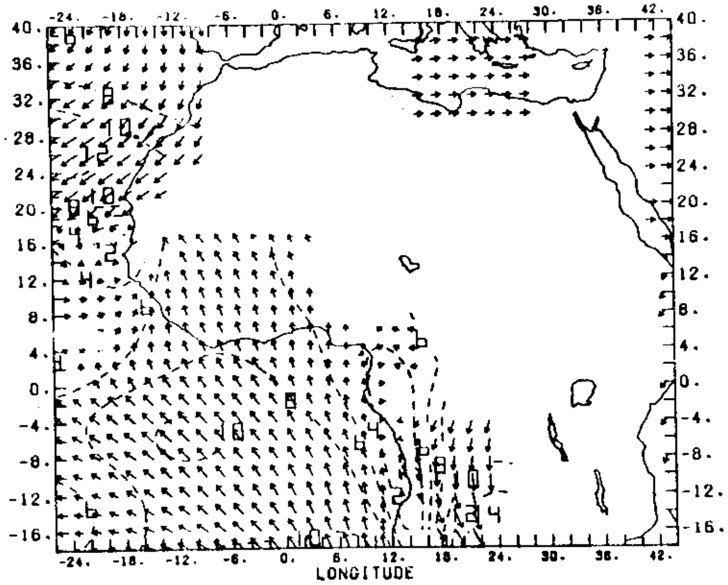


FIG. 14. Satellite-derived low level winds for 1200Z, July 18, 1979.

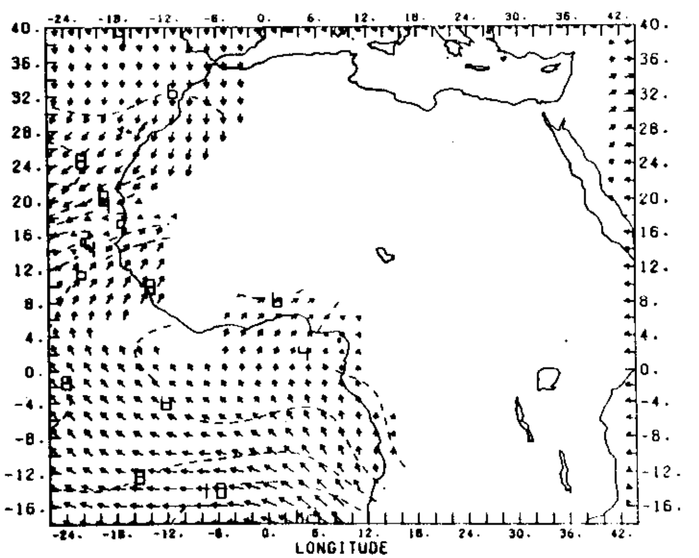


FIG. 15. Satellite-derived low level winds for 1200Z, July 20, 1979.

each step have been discussed by various researchers, among whom are Izawa and Fujita (1968), Hubert and Whitney (1971), Hasler and Smith (1976), Fujita *et al.* (1975), Bauer (1976), Suchman and Martin (1976), Hubert (1979) and Balogun (1982). In spite of the enthusiasm for satellite-derived cloud drift wind, it was also soon realized that the data set was a meteorologically biased set, that is, such data could only be obtained in cloudy areas. Attempts were therefore also made to estimate water vapour drift winds from satellite measurements. These attempts, (Mosher, 1977; Johnson, 1979; Kaestner *et al.*, 1980; Balogun, 1982 and several others) have been largely successful and have provided useful air motion data in cloud free areas.

Attempts at computing cloud drift winds over tropical Africa from METEOSAT data are shown in Figures 14-19. Figures 14 and 15 represent flow at the low levels of the troposphere (900-850 mb). Figures 16 and 17 represent flow at the mid-troposphere (650-450 mb) and Figures 18 and 19 represent atmospheric flow at the upper levels of the troposphere (200 mb). In each case, motion fields were computed from a sequence of three half-hourly photographs from the METEOSAT. Motion at the low levels was obtained by tracking low level cumulus cloud organization. Vectors in Figures 14 and 15 represent the direction of low level monsoon flow and the isotacs represent the strength of the flow. It is observed that winds were stronger on the 18th of July at the Gulf of Guinea than on the 20th of July, 1979. Such wind fields, and the noticeable changes in wind direction and strength which they can exhibit within forty eight hours could not have been obtained from conventional wind data. The significance of such wind changes in the Gulf of Guinea and the southern Atlantic to weather events in West Africa is still under study by the author and his colleagues at the University of Ife, Nigeria.

Figures 16 and 17 represent mid-tropospheric flow. The important thing about these windfields is that they were obtained by tracking water vapour fields. Carefully tracked imageries of moisture in the water vapour bands (5.7-6.3 μm) are thus capable of revealing atmospheric motion between 650 mb and 450 mb level in the atmosphere. The subtropical high pressure system is very prominent in the northwestern portion of Africa in both figures. Figure 16 contains more water vapour wind vectors and apart from showing the subtropical high pressure system also shows a wind maximum (maximum of 12 ms^{-1}) around Latitude 12° N. This wind maximum can be associated with the African Easterly Jet (AEJ) whose core is known to be situated at about 700 mb level. Water vapour

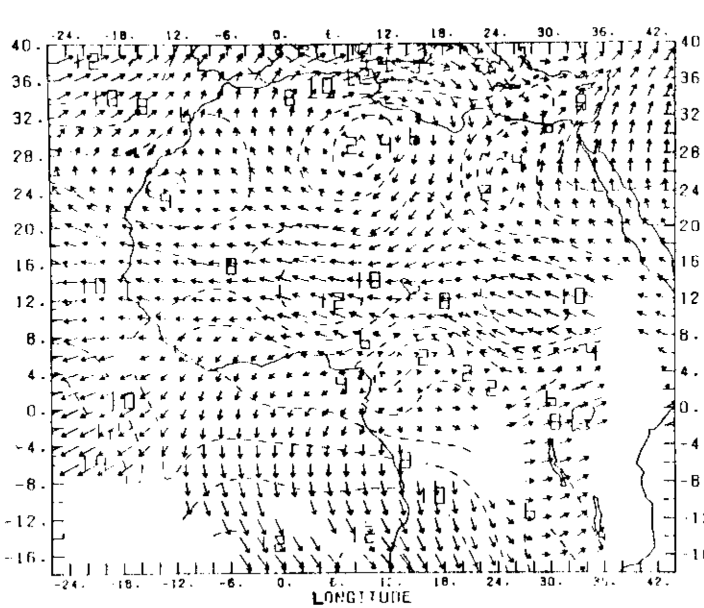


FIG. 16. Satellite-derived middle level winds for 1200Z, July 23, 1979.

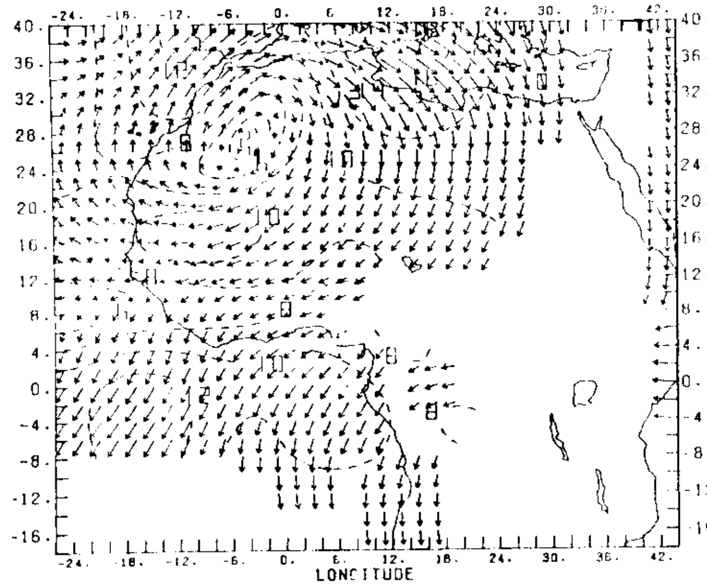


FIG. 17. Satellite-derived middle level winds for 1200Z, July 15, 1979.

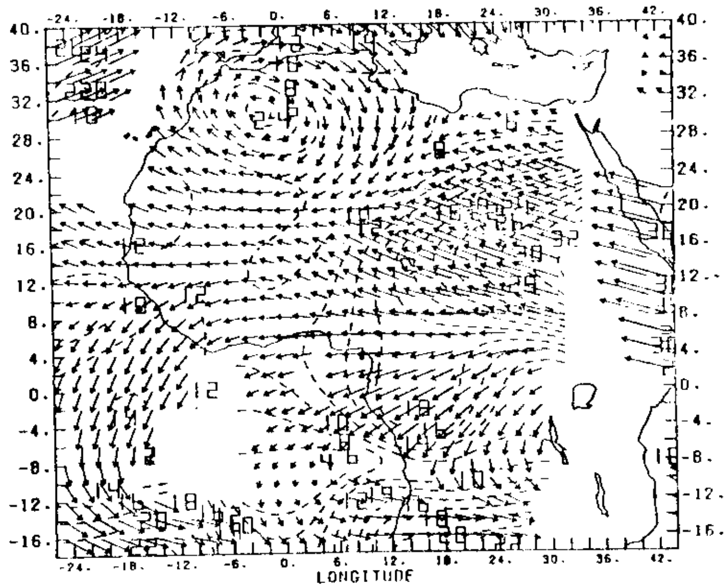


FIG. 18. Satellite-derived upper level winds at 1200Z, July 25, 1979.

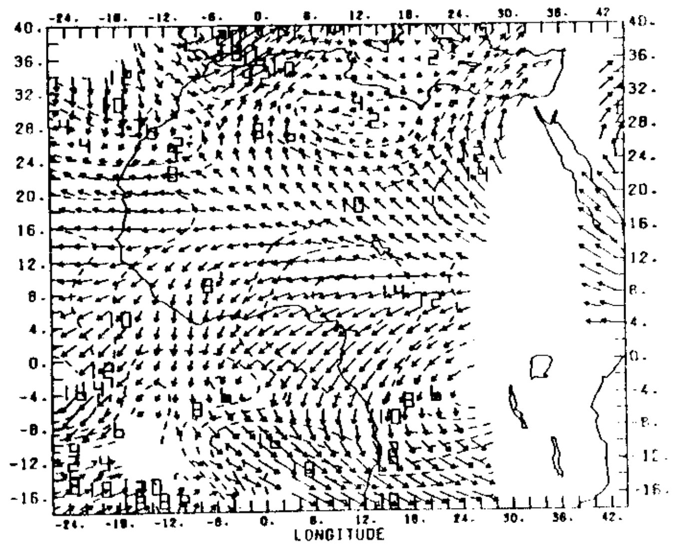


FIG. 19. Satellite-derived upper level (200 mb) winds at 1200Z, July 18, 1979.

drift winds therefore provide a means of studying the characteristics of this jet and its impact on the weather systems of Tropical Africa.

Figures 18 and 19 are samples of the upper level wind field obtained by tracking cirrus clouds. The subtropical high pressure systems in the two hemispheres and the Tropical Easterly Jets (TEJ) are indicated in the two diagrams. These systems are more prominent on July 25, 1979 than on July 18, 1979. These windfields have been computed from METEOSAT data.

At this juncture some relevant questions may be asked. How accurately can the cloud displacements represent the wind? How accurately can different cloud trackers reproduce the same set of winds? How internally consistent are these drift winds? These questions have been addressed by some researchers referenced earlier and the conclusion is that flow fields obtained by tracking cumulus and cirrus clouds approximate the flow at the low levels (900-850 mb) and at the upper levels (200 mb) to within the accuracy of currently available ground truth data (that is data from raw-wind system). The error characteristics of water vapour drift winds are still being determined but the initial results of computations are very encouraging.

Estimates of Rainfall from Satellite Data

Publications by Martin and Scherer (1973), Barret and Martin (1981), Atlas and Thiele (1981) have reviewed the different stages in the development of precipitation measurement from space. The problems and prospects of monitoring rainfall from space were fully discussed in those publications. Attempts are often directed towards achieving two goals, namely: to delineate accurately rain areas from satellite imagery and to make quantitative estimates of rainfall from satellite radiance measurements. The success in attaining the first goal is impressive but in spite of some encouraging results, there are still major obstacles in the way of achieving the second goal. This is because most of the results obtained so far rest on uncertain assumptions. Satellite-derived rainfall estimates however hold promise in providing data for rainfall inventories, droughts and floods, water resources management, crop growth and production etc.

Barret (1980) has developed a cloud indexing method to monitor rainfa... ..om satellite imagery over some North African countries. This method establishes cloud indices for all significant cloud cells observed in satellite images and related conventional observations. These methods have been used operationally with some success in some countries. Results of the applications of this method for rainfall estimation over the Sahel and south of Sahel is not available to the author and therefore its success or failure over such areas can not be discussed in this paper.

Barret (1970), Woodley and Sancho (1971), Kilonsky and Ramage (1976), Scoffield and Oliver (1977), Stout *et al.* (1979), Barret (1980) have discussed in detail such techniques as brightness technique, cloud system life history technique, highly reflective cloud technique, threshholding technique, cloud indexing technique, parameterization technique etc. Some of these can only be applied with confidence over the ocean areas and some have been tested only in the temperate regions without consideration for the special circumstance of the tropical land areas. Difficulties in organizing rainfall data from conventional sources and almost complete absence of useable radar data needed has retarded the process of developing a scheme for estimating rainfall from satellite radiances over the countries around the Guinea coast. Preliminary investigation by the author (see Figures 20 and 21) using rainfall figures from rain gauges and cloud cover estimates from ESSA satellites over Nigeria for the coastal stations (coast to Latitude 10° N) and the inland stations (Latitude 10° N to 14° N) indicate that while an association between monthly mean rainfall and cloudiness may be obtained for inland stations, there may be considerable difficulties in drawing such conclusion between rainfall and cloudiness for the coastal regions. Most of the precipitation inland is from convective cloud. Precipitation along the coastal areas is from both convective and non-convective clouds and variations in cloudiness do not necessarily follow the variations in mean rainfall amount. Current efforts are being made to establish some relationship between cloudiness and rainfall using data from the METEOSAT for the West African land areas. Of interest at the University of Ife also is the establishment of rainfall inventory for the West African Squall line system using data from the same satellite. Progress on these projects depends on availability of funds. Such investigations should prove useful to agricultural and water resources management over the region.

Satellite Studies of the African Easterly Waves

African Easterly Waves or simply African Waves are the wave-like disturbances which propagate westward across West Africa and the Atlantic Ocean. Early observational studies of these waves by Arnold

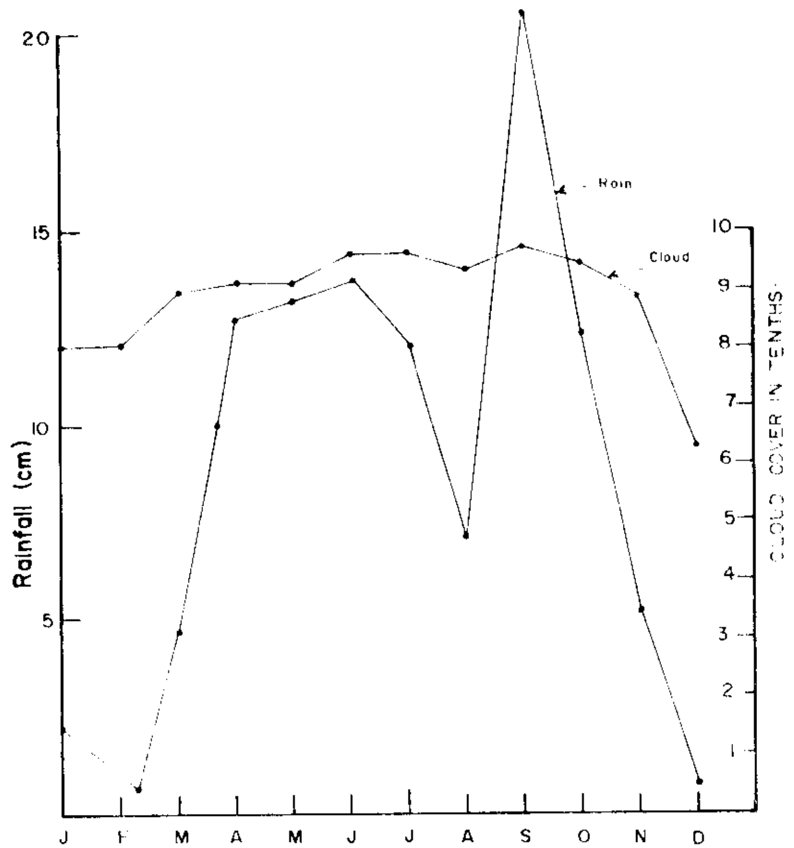


FIG. 20. Monthly mean cloud amount and monthly mean rainfall between the coast and Lat. 10°N over Nigeria.

(1966), Carlson (1969), Frank (1970), Burpee (1972), emphasized the importance of the wave system to the development of tropical cyclones in the Atlantic Ocean. Frank (1970) has shown that as many as half of all Atlantic Tropical cyclones develop from the African waves. More recent studies by Burpee and Dugdale (1975), Balogun and Teeson (1975), Rennick (1976), Reed *et al.* (1977), Thompson *et al.* (1979), Albignat and Reed (1980), Spencer (1981) focus attention on the origin, structure, and

energy transformations of the wave system as it moves across the tropical African region and the Atlantic Ocean. In most of these studies satellite photographs have been used in conjunction with conventional data. Burpee (1972) suggested that the waves originate at 700 mb level near Longitude 30-35° E and that the waves are most intense at about Latitude 12° N. Later studies show that the waves amplify mainly between longitude 0°-10° E and that the waves do not have the same structure in their course. The waves are known to derive their energy from the baroclinic and barotropic

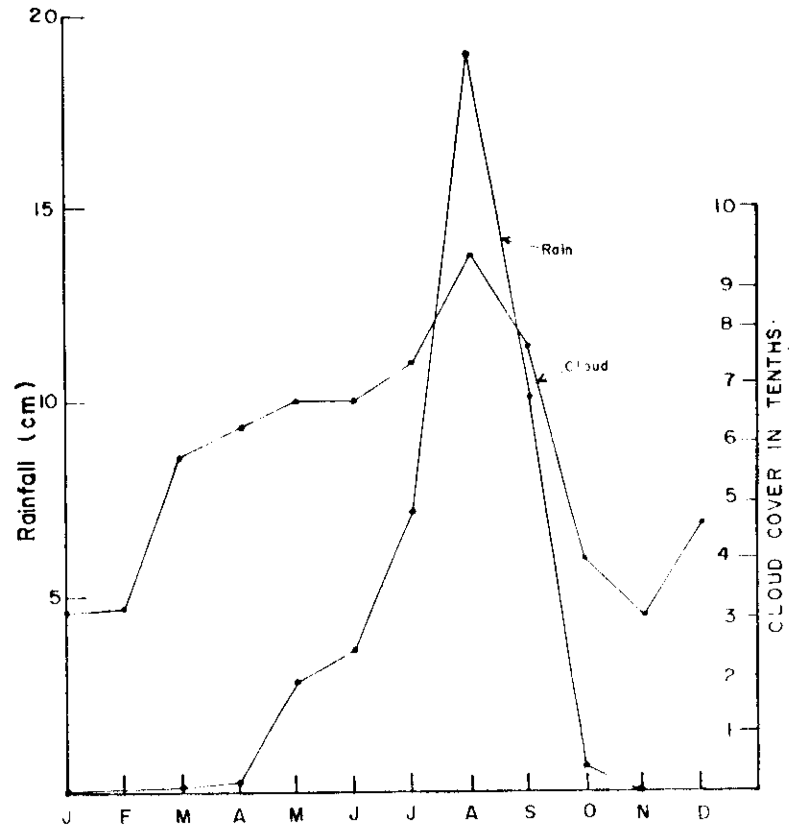


FIG. 21. Monthly mean cloud amount and monthly mean rainfall between Lat. 10°N and Lat. 14°N over Nigeria.

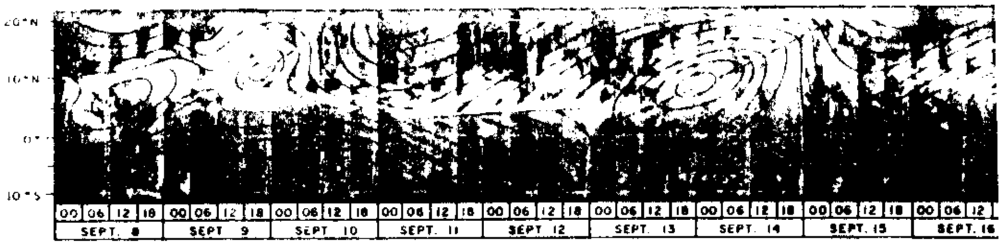


FIG. 22. (See text). After Balogun and Tecson 1975.

instabilities of the mean flow. The formation of these waves is tied to the presence of the AEJ. Waves form in the zone of cyclonic windshear on the south side of the jet axis which itself is located north of Lat 12° N. Waves intensify as they propagate across West Africa with a period of 3-5 days a mean wavelength of 2,500 km and a westward phase speed of 7-9 ms $^{-1}$. The importance of these wave systems to Tropical Africa is that they modify weather events over the region. Convergence and precipitation feature prominently ahead of the trough line of the wave system and squalls are known to develop in that section of the trough.

Composited satellite data have been very helpful in understanding the wave structure. Figure 22 is a time latitude section of SMS infrared pictures at six-hour intervals from September 8 to September 16, 1974. This mosaic is composed of longitudinal rectangular strips five degrees wide and centered at 23.5° W near 10° N and extending from 10° S to 20° N. Superimposed on this mosaic is the 700 mb wind analysis of observations from ships along 23.5° W. The heavy solid line indicates the trade wind confluence zone, and the trough axis appears as a heavy dashed line. Figure 22 is an illustration of how satellite imagery could be used to elucidate an atmospheric event.

SURFACE ALBEDO MEASUREMENTS FROM SATELLITE DATA OVER WEST AFRICA

The recent or more properly the on-going drought conditions over the tropical African region (Sahel, parts of Sudan, Ethiopia, Somalia, etc.) have engendered considerable interest in the climate of desert and semi-desert regions of the world among various scientists in recent times. The social, political and environmental consequences of the drought have been discussed by Glantz (1977 a,b)) and many others. An important aspect

of the discussions on the drought condition is the role played by man in bringing about such conditions. It is believed by some scientists: Charney (1975), Berkotsky (1976), Otterman (1977), and some others, that the drought situation over the desert regions of the world may have been a result of increased surface albedo over those regions and that the increased albedo could be traced to man's activity in the regions. The reasoning goes as follows. As a result of overgrazing and other poor land management practices, these semidesert regions are further deprived of the little vegetation they have. The reduced vegetation leads to increased albedo. The high albedo means that more of the solar radiation that impinges on the earth surface is reflected back to space. This leads to a net radiative loss over the regions relative to its surroundings. The atmosphere near the ground cools and sinks. Sinking motion in the atmosphere is not conducive to the growth of clouds and because of the reduction in cloud formation, there is also a reduction in precipitation. There are a few scientists who hold contrary views but the weight of the opinion is in favour of such a theory or a slight modification of it.

The Sahara desert is currently the world's largest desert. It extends from the Atlantic Ocean to the Red Sea. The Sahelian region extends from west to east and lies at the southern periphery of the Sahara desert. It receives a long term average annual rainfall of between 200-600 mm. As it is a marginal climatic zone it is subject to a wide variation of precipitation in both time and space.

The Sahelian region encompasses six countries: Senegal, Mauritania, Mali, Niger, Bourkina-Fasso and Chad. The satellite therefore becomes a useful tool in monitoring atmospheric events over the region. In particular, computations of albedo variations over the region between 1967-1974 from satellite data have been carried out (Norton *et al.*, 1979) using SMS-1 imageries. The unexpected finding from that investigation which has been confirmed by observations from Landsat is that overgrazing from arid and semiarid regions has a tremendous impact on increasing surface albedo. Figures 23-25 from Norton *et al.* were computed from SMS imageries and confirm that satellite data could be used to monitor albedo changes over a large territory.

It should be noted at this juncture that apart from using satellite data for estimating albedo changes, satellite data is also becoming very useful in documenting incident and net solar radiation for agricultural, weather and climate monitoring. The existing ground-based pyranometer network produces very limited information on net solar radiation estimates.

Temperature and Moisture Profiles from Satellite Soundings over Tropical Africa

Even in the parts of the world where radiosonde facilities to measure temperature and moisture profiles in the atmosphere are relatively abundant, observations are made, probably for economic reasons, once in twelve hours. Radiosonde facilities over Tropical Africa are few and far between. Observations are usually made once a day at most of the radiosonde stations if at all. Maps showing temperature and moisture fields over tropical Africa for weather forecasting purposes are therefore difficult to prepare. Climatological maps have limited use in weather forecasting. Some examples of estimates of moisture content and temperature profiles over parts of West Africa computed from satellite data are presented in

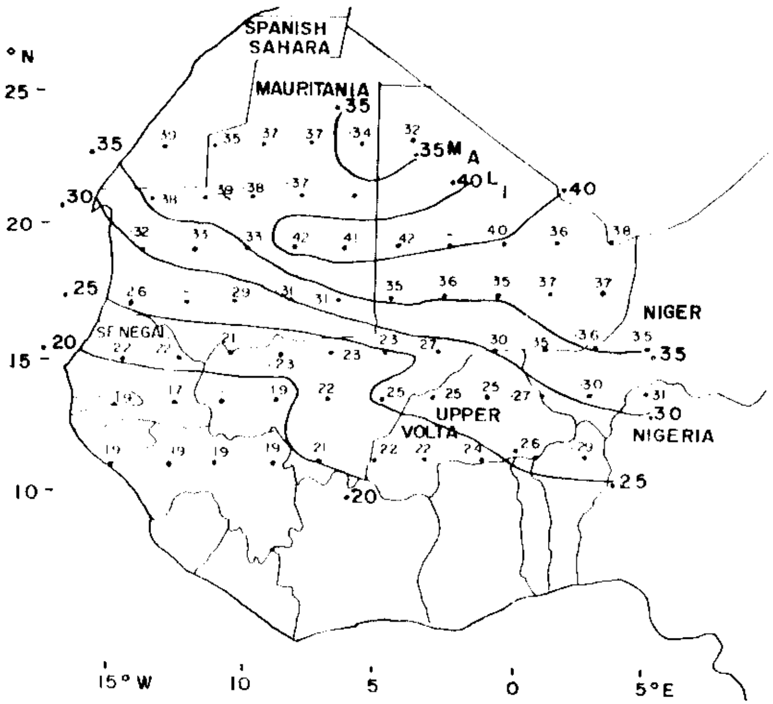


Fig. 23. Surface albedo over the Saharan Region for 19 November 1967 (1323Z) by Norton *et al.*, 1979.

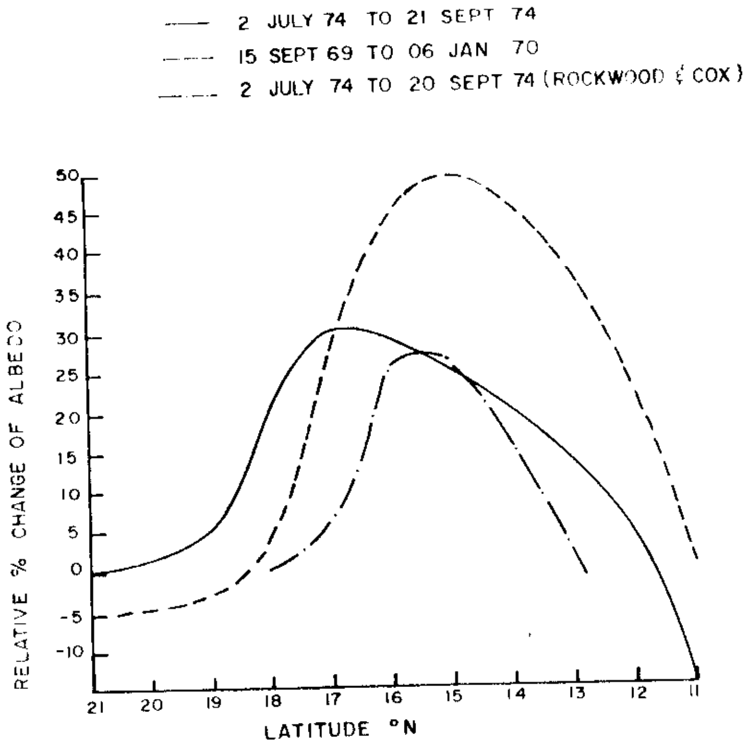


Fig. 24. Seasonal surface albedo change over the Sahel (after Norton *et al.*, 1979).

this paper to illustrate the fact that satellites can provide such information on an operational basis if the facilities and the manpower are available.

Literature now abounds on the theories relating satellite radiance measurements to the temperature and moisture distributions in the atmosphere. Details of the various methods used and the different stages in the development of the methods can be obtained from Kaplan (1959), Wark and Fleming (1966), Malkevich *et al.* (1969), and in more recent publications by Smith and Howell (1971), Smith *et al.* (1979), Lauriston *et al.* (1979), Hayden *et al.* (1981).

The concept of determining the vertical profile of an atmospheric parameter, be it temperature, water vapour or ozone from spectral radiance measurements, is based on the fact that atmospheric absorption and transmittance are highly dependent upon the wave length of the radiation and the amount of the absorbing gas. At frequencies close to the centre of absorbing gas, a small amount of gas results in considerable attenuation in the transmission of radiances and therefore most of the outgoing radiation arises from the upper levels of the atmosphere. On the other hand at frequencies which are far from the centre of the band, a relatively large amount of absorbing gas is required to attenuate transmission, therefore at those frequencies most of the outgoing radiation arises from the lower layers of the atmosphere.

For the determination of temperature, the appropriate absorption bands are those of carbon dioxide at short wave and long wave infrared, that is at 4.3 μm and 15 μm respectively, and that of oxygen at microwave lengths, that is, at wavelengths of 0.5 cm. The profiling of moisture is accomplished by utilizing the absorption bands of water vapour in the infrared at the wavelengths of 6.3 μm and 18 μm and in the microwave at 0.8 cm and 1.35 cm. The satellite radiance measurement in these spectral intervals depends both on the concentration and the temperature of the absorbing component. The concentration of CO_2 in the atmosphere is uniform. That of water vapour is not. The problems of temperature retrieval are therefore more tractable than those of moisture retrievals.

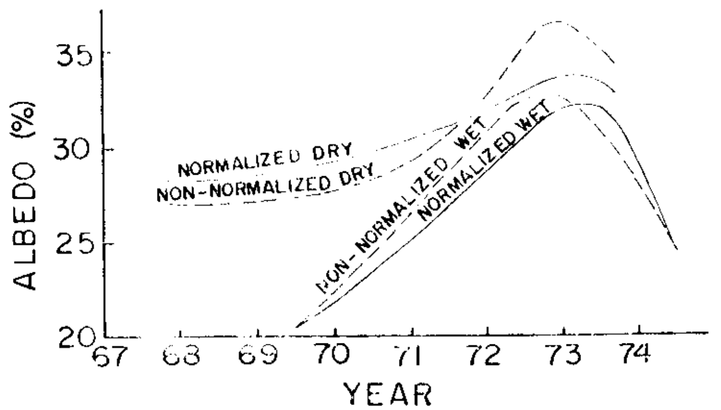


FIG. 25. Quasi-annual variation of the Saharan mean albedo (12°N to 18°N) for wet and dry season (after Norton *et al.*, 1979).

The radiative transfer equation can be written as,

$$R_{(\nu)} = B\,[\nu, T_{(x_0)}]\;\tau\,[\nu, x_0] - \int_0^{x_0} B\,[\nu, T_{(x)}]\; d\tau/dx\,[\nu, x]\; dx$$

The spectral radiance is given by $R_{(\nu)}$. The planck radiance at frequency ν and temperature T is denoted by $B(\nu, T)$. The independent variable x can be any single value function of pressure and $\tau(\nu, x)$ is the fractional transmittance of the atmosphere above the level x for radiation at frequency ν. The subscript 0 refers to the surface. The first term is the boundary term and represents the component of the outgoing radiation that arises from the surface and is attenuated by the atmosphere. The other term originates in the atmosphere itself and is weighted by the function $d\tau/dx$. Figure 26 shows the weighting function for eight channels of a sounding spectral interval.

The equation shown above requires special treatment in that the solution is non-unique. Several algorithms for solving the equation are described in the literature.

The estimation of moisture profile in the atmosphere is not as straightforward as the estimation of temperature profile. It is in fact more meaningful to estimate total precipitable water (i.e. the total atmospheric water vapour content in a vertical column of unit cross-sectional area extending between the earth's surface and the "top" of the atmosphere. Over ninety-five per cent of the vapour is between the surface and 300 mb however), than to estimate the vertical profile of water vapour. Detailed accounts of the systematic approach to retrieving water vapour interactively are now available at a few research centres in Europe and the United States of America. An illustration of the results of precipitable water retrieval over some locations in West Africa presented in this paper has been accomplished by the author using the facilities of the National Earth Satellite Service (NESS) laboratory at Madison, U.S.A. A summary of the problems and the assumptions that are involved in estimating moisture content from satellite-measured radiances have been given by Hayden (1981). The main elements of the philosophy behind the moisture retrieval at NESS is as follows. Three channels on the High Resolution Infrared Radiometer Sounders (HIRS) on both TIROS-N and NOAA-6 satellites are used. These channels are spectrally located at 8.3, 7.3 and 6.7 μm and covered the atmospheric regions between the ground surface to about 300 mb level. Temperature and moisture profiles are obtained mainly from atmospheric components of the radiance measurements rather than

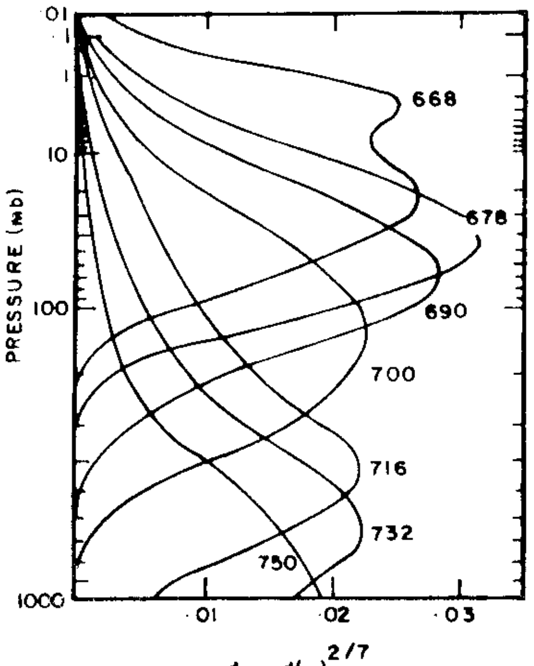


FIG. 26. Transmittance weighting functions in the 15 μm CO_2 band. Shown beside the peaks of the curves are the wave numbers (cm^{-1}).

the total radiance measurement, using multiple regression. The regression coefficients are obtained from an independent sample of current radiosonde measurements regressed against brightness temperature calculated from same radiosonde measurements. Surface contributions to radiance measurements are correctly identified and removed. In the case of retrieval over West Africa, the regression was done against climatological data as current radiosonde data was not available.

Figures 27, 28 and 29 show temperature profiles at three locations over West Africa on October 21st 1981. Figure 30 shows the temperature distribution on the 700 mb surface. Although vertical temperature profiles do not show inversions characteristic of the atmosphere over the region, the differences between the profiles and the distribution of temperatures

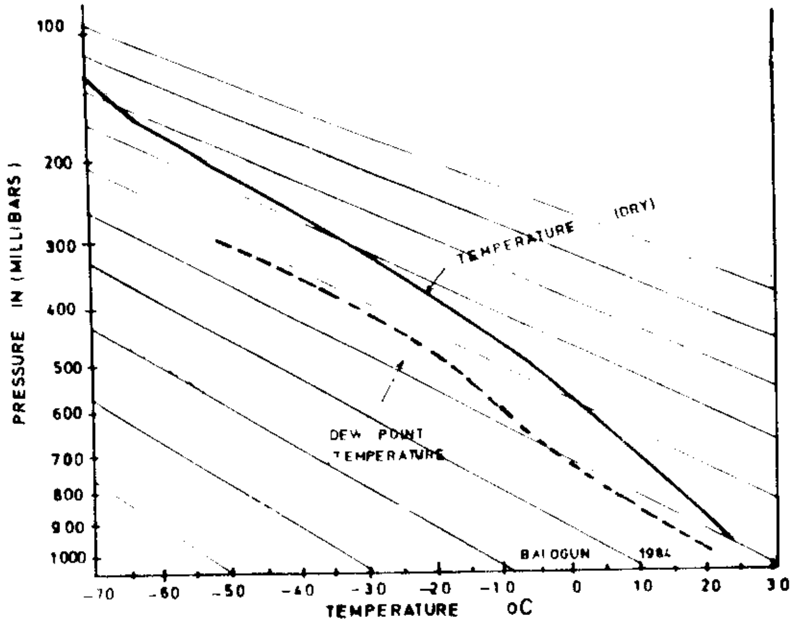


FIG. 27. Vertical distribution of temperature at lat. 12.45N, long 8.43E from NOAA-6 satellite measurements, 21 October 1981.

on the 700 mb surface confirm that satellite derived temperature fields can at least indicate useful temperature gradients over areas of interest.

Figures 31 and 32 show the distribution of precipitable water over parts of the Gulf of Guinea and some parts of the Sahel respectively. The values of precipitable water obtained compare very well with those obtained from radiosonde measurements. More studies of temperature and moisture profiling in the tropical African areas need to be carried out so that the reliability and the errors characteristic of such data sources can be established.

One also needs to mention at this point the possibility of estimating the skin temperature of earth's land and sea surfaces. The need to estimate surface energy budgets has prompted research in those areas. The retrieval goal for sea surface temperature (SST) of a root mean square accuracy of 1.0°C has largely been achieved and SST maps for many ocean areas have been produced. The potential use of such maps in the study of upwelling processes along the Guinea Coast of West Africa and the characteristics of ocean surfaces along the coast of East Africa is immense.

There are also on-going experiments to map soil surface temperature over the Sahel with the ultimate goal of developing the ability to monitor soil moisture over the region. The TAMSAT (Tropical Agricultural Meteorology using satellite and other data) programme of the University of Reading, England, has for some time now been looking into the potential use of satellite and other data to aid agriculture in the Sahel region. This programme, which is sponsored by the United Kingdom Overseas Development Administration, looks into the possibility of inferring soil moisture from surface temperature derived from thermal infrared channel of METEOSAT. The TAMSAT programme also operates in collaboration with the Agrihymet Centre, Niamey, Republic of Niger.

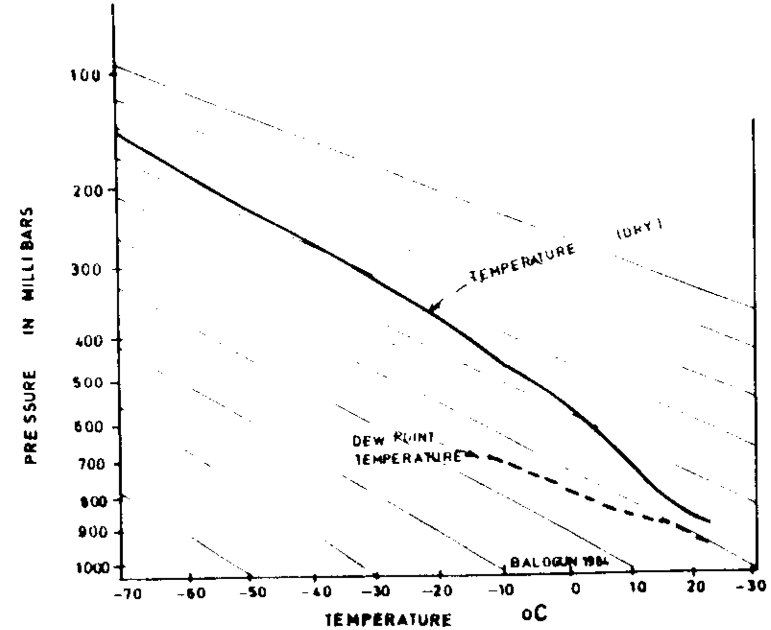


FIG. 28. Vertical distribution of temperature at lat. 12.45N, long. 8.43E from NOAA-6 satellite measurements, 21 October 1981.

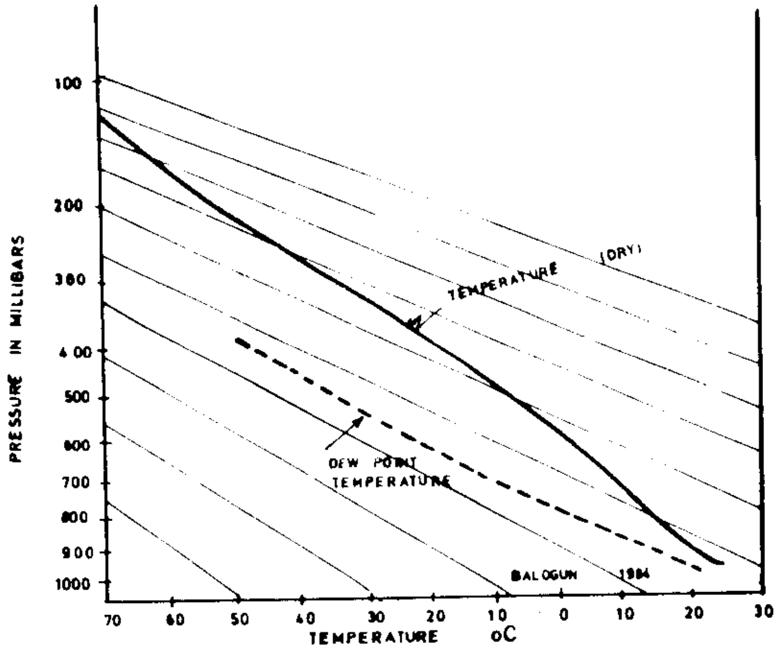


FIG. 29. Vertical distribution of temperature at lat. 15.9N, long. 15.53E from NOAA-6 satellite measurements.

The basic assumption in retrieving surface temperature from satellite observed radiances is that the emissivity of the earth's sea and land surfaces is near unity and that in the absence of cloud and atmospheric attenuation the brightness temperature observed with space-borne window radiometer is equal to the surface skin temperature. Cloud and water vapour absorption usually prohibit direct interpretation of the window channel data. Algorithms have been developed in various research centres and applied to satellite measured radiances to alleviate the influences of clouds and water vapour absorption.

CONCLUSION

An attempt has been made in this paper to discuss in a limited way the potential uses of satellite-observed data in the understanding of the weather and climate over Tropical Africa. Satellite observation in conjunction with conventional observation can provide useful information on rainfall climatology, water resources, crop survey and forecasting, locust control and drought assessment. With the combination of such data sources it should be possible to carry out precipitation impact assessment on agricultural production and to estimate soil moisture budget over a large area.

There are some pertinent questions that may be posed at this point. Is it really necessary for African nations to use satellite data for weather monitoring purposes when the few conventional facilities now available to them have not been fully utilized? The truth is that the satellite observations have made it possible to maximise the use of the sparse data since the data are by themselves of very limited use. Can African nations afford satellite data? No African nation is planning to launch a weather satellite or any satellite in the near feature that the author is aware of. African

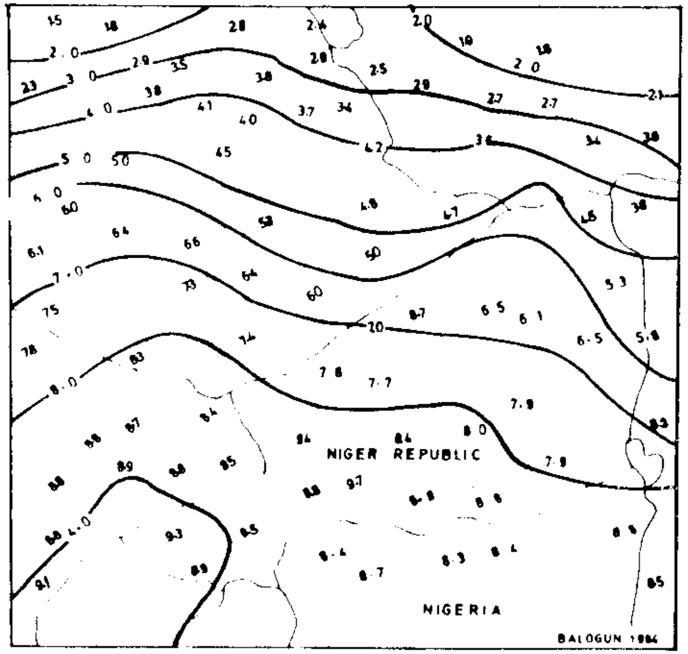


FIG. 30. Temperature distribution (in degrees centigrade) at 700mb over the Sahara from NOAA-6 satellite measurements, 21 October 1981.

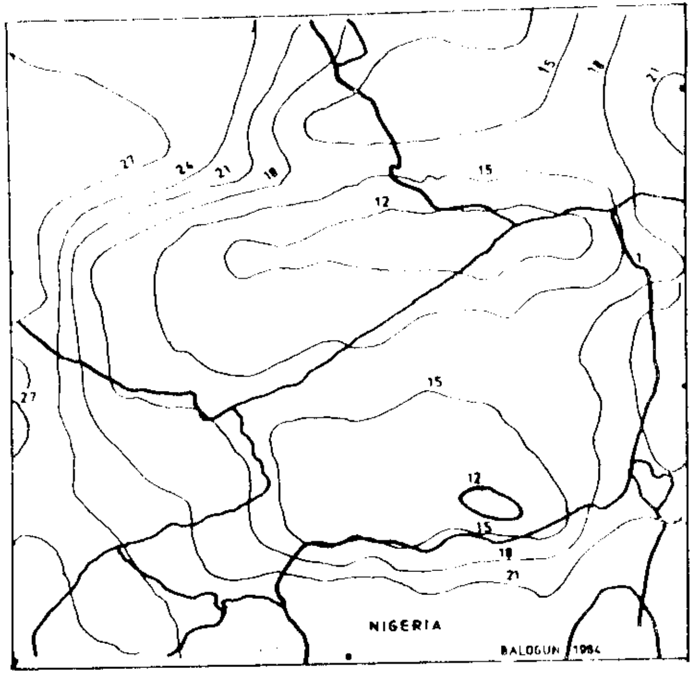
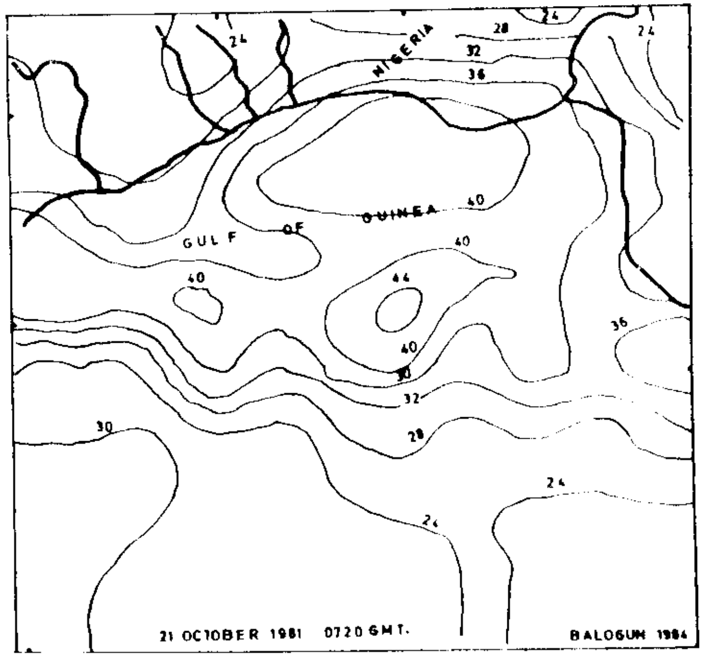


FIG. 31. Precipitable water (in mm) over the Sahara desert from NOAA-6 satellite measurements, 21 October 1981, 0720 GMT.



nations will rely, at least for some time to come, on observations made by satellites launched by other nations. African nations can use data from existing satellites either by an agreement with countries that own those satellites or by acquiring the wherewithal to receive and interpret data from those satellites. At this time it is at least possible to do the latter without too many formalities.

It is therefore important for the African countries to develop the know-how to receive and interpret satellite data. In the case of the weather, it is obvious from the points raised in this paper that weather systems over the tropics differ remarkably from those of the temperate regions. Techniques applicable in the temperate regions are sometimes different from those that may be useful in tropical areas.

Observation from space provides an important means of monitoring weather systems on a large scale. If Africa should know at least what other countries who now own these satellites know about her, then her scientists need to develop the skill for interpreting the data from these satellites. The need is even greater if they hope to develop satellite facilities of their own in the future.

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