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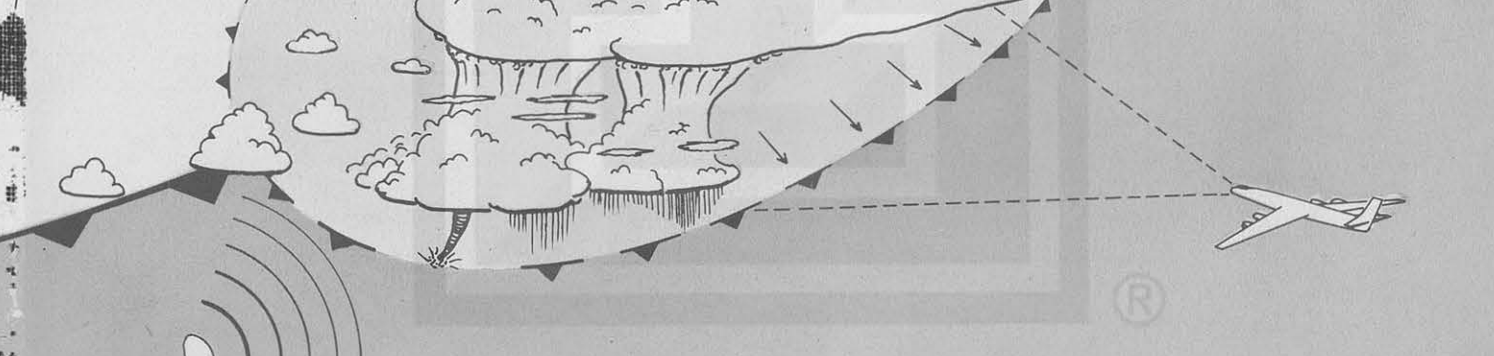
SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences
The University of Chicago

EASTERLY WAVE ACTIVITY OVER AFRICA AND IN THE ATLANTIC WITH A NOTE ON THE INTERTROPICAL CONVERGENCE ZONE DURING EARLY JULY 1961

by

James E. Arnold



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The research reported in this paper has been sponsored by the Environmental Science Services Administration under grant Cwb WBG-34.

EASTERLY WAVE ACTIVITY OVER AFRICA AND IN THE ATLANTIC WITH A NOTE ON THE INTERTROPICAL CONVERGENCE ZONE DURING EARLY JULY 1961[1]

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ABSTRACT

During the early part of July 1961, a series of easterly waves moved across central and western Africa into the Atlantic Ocean. Most of the waves retained their identity during their Atlantic crossing, moving along the ITCZ. The waves tended to decrease in intensity, as determined from cloud activity observed by TIROS III, as they moved from the eastern Atlantic to the central Atlantic region and then increased in activity again as they approached the Caribbean Sea. Most of the cloud activity associated with the waves was confined to the southern portion of the wave in the weak stage, but became bimodal, i.e., two distinct cloud masses, as the wave intensity increased. During the observation period, the Intertropical Convergence Zone was usually located near the base or southern portion of the cloud activity zone associated with the wave. Cloud systems of successive waves in the wave train were often connected by cloud bands associated with the ITCZ. The structure of the cloud bands between the wave is assumed to be indicative of the structure of the ITCZ in that region and exhibited strong tendencies for multiple banding.

1. Introduction

Although series of waves have been observed propagating across much of the Pacific, similar observations of wave trains in the Atlantic have been restricted until recently by the lack of regular data.

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Since it is recognized that hurricanes develop from pre-existing systems (Riehl, 1954), the knowledge of formation areas and the regularity with which the disturbances develop is important. Since standard observations are almost completely lacking in the tropical Atlantic, studies of waves in the tropical western hemisphere have been confined to the Caribbean and Gulf of Mexico. The formation area of the waves is often assumed to be in the same area where they have first been observed by surface data collection points. On the other hand, numerous hurricanes have been observed in the eastern Atlantic and several have been noted to traverse much of the Atlantic before entering the Caribbean region.

Early work by Riehl (1954) on studies of tropical disturbances revealed that some of the intense waves must have developed as far eastward as Africa. Chancellor (1946), in a study of weather patterns over Africa indicated that the disturbance lines observed there were actually associated with waves that developed in the eastern side of the Sahara anticyclone and traveled westward in the general circulation. That these waves continued to propagate into the Atlantic creating some of the east Atlantic hurricanes seemed inevitable. Eldridge (1957) has also documented the regular nature of major disturbance lines crossing West Africa and noted a period very similar to the wave interval observed by Chancelor. In both cases the waves were most prominent in the monsoon dominated southern coast of western Africa and in both cases the waves or disturbance lines passed into the Atlantic. Erickson (1963) has documented an example of an African disturbance which was responsible for an incipient hurricane and Fritz (1962), and Fujita and Arnold (1963) have indicated that the origin of Hurricane Anna was at least as far eastward as Africa.

Since it is now possible to examine the Atlantic area with the use of satellite data, thus filling the otherwise data void area, a comparison can be made between the African disturbances and the Atlantic and Caribbean perturbations. It is the purpose of this study to provide an initial examination of the Atlantic extension of the African disturbances, their frequency and their behavior as they cross the Atlantic.

Primary data used consisted of photographs and infrared information from TIROS III. Radiation data was reduced from the original analog trace furnished by NASA and is presented for representative examples in intervals of 10 degrees of equivalent black-body temperature. A correction is made for instrument degradation but not for atmospheric absorption and viewing angle. For the purposes of this study, it was found that a 10 degree temperature interval was sufficient to describe the cloud pattern although the initial analysis was done for every two degrees. Standard synoptic data were taken from the Northern Hemisphere Data Tabulations and charts furnished by the United States Weather Bureau.

2. Wave Activity over Africa and in the Atlantic

TIROS III observations during mid-July 1961 indicated the presence of a wave train or series of waves that stretched from the African coast into the Caribbean Sea along what appeared to be the Intertropical Convergence Zone. Satellite observation of the wave train over Africa was difficult as the convective activity associated with the summer monsoon complicated the cloud field; however, examination of the time cross-sections for radiosonde stations across Africa revealed a regular oscillation in the wind field, indicating the passage of a wave-like feature over the continent. The easternmost station where the oscillation in the wind field became apparent was Fort Lamy (12.2N, 15.0E) shown in Fig. 1. In this particular case the lower 2 km was dominated by the monsoon while the winds between 2 and approximately 12 km underwent a periodic variation with a period of 2 1/2 to 3 days. Westward movement of the waves across Africa from Ft. Lamy averaged 10 degrees per day with the southern end of the wave trailing the northern end. This north-northwest to south-southeast orientation seems to have also been present in the disturbance lines discussed by Eldridge and is apparently a common orientation of moving systems in this area. Reflection of the traveling waves in the surface observations was usually insignificant with the diurnal thunderstorms associated with the summer monsoons masking much of the activity associated with the waves. Dakar, the westernmost upper-air station, provided the last opportunity to examine the waves as they moved westward into the Atlantic. As can be seen from Fig. 2, most of the waves exhibited a pronounced cold core with prominent perturbations in the wind field as they passed over Dakar.

With the use of TIROS III data from July 12, the date of launch, onward, an association could be made with the cloud features in the Atlantic and the waves in the wave train over Africa. The wave W-3, which has previously been studied by Fujita and Arnold (1963) as the incipient disturbance of Hurricane Anna, had just passed into the Atlantic on July 12 and provided a reliable anchor point in connecting the continental waves observed in the winds aloft data with the cloud patterns associated with oceanic waves.

Fig. 3 illustrates the continuity of wave movement during the observation period. The wave interval off the coast of Africa seemed to have been greatly influenced by a subtropical trough, shown in Figs. 4a and b, which extends south into the tropics. The wave which seemed to be most effected by the trough was W-3, also the most intense wave in the train at this time, reaching an almost complete stop in westward motion while simultaneously intensifying. From the slope of the movement verses time lines for individual waves in Fig. 3, it is apparent that a similar effect must have been present for all the waves prior to W-4. This would be in good agreement with earlier findings by Cressman (1948) concerning the interaction between the tropics and the subtropical weather patterns. Another effect of the interaction between the tropical and subtropical flow seems to have been the great reduction in wave spacing between W-1 and W-2, and W-4 and W-5. That both W-1 and W-4 dissipated could be indicative of a preferred wave spacing, or at least a minimum wave spacing which would permit adjacent waves to remain active. The actual interval between the waves seemed to vary between 25 degrees over Africa to as close as 10 degrees over the ocean. The preferred spacing over the ocean seemed to be about 20 degrees, but as the waves reached the Caribbean area the interval was frequently distorted by the northwestward movement of some of the waves while others in the train continued a westerly course.

The Channel 2 radiation map of the tropical North Atlantic for July 12, 1961 (Fig. 5) illustrates the wave train superimposed on the Intertropical Convergence Zone. At this time the eastward moving subtropical trough shown in Figs. 4a and b has just passed over the wave W-2 causing a subsequent reduction in westward travel speed while W-3 continued moving, thus decreasing the wave interval. The principal ITCZ seems to be continuous across the Atlantic at this time and it is evident that the waves are superimposed upon it. As best as could be determined, the waves traveled along the convergence zone or at least were connected by regions of cloud activity between successive waves. In the western Atlantic, the cloud band splits near 40W with one branch going northwest and gradually disappearing, while the other branch intersects the South American coast.

In the vicinity of the branch in cloud activity, wave movement was consistently along the northern line although the southern extension seemed to be present much of the time. Although the branch in cloud activity occurs in an area where there is almost a total absence of surface data, the southern extension of the cloud band corresponds well with the climatological position of the surface pressure trough. Examination of available data for the northern coast of South America during the month of July, 1961 revealed that at the time in question the actual surface trough must have coincided closely with its climatological position. This being true, movement of the waves seems to have been controlled by the upper level circulation which closely paralleled the northern cloud branch extending toward the Caribbean (Fig. 5). An examination of ship reports in the area during the month of July and data from the Meteor Expedition indicates a tongue of warm water should underlie the southward extending cloud band. If this is the case, cloud development should be enhanced and could also contribute to the observed cloud pattern.

The paths that individual waves took across the Atlantic and the location of the ITCZ varied from day to day as the flow pattern around the Atlantic High varied, but they seemed to consistently reach furthest south in the mid-Atlantic. Although the subtropical High probably controlled the position of the convergence zone, the convergence zone itself always was closely coincident with the Tropical Atlantic warm water axis (which reaches a minimum in temperature excess from the surrounding ocean in the central Atlantic) that extends from Africa to South America. There was a definite tendency for the cloud activity associated with the traveling waves to reach minimum intensity in the central Atlantic where the warm water temperature anomaly was the least, as inferred from the Meteor data. If it does exist, the water temperature effect of cloud activity evidently can be overridden by atmospheric conditions. This is evident from the fact that later in the 1961 storm season several waves apparently developed into hurricanes when under the influence of the subtropical trough even though the waves themselves were in the same geographic location as the waves in this study, W-1 through W-5, reached minimum intensity. Atmospheric control over basic cloud development has been reported by Malkus and Riehl (1964) and current work by the author indicates that large warm and cold pools of water in the Gulf of Mexico greatly influence cloud activity under proper atmospheric conditions.[2]

A radiation map of the western Atlantic wave activity on July 18 when three waves were undergoing intensification is shown in Fig. 6. The westernmost wave, W-2, will be examined in more detail later; however, it is significant to point out that this wave moved in a northwestward direction very closely approximating the axis of warm water observed at the time in contrast to the developing wave, W-3, which maintained a course that was more westerly. The absence of a connecting ITCZ between W-2 and W-3 is apparent in the photograph of the system in Fig. 8 as well as in the radiation map. Although the area between W-3 and W-5 lies in the gap in radiation data between orbits, a photograph that covers part of the area westward from W-5 shows a connecting cloud band between the two waves.

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[2] Research being conducted for the Office of Naval Research, Contract Nonr 2119 (04). Texas A & M Research Proj. 286-H.

The cloud covered area in the vicinity of W-5 is exceptionally large for a wave system in the central Atlantic during this period and seems to be the result of a subtropical trough extending into the tropics over the wave. The vertical structure of the mid-Atlantic trough shown in Figs. 7a and b over W-5 is hard to determine due to a scarcity of data; however, the resemblance between the overall picture at this time and that associated with the initial intensification of W-3 on July 12 (Figs. 4a and b) illustrate the apparent interaction between the subtropical system and the easterly wave. That additional factors must contribute to further intensification of the wave is apparent from the fact W-5 and W-3 did not continue to intensify. Observations of following days indicate that no significant system developed from this additional area of activity and that W-5 remained the principal area of activity in this section of the wave train.

3. Cloud Organization in the Developing Wave

As has been pointed out, the waves in the train tended to increase in intensity once they reached the western Atlantic. Although a continuous daily observation of all the waves was impossible, they all appeared to have a similar history of cloud intensification and weakening. One of the waves, W-2, covered by radiation data on four days of its life gives a good representation of both the decay and development of an individual wave. The wave, W-2, is shown in what is probably its most intense stage in Figs. 8 and 9. At this time, the wave was over the Windward Islands and exhibited a cloud pattern in the general bar shape described by Fett (1964) as being representative of the tropical disturbance stage. The cloud pattern here, however, is one in which there is a distinct bimodal feature within the general bar shape. The bimodal pattern is one which has a predominantly large cloud in the southern part of the wave along the ITCZ, that will be called the base cloud, and a secondary cloud northeast of the base cloud, that will be called the crest cloud. Examination of the photograph of the system in Fig. 8 reveals what appears to be a circulation center in the base cloud and which is also supported by the surface stations in the area shown in Fig. 9. Further comparison between the surface reports three hours later than the time of the photograph indicates that the principal cloud activity is near the wave axis with the crest cloud being in the area of strongest cross-gradient flow in the northern part of the wave. Extensive amounts of cirrus seem to be associated with the core clouds in the base and crest clouds and a cirrus veil has drifted over most of the cloud activity.

The past history of the wave, W-2, is depicted by the radiation maps of the disturbance shown in Fig. 10a through 10d. The wave was first observed on July 12 (Fig

10a) as it was decreasing in intensity while moving westward from Africa. At this time, the base cloud is the main feature in the cloud pattern and is orientated along the ITCZ, although there is still a pronounced northward bulge. By July 14 (Fig. 10b), the wave showed some decay and, while high convective elements were present, the orientation of the wave was entirely along the convergence zone. Cloud tops were still very cold, -52C, with most of the lower clouds masked by cirrus of varying density. Although it is doubtful that any organization in the circulation existed at this time, low cloud features extending beyond the cirrus (photograph not shown) indicate that the axis of the system lies in the vicinity of the coldest cloud tops.

Radiation coverage of the system W-2 was not available on July 15 or 16; however, continuity places the wave in the vicinity of a weak ring cloud observed in the pictures taken by the satellite on July 15 (Fig. 14). If the feature observed on July 15 were W-2, it was probably at its weakest stage and re-intensification would have begun from that point. There are indications that the upper-level trough that effected W-5 on July 18 had begun to develop on July 14 or 15 in the mid-Atlantic. If this were the case, the mid-Atlantic intensification of the waves following W-1 could have been partially a result of the interaction of the two systems. By July 16, the cloud pattern of the wave W-2 would probably be somewhere between that present in the radiation data on July 14 and July 12.

On July 17 (Fig. 10c) the cloud pattern present in the radiation data indicated that the system had undergone intensification. The system had developed a significant latitudinal expansion from its July 14 radiation pattern and a small cold cloud top has become apparent northeast of the base cloud. The gradient of the cloud top temperature contours is indicative of thin cirrus spreading beyond the core clouds, although at large distances from the central cloud it is difficult to distinguish between the edge of the thin high clouds and the lower clouds.

By July 18 (Fig. 10d), the base and crest cloud features had become prominent in both the radiation data and the photograph. The thin cirrus veil that is faintly present in the photograph is distinguishable in the radiation data and there are indications that the cirrus streamers are being carried some distance from the original system.

Most of the systems in this series seem to have followed a similar pattern of cloud development. All the waves included the bimodal stage when the development continued past the simple intensification of the convergence zone cloud activity. Another example of bimodal development is W-5. Although the history of W-5 will not be discussed here, the cloud organization early in its life can be seen in the radiation pattern in

Fig. 6. At this time, the clouds seem to be associated with the convergence-zone simple intensification stage. The same wave in its most intense stage is shown in Fig. 11, where it can be seen that a definite bimodal system has developed. Contrary to W-2, however, the circulation center can be located well in front of the cloud mass. As before, the circulation is supported by the surface data plotted in Fig. 12, which shows a time cross-section for Kingston, Jamaica. A comparison between W-2 and W-5 in their respective photographs reveals that the cirrus coverage is more extensive over the latter. Although W-5 is probably older than W-2, the former matured under more favorable conditions. It will be recalled that the intensification of W-5 began in the presence of a trough that was well developed at low levels, thus enhancing convective activity. Later, between July 22 and July 23, the system must have come under the influence of an upper divergence field between the high level anticyclone over Hurricane Anna and the trailing vortex developing at the time the photograph in Fig. 11 was taken. One of the more interesting characteristics of W-5 is that it did not develop more fully, considering its more favorable environment.

An additional feature that both systems have in common is their decay soon after the last stage shown. The answer to this sudden dissipation seems to lie in the upper air flow. In the case of W-2, the wave developed under a large tropical anticyclone, but, because of the development of Hurricane Anna immediately behind the wave and the presence of a high level trough over the storm area, it was forced into a region of strong high level convergence which destroyed the ventilation necessary for storm development. The wave W-5 seemed to undergo its major intensification in connection with a high level stream line divergence field set up between the anticyclone associated with Hurricane Anna and her trailing vortex. The trailing vortex, in this case, seems to have gradually moved over the wave and, as in the previous case, the upper level ventilation was cut off causing the system to dissipate. It will be recalled that Frank (1963) examined a case where the opposite situation occurred and the trailing vortex established a second hurricane.

The only exception to the development of a bimodal pattern was W-3, which already had the bimodal pattern when detected off the coast of Africa. It maintained this pattern during its entire Atlantic crossing, indicating that it was well developed even over Africa, in contrast to the other waves. Its life history has been examined by Fujita and Arnold (1963) in a study of its early stage using the TIROS radiation data and by Arnold (1966) covering the period from its mid-Atlantic position through dissipation. Its behavior is analogous to other waves in the train with the exception that it continued to develop into a hurricane.

The wave W-0 was in the bimodal stage in the Caribbean on July 12, and although the wave was not covered by the satellite data it was apparent from the standard synoptic data as the wave moved through the Caribbean and the southern Gulf of Mexico. The fact that the wave did not continue to develop is an additional reminder that continued intensification of individual waves is a very selective process.

It should be emphasized that the cloud patterns observed here in connection with wave development are very likely a characteristic of waves that go through their initial stages of intensification in the equatorial trough and those perturbations which develop in the unstable easterly flow in the Caribbean and Gulf of Mexico may exhibit different characteristics. A more schematic illustration of the development of an individual wave as indicated from observations in this study is shown in Fig. 13.

Phase 1 of the development is characterized by increased cloud activity along the convergence line. The area of enhanced cloud activity can be composed of several areas of banded clouds extending to great heights or one in which numerous cumulus buildups are capped by a cirrus mantle. The region of vigorous activity usually fades into the convergence zone band which itself is composed of clouds in bands but with little vertical development.

Phase 2 cloud features have a slight northward bulge indicating that the wave is beginning to intensify. The cloud field can be dominated by cirrus masking the individual cloud towers. Cloud cover tends to be predominately in the base cloud, which may lie behind or over the wave axis.

Phase 3 is the final stage of the waves in this series that did not continue to develop into a tropical depression. The cloud pattern is bimodal, i.e., there is a base cloud which may cover several degrees of latitude and a crest cloud which at this stage is usually smaller. While the base cloud may lie on both sides of the wave axis, the crest cloud is found on the east side of the trough line and usually about four degrees from the center of the base cloud. If convergence is very strong over a large area behind the wave axis, the bimodal cloud pattern observed at this stage may give way to the bar-type cloud. The location of the circulation center with reference to the cloud mass can be either in the base cloud itself, as in W-2, or well ahead of the base cloud as in W-5. The time interval between phase 1 and phase 3 is governed to some extent by the specific conditions in the vicinity of the wave; however, four days seemed to be a representative time period.

It is difficult to determine if the bimodal structure of waves observed in this series was simply an additional form of the more commonly observed bar-cloud system associated with incipient or developing north-south waves or a special wave system in itself. Palmer's

(1952) work concerning convergence systems created by traveling waves in the basic easterly current which was summarized and expanded by Riehl (1954), treats waves in two basic current forms, those associated with a convergent base current and those associated with a non-convergent base current. Since the Atlantic pressure trough and assumed convergence zone usually intersect the South American coast, those waves usually examined in the Caribbean fit more or less into the category of waves in a non-convergent current for which the usually observed bar-shaped cloud would seem to be a representative cloud distribution. On the other hand, the waves observed here were usually found to exist in a convergent field, which would certainly modify the convergent field set up in the vicinity of the propagating wave. Palmer illustrates such a case for a system traveling on the earth's equator in which a convergence system analogous to that implied by the cloud pattern observed in waves W-0, W-2, and W-3. The fact that the waves observed here are north of the equator would modify the convergent pattern described by Palmer but basic similarities should remain. There were indications that as the waves moved away from the trough and the convergence zone area the cloud distribution began to more closely resemble the bar-shaped cloud discussed by Fett (1964) and illustrated by Fig. 11. It would be difficult, from the satellite photographs alone, to separate the effect of the change in the lower level convergent field caused by the wave moving away from the ITCZ with the expected spreading of the cirrus tops of the cumuliform activity as the system aged.

It is also important to stress the fact that no new systems developed in this wave train during its Atlantic crossing; however, the possibility of such developments can not be excluded, especially in the Gulf of Mexico and the Caribbean as Merritt (1964) has pointed out. The principal question raised is of the maximum number of waves possible on a convergent current.

4. The Intertropical Convergence Zone

Cloud bands associated with the Intertropical Convergence Zone in the mid-Atlantic on several of the days in early July were markedly persistent and well pronounced. Major cloud bands were frequently noted between existing disturbances and at times covered up to 15 degrees of longitude. Since ship data were sparse near the banding, the relationship between the cloud patterns and the actual convergence field is speculative.

The continuity of the convergence zone across the Atlantic has been previously indicated in the radiation data from the TIROS radiometer for July 12, shown in Fig. 5, and is representative of the period. However, since much of the cloud system that appeared to be associated with the convergent field was of a low cloud nature, as inferred from the radiation data, the medium resolution radiometer on the TIROS vehicle was not adequate for a detailed examination of the cloud structure.

In the photographs taken by TIROS, the clouds associated with the convergence field are much more prominent. Mosaics of the tropical convergence zone reveal the varying degrees of intensity and complexity of cloud features. Unfortunately some area in the convergent field between two individual waves could not be followed on consecutive days; however, a reasonable idea of the band structure can be obtained from the available data. Since the cloud banding in the convergence zone between waves exhibited a tendency to vary with the intensity of the systems bounding the region, it is convenient to illustrate the cloud bands associated with the convergence zone by representative samples of three degrees of intensity.

The cloud bands associated with the convergence field in the mid-Atlantic when the bounding waves are relatively weak are shown in Fig. 14. On this day, July 15, two principal bands are present and, although they are reasonably well defined, the individual elements in the bands are loosely organized. The wave, W-3, previously mentioned is just off the east boundary of the picture while W-2, illustrated in a previous section, is present as a weak cloud system in a ring-shape in the lower central portion of the picture. At this time, W-2 is coincident with the southern major convergence band with little or no connection with the more continuous band to the north. W-1, which appeared to die in the wave train (Fig. 3), would have been just on the western boundary of the picture. The cloud population in regions between the convergence bands and north of the northern band is relatively large, but consists of groups of cumulus clouds with little appreciable vertical development. In this example, some alignment of the individual elements within the major convective bands can be detected; however, the contributing effects of winds at different levels are ambiguous. Areas outside the major bands exhibit what Malkus and Riehl (1964) have termed parallel-mode cloud streets in the low-level flow.

Concurrent with an increase in the wave intensity of the train was an increase in organization of the cloud bands associated with the convergence field. This second stage is illustrated in Fig. 15 where the wave W-0 can be seen in the picture in addition to the convergence bands. The northernmost cloudband can be seen entering the wave while one and possibly two additional bands are present to the south. The delineation between the northern band and the inversion-dominated area of cumulus activity to the north can clearly be seen at this stage as a clear moat between the two systems. Within the better developed parts of the wave and the cloud bands, contrary to the first case, the larger elements are aligned approximately to the upper wind flow, as best as can be determined. The wind shear in the upper convective layer seems to be large enough to produce numerous short cloud bands at an angle to the main cloud line. In areas where the cumulus activity is not so vigorous, the simple parallel-mode cloud streets are present. Cloud organization of an almost identical nature was present on July 14 between waves W-2 and W-3 and on July 16 bounding W-3 when all the waves were at approximately the same intensity as that of W-0 shown here.

The third stage of band organization is shown in Fig. 16. The bands shown here lie between the rapidly evolving Hurricane Anna to the west and an easterly wave just visible on the eastern boundary of the mosaic. Although the cloud bands associated with the convergence field give no indication of buildups of any significant amount in the radiation data, shearing of the cloud tops or cross banding is prominent in the northern cloud band. Such a feature indicates that a significant amount of vertical shear is present in the convection layer. This would indicate either that the top of the shear-free, relatively speaking, easterly flow regime has lowered on a macroscale or that mesoscale circulation features have greatly modified the flow characteristics in the vicinity of the convection band. Parallel mode banding can be seen in numerous portions of the mosaic and seems to be the dominant cloud alignment feature. Here, as in the previous stages, the cloud bands enter the wave system, or more specifically, the wave is superimposed upon the convergence bands. The northern band enters the crest cloud of the bimodal wave system while the long band to the south, although not so apparent from the photograph, enters the base cloud. Again on July 18, a similar banding pattern with respect to W-3 was present. In this final and intensely organized phase of band development, the individual bands have become distinct and the clear moat between the tropical convergence zone and the cloud region to the north is very well developed.

Thus, it is apparent that the mid-Atlantic convergence zone was well organized and the resulting cloud pattern was one of long cloud bands between waves in the wave train. For the most part, the bands seemed to be composed of low clouds and of aggregates of cloud groups in the less organized phases. Band intensity and organization seemed to vary with wave intensity in the wave train which implies that the two are probably related to yet a third parameter, hemispheric flow. As the waves became more intense, the cloud bands tended to converge into the wave systems. There were some indications that a major cloud band existed near the equator, most prominent just south of the equator near the coast of Africa and extending northwest into the region north of the equator in the central Atlantic.

In many respects, the cloud bands and the inferred convergence field observed here are similar to those described by Fletcher (1945), which consisted of several solenoidal fields set up as the air moved to and away from the thermal equator. There is also the strong possibility that some of the bands are initiated by streamline convergence between the Easterlies near the equator and the subtropical flow around the North Atlantic anticyclone.

5. Conclusions and Recommendations

During the period under study, there was a definite connection between disturbances over Africa and inferred wave activity in the Atlantic. It was found that most of the waves traversed the Atlantic and no new waves developed in the train. A minimum in wave intensity was noted in the central Atlantic. The waves examined seemed to undergo a definite life cycle with the first indication being an increase in the amount of cloud associated with the ITCZ. Continued development of the wave led to a bimodal cloud distribution which was broken down into the crest cloud situated east of the wave axis (upwind) near the crest of the inverted pressure trough and a base cloud along the axis of minimum pressure. In waves studied, development and decay followed similar cloud pattern changes, although the waves examined here that decayed did so from relatively weak stages with maximum winds probably less than 20 knots.

The waves themselves were embedded in cloud bands associated with the ITCZ, which was well organized in the mid-Atlantic for the entire period. Cloud bands which are assumed to be manifestations of the ITCZ were usually of a multiple nature and varied in intensity with the waves in the wave train. There was a definite lack of cloud bands connecting individual waves in the extreme western Atlantic and Caribbean Sea, which could be the result of the South American landmass influence on the pressure and flow field, or of the wave intensity which was generally strong in that area.

A continued investigation of wave development in relation to the ITCZ and hemispheric circulation is of extreme importance, especially with respect to hurricane development. Relatively little is known about the air-sea interaction process and its effect on cloud development. It would be of interest to investigate the behavior of cloud systems as they crossed different oceanic surface regimes for associated intensification or decay of developed systems. The knowledge of wave number in the Atlantic, Caribbean, and Gulf of Mexico during the hurricane season would provide an insight into the formation question. Finally, it would be advantageous to develop numerically, basic convergence patterns created by a wave traveling through and away from an equatorial trough zone situated away from the earth's equator. Such models could then be compared with satellite-observed cloud patterns associated with suspected waves in the easterlies.

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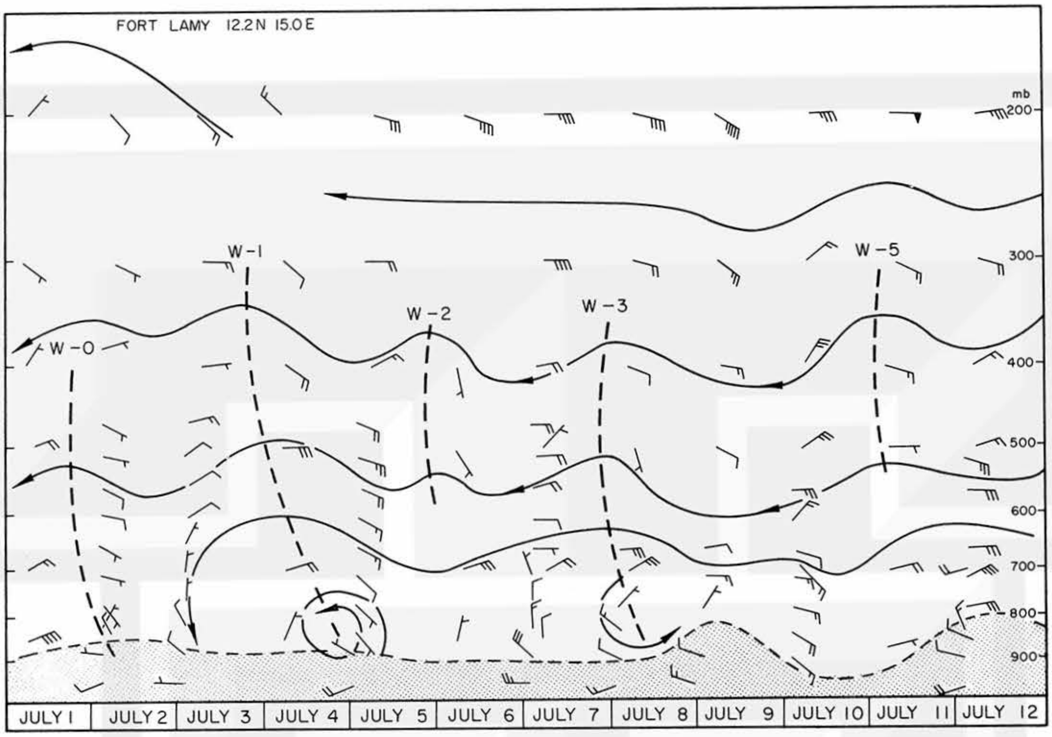


Fig. 1. Time cross-section of winds aloft for Fort Lama, July 1-12, 1961. Westward moving waves are indicated by heavy dashed lines.

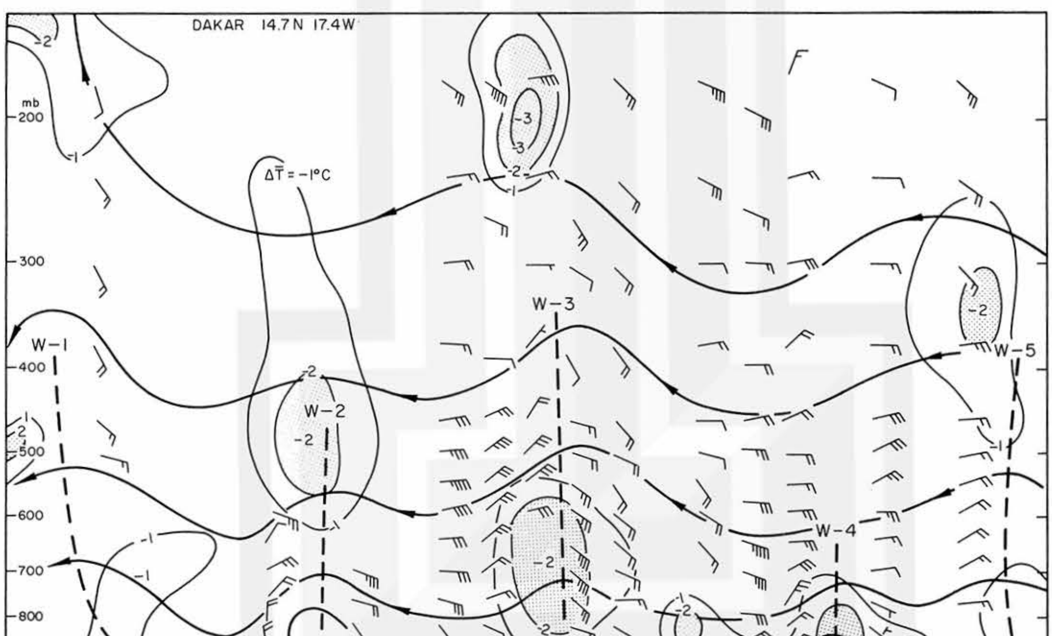


Fig. 2. Time cross-section of winds aloft and cold temperature anomalies for Dakar, July 5-16, 1961. Westward moving waves are indicated by heavy dashed lines.

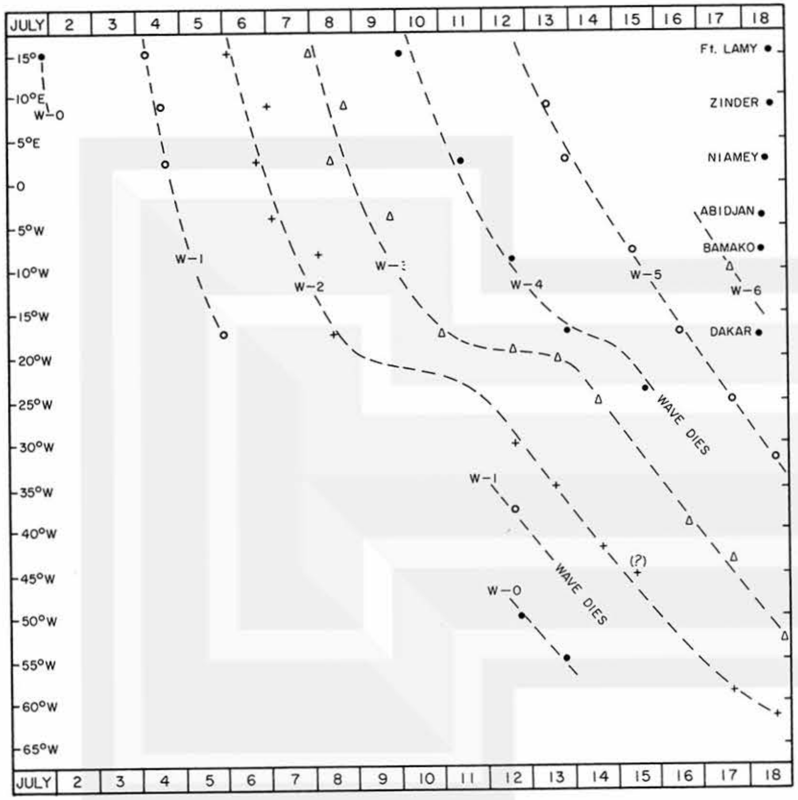


Fig. 3. Diagram of wave movement vs. time during July 1-18, 1961. Wave locations over Africa were determined by winds aloft data from upper-air stations shown on right, and then joined with cloud system movement over the ocean from satellite data. Waves W-2, W-3, and to a lessor extent, W-4 came under the influence of a subtropical trough which retarded their westward motion near the coast of Africa.

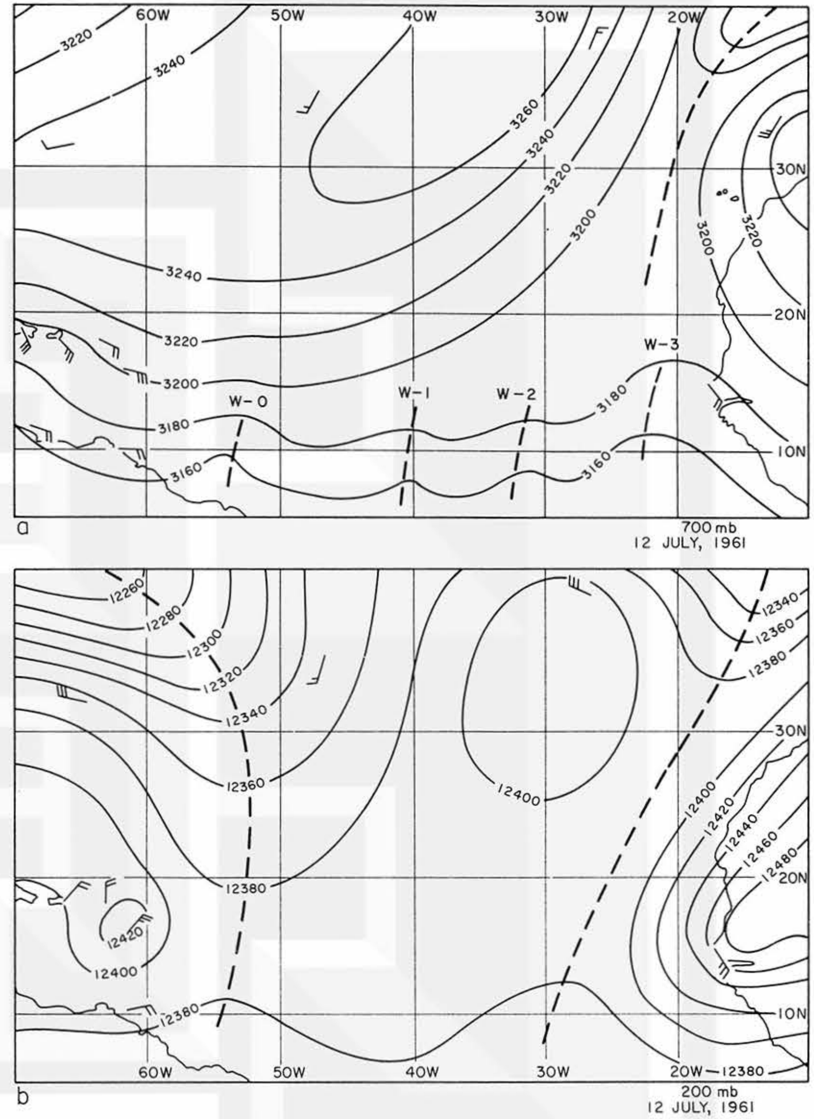


Fig. 4. a) 700 mb chart of the Atlantic region for 1200Z July 12, 1961 (contour interval 20 m). b) 200 mb chart of the Atlantic region for 1200Z July 12, 1961 (contour interval - 20 m).

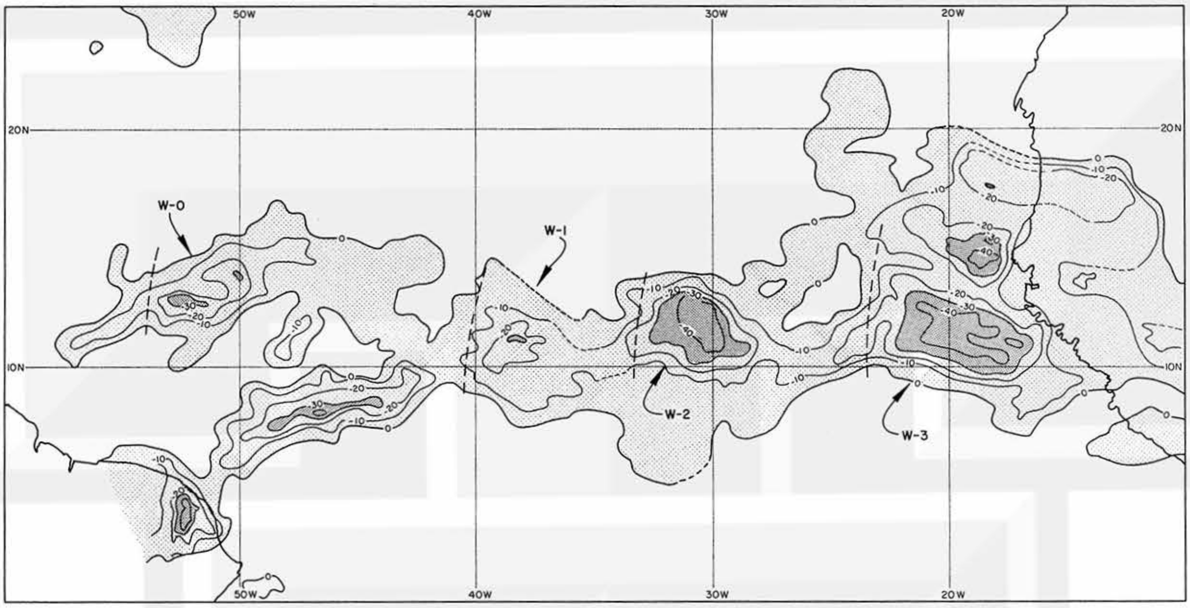


Fig. 5. Composite radiation map of the cloud activity in the tropical North Atlantic between 1424 and 1746 GMT on July 12, 1961. Four easterly waves and the cloud band associated with the ITCZ are included. Temperature contours are for 10C intervals.

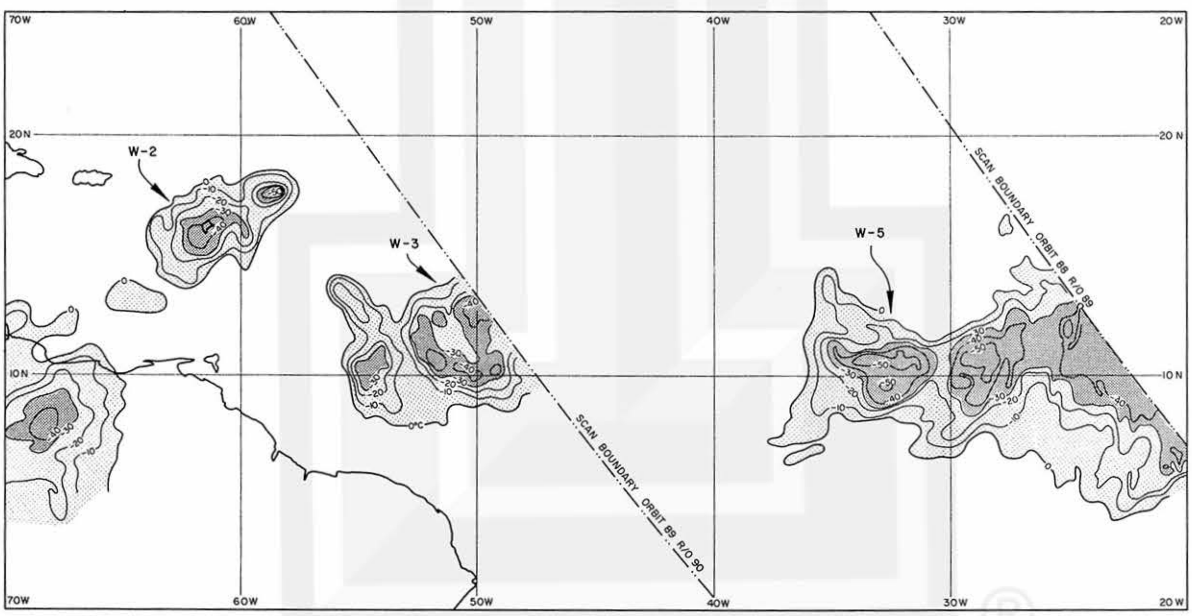


Fig. 6. Composite radiation map of the cloud activity in the western Atlantic and the eastern Caribbean between 1414 and 1552 GMT on July 18, 1961.

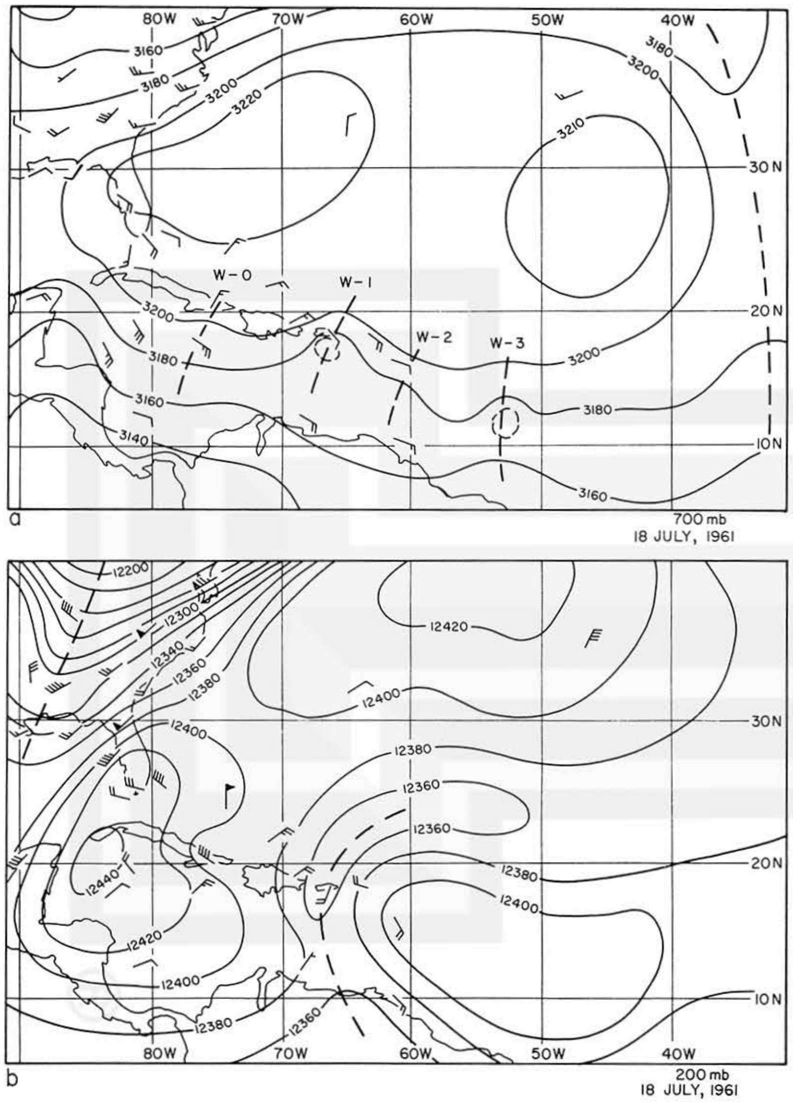


Fig. 7. a) 700 mb chart for 1200Z July 18, 1961 over the western Atlantic and Caribbean (contour intervals 20 m). b) 200 mb chart for 1200Z July 18, 1961 over the western Atlantic and Caribbean (contour intervals 20 m).

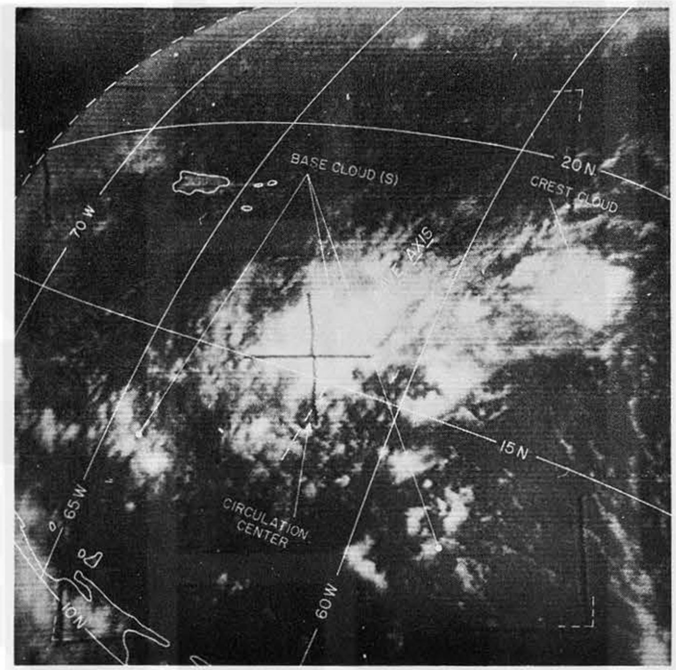


Fig. 8. TIROS III photograph R/O 90 Frame 21, 1557 GMT wave W-2 at its most intense stage on July 18, 1961. The circulation center seems to be imbedded in the base cloud.

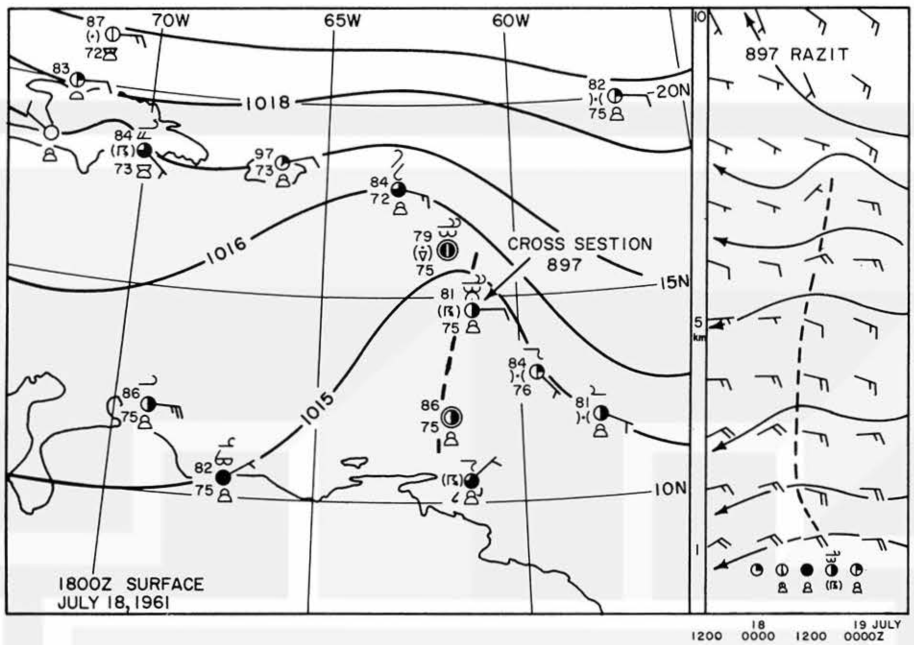


Fig. 9. Surface map for 1800 GMT July 18, 1961 showing the easterly wave W-2. Time cross-section at right is from Razit and includes the time of wave passage.

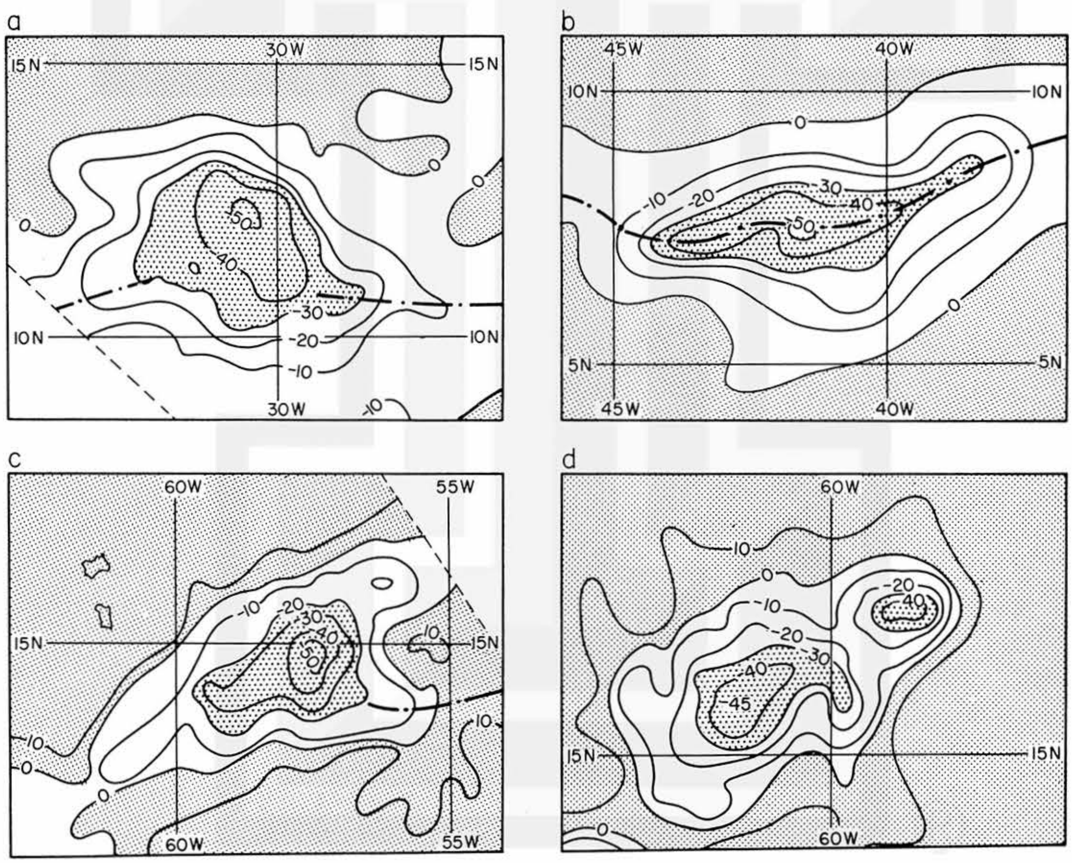


Fig. 10. Change of cloud top features of W-2 as determined from radiative temperature contours as the wave crossed the Atlantic. Weakening phase; a) July 12, 1961, b) July 14, 1961. Intensifying phase; c) July 17, 1961, d) July 18, 1961.

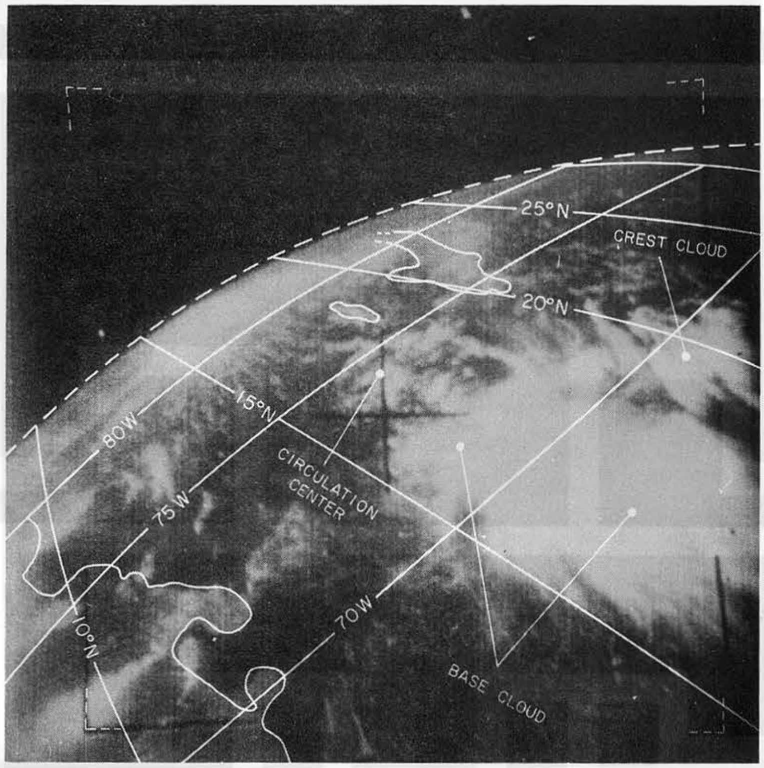


Fig. 11. TIROS III photographs R/O 161 frame 11, 1437 GMT of wave W-5 at its most intense stage on July 23, 1961. Note that the circulation is well in front of the bimodal cloud pattern. Hurricane Anna is on the western horizon.

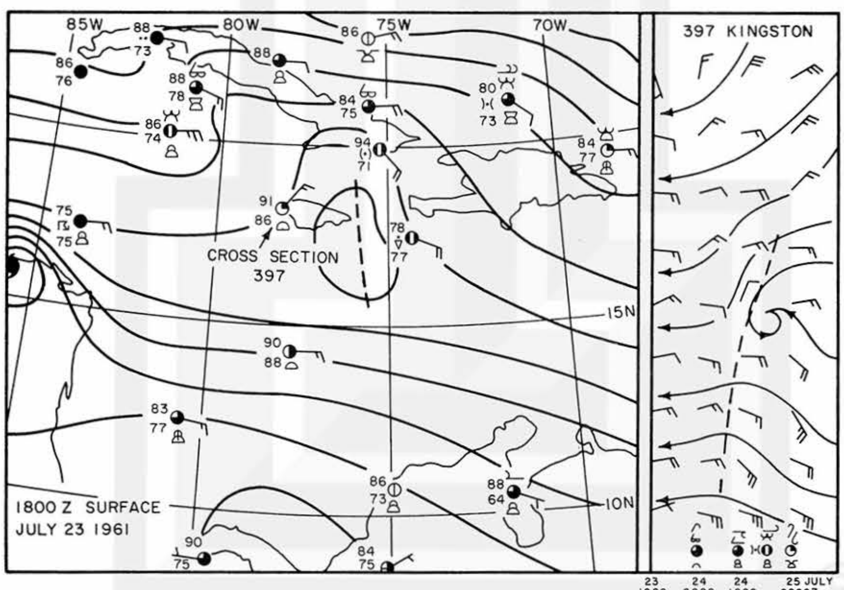


Fig. 12. Surface map for 1800 GMT July 23, 1961 showing the easterly wave W-5. Time cross-section at the right is from Kingston and includes the time of wave passage.

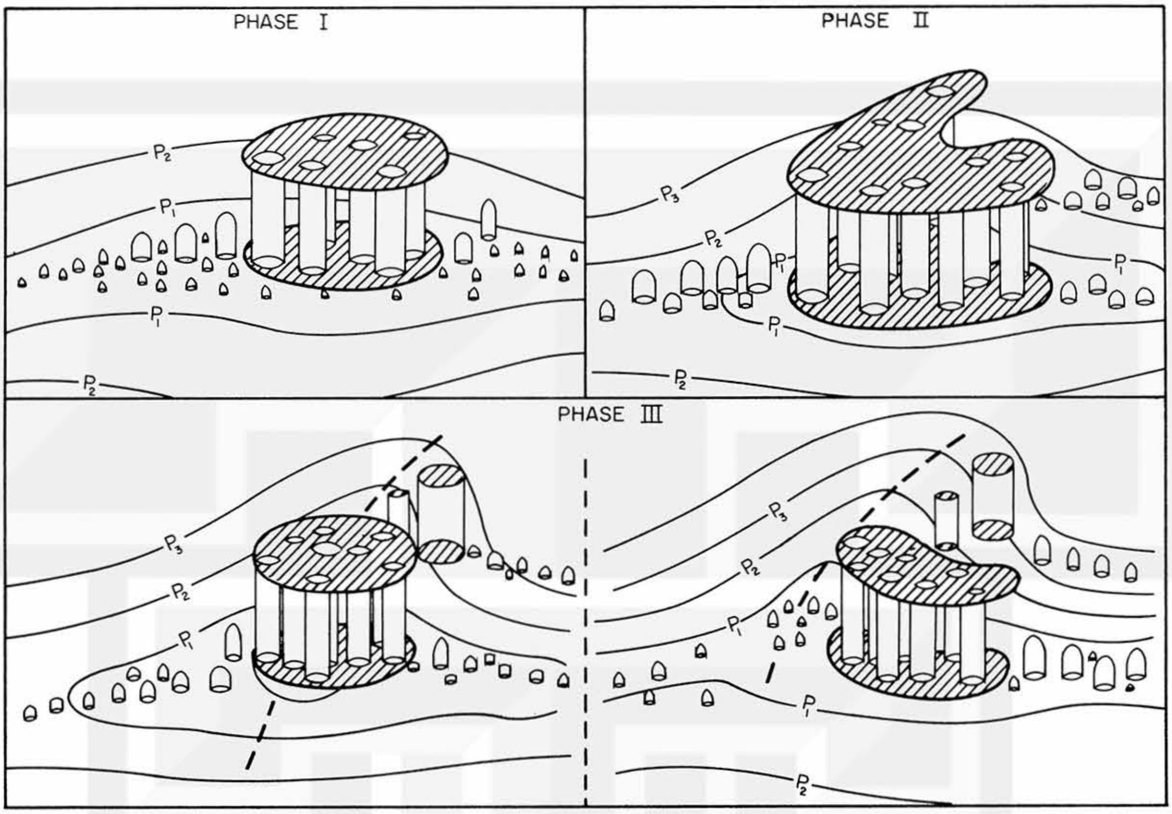
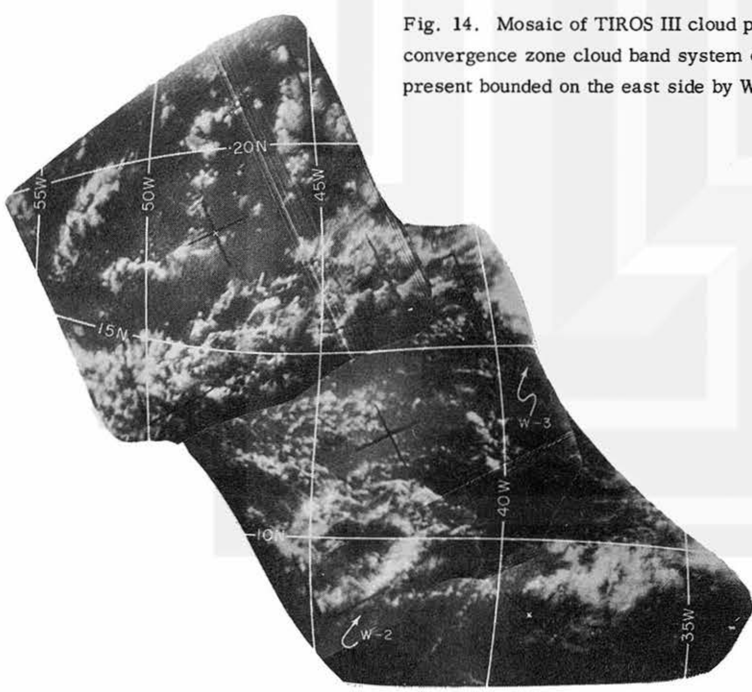


Fig. 13. Schematic illustration of cloud organization in the developing wave within the convergence zone trough. a) Phase I, intensification of cloud activity in the main convergence cloud band. b) Phase II, northern bulging of cloud activity associated with the developing north-south trough line. c) Phase III, developed bimodal cloud pattern within the easterly wave. d) Phase III, developed bimodal cloud pattern behind the trough line with a recognizable circulation feature in the low cloud field ahead of the main cloud system.

Fig. 14. Mosaic of TIROS III cloud pictures, R/O 47 showing a weakly organized convergence zone cloud band system on July 15, 1961. Two major cloud bands are present bounded on the east side by W-3.



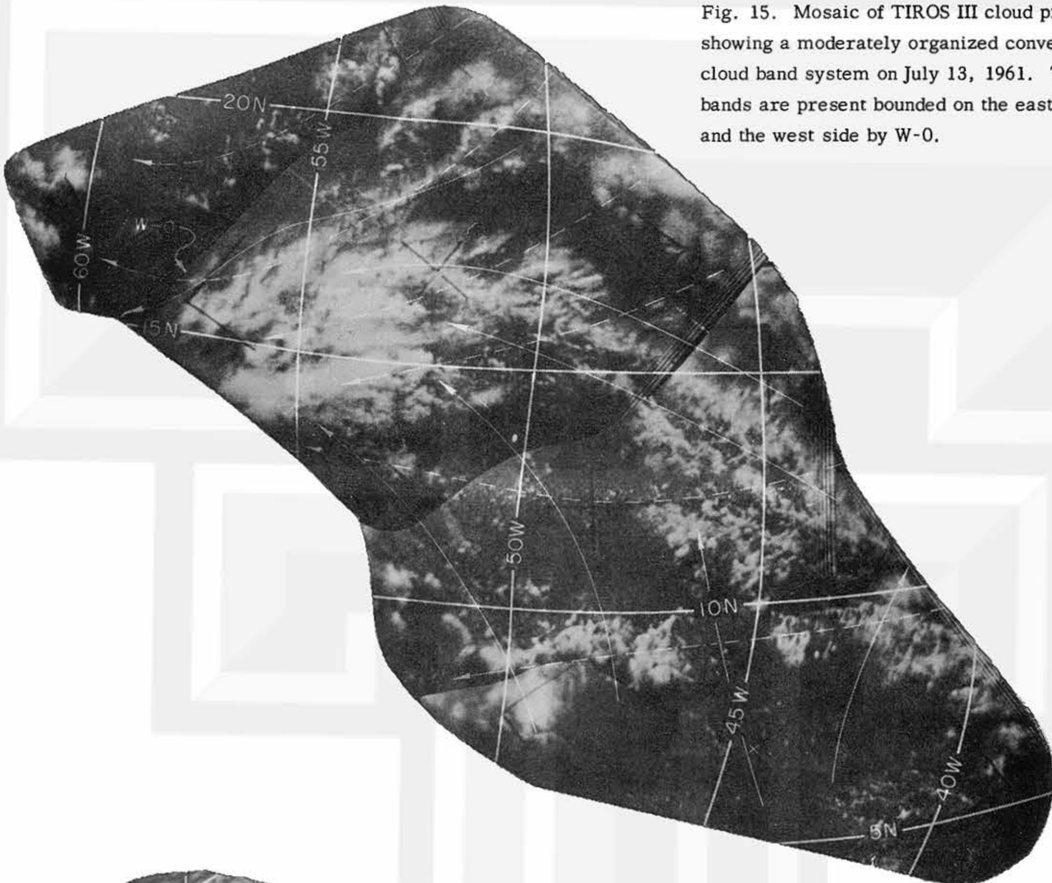


Fig. 15. Mosaic of TIROS III cloud pictures, R/O 47 showing a moderately organized convergence zone cloud band system on July 13, 1961. Two major cloud bands are present bounded on the east side by W-1 and the west side by W-0.

Fig. 16. Mosaic of TIROS III cloud pictures, R/O 47 showing a strongly organized convergence zone cloud band system on July 17, 1961. Two major cloud bands are present bounded on the east side by W-5 and the west side by developing Hurricane Anna, still in the easterly wave stage. W-4 disappeared from the cloud field soon after it left the coast of Africa.

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