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SYNOPTIC CASE STUDY OF TROPICAL CYCLOGENESIS UTILIZING TIROS DATA

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ABSTRACT

On September 12, 1961, an unnamed tropical cyclone formed over the northern Bahama Islands, then moved northward reaching the North Carolina coast near Wilmington on September 14. TIROS satellite pictures of the formation area are available every 24 hr. for a 5-day period extending from September 10 to 14. Some of the problems in fitting satellite pictures to a rather complicated synoptic pattern are discussed. Development occurred within the confines of a cold Low which existed in the upper troposphere. Comments are made on this process, and in particular, on the role played by the upper tropospheric anticyclone.

1. INTRODUCTION

The launching of the first TIROS satellite opened a new concept in the field of weather observation. Not since the perfection of radar during and following World War II has so much interest and attention been focused on an observing tool.

Of all meteorologists, tropical forecasters probably will reap the greatest benefit from the satellite pictures. This fact is due to both the sparsity and, in general, the poorer quality of conventional weather data in the Tropics. The truth of this statement was well exemplified by the 1961 hurricane season when TIROS gave the first indications of hurricane Esther and also took pictures of hurricanes Anna, Betsy, Carla, and Debbie (Dunn [3], Moore [10]). In particular, the unnamed storm which occurred from the 12th to the 15th of September 1961, offers an excellent opportunity for a case study. This storm formed over the northern Bahama Islands on September 12 and moved northward striking the United States coast near Wilmington, N.C., on September 14. Fay [4], gives an excellent account of the storm's history after landfall. The unique feature about this storm is that TIROS pictures are available of the formation area every 24 hr. for a 5-day period extending from September 9 to 14.

This case study reveals some interesting points in regard to the question of fitting TIROS cloud pictures to a rather complicated tropical synoptic pattern. An important task in using the satellite pictures is the interpretation of cloud patterns in terms of circulation features. Much of the literature on the subject of satellite meteorology in recent months has dealt with this problem. The question of interpretation and association is complicated in the Tropics by the structure of the tropical atmosphere. It has long been known that over the western portions of the major oceans in summer the atmosphere consists of two primary flow layers. First, there are the low-level easterly trade winds in which are embedded waves or in some cases vortex perturbations. The upper troposphere is characterized by numerous traveling anticyclones and cyclones which seem to be best defined near the 200-mb. level. Weather may be produced by disturbances at either of these levels, although knowledge of the cloud distribution about the upper tropospheric systems is still limited. Therefore, the problem in the Tropics is not only one of inferring a circulation feature from the cloud patterns but also determining the level of circulation.

Perhaps the greatest contribution which satellite pictures can make to the tropical forecast problem is in the recognition of potential storm-developing situations. Work is already being carried out on this subject. For example, Hubert [6] discussed the potential of satellites for hurricane surveillance. Koteswaram [8] has studied cloud patterns associated with a tropical cyclone in the Arabian Sea, and Fritz [5] analyzed the cloud structure leading to the formation of hurricane Anna in 1961. Conclusions at the present are tentative and untested; however, there appears little doubt that full-fledged hurricanes show definite characteristics which are easily identifiable on the satellite pictures. Pictures taken of the Atlantic hurricanes during 1961 proved this point. On the contrary, cloud patterns associated with developing situations pose a problem.

One of the purposes of this short note is to discuss some of these problems by presenting the cloud structure which occurred in one case of tropical cyclone development from a pre-existing cold Low in the upper troposphere. This cycle of development is not nearly as common as the more typical easterly-wave-to-tropical-storm sequence. The second point of the paper will be to comment on this development process and, in particular, on the role played by the upper tropospheric anticyclone.

2. SYNOPTIC DISCUSSION

Figures 1–6 show the 200-mb. streamline charts at 0000 GMT, September 10 to 14, except for figure 4 which is a 1200 GMT map. Superimposed on these charts are the nephanalyses made from the TIROS photos. The broken line indicates the limit of the pictures. Circulation centers are shown by a small circle, "C" referring to cyclones and "A" to anticyclones. Previous 24- and 48-hour positions are shown by an "x." The corresponding surface charts are presented in figures 7–11. Figure 7 shows the whole Atlantic area and is included merely to set the stage synoptically, while figures 8–11 are restricted to the area of interest. It should be noted that figure 8 is for the same time as figure 7. Isobars are drawn for a 2-mb. increment and the trough is designated by the heavy dashed line. Surface reports which include winds, present and past weather, and the cloud group are shown only in the immediate vicinity of the trough.

TIROS pictures at 2120 GMT, September 9, (fig. 12) suggest a vortex northeast of the Bahama Islands which fits nicely with a 200-mb. cold Low (fig. 1). This Low moved slowly westward for the next two days, intensifying downward in the vertical as indicated by the increasing amplitude of the surface trough (figs. 8–9). Prior to the 11th the pressure pattern on the surface was very flat with little indication of a trough. In agreement with the increasing surface amplitude, an area of heavy showers developed along and to the east of the surface trough. Six-hour rainfall amounts of 1 or 2 in. were common at stations in the extreme northeastern Bahama Islands with the passage of the trough. Ship reports indicate that on the 12th the shower area extended about 300 mi. northeastward from the Bahamas. This is not evident from ship's data plotted on figure 9. However, ship reports on the intermediate 6-hourly maps clearly verify the increase in weather. For example, there were ten ships in this area reporting on the 0600, 1200, and 1800 GMT charts and of these eight reported either showers or thunderstorms.

On September 12 the high-level cold Low was forced rapidly southwestward and replaced by a thermal High. This was undoubtedly accomplished by the release of latent heat in the area of intense convection. The first indications of these rather dramatic changes in the high-level pattern are shown on figure 4. Note the change from cyclonic flow over the northern Bahama Islands on figure 3 to anticyclonic flow on figure 4. One might argue that the small anticyclone carried near Bermuda on figures 1, 2, 3, and finally as a cusp on figure 4 moved southwestward and is the one shown on figure 5 near the Bahama Islands. Two points can be made against this reasoning. First, a time section for Bermuda shows the 200-mb. wind changes were in agreement with the northward motion of a ridge line. This can be seen on figures 4 through 6 where the 200-mb. wind at Bermuda increases from light northeasterly on figure 4 to strong easterly on figure 6. If the anticyclone had moved southwestward a shift to westerly winds should have occurred. Second, the anticyclone on figure 5 was associated with a large area of cloudiness, yet TIROS pictures do not show any such area moving southwestward from the vicinity of Bermuda. For those still unconvinced, it is really immaterial. An anticyclone of the magnitude shown on figures 5 and 6 cannot be tracked into this area, which means very strong *local intensification* occurred. This is the important point being made. By 0000 GMT September 13 (fig. 10) shortly after the appearance of the thermal High in figure 4, a weak closed circulation appeared in the surface pressure pattern near Grand Bahama Island (about 90 mi. east of Miami, Fla.). Surface reports did not confirm a west wind until the vortex moved north of Grand Bahama 6 hours later; however, pictures taken of the Miami radarscope show convective cells moving from the west at this time.

The thermal High continued to intensify on the 13th (fig. 5) and a sharp shear line developed along the Florida peninsula separating the outflow of hurricane Carla from that of the tropical depression. It should be mentioned that the outflow pattern from hurricane Carla shown on this set of 200-mb. charts is a classic. Figure 11 shows that the surface circulation moved almost due north from its formation point and intensified slowly. Maximum winds at 0000 GMT September 14, were 25–30 kt. with a central pressure near 1010 mb. The vortex probably reached the tropical storm stage about 12 hr. later as it moved onshore near Wilmington, N.C. Several stations revealed winds of 35 kt. at this time. Details on the track of this storm beyond 0000 GMT September 14, may be found in Fay's paper [4].

Figures 12 through 15 are selected TIROS pictures used in deriving the nephanalyses shown in figures 1, 2, 3, and 5.

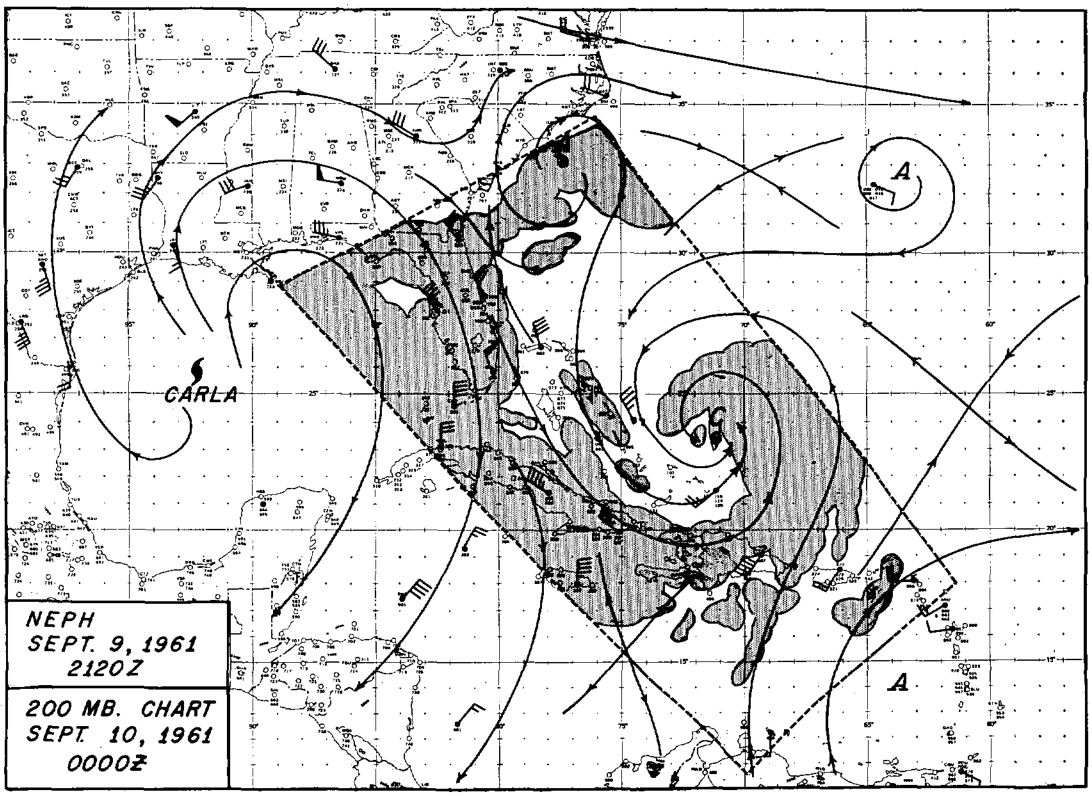

Figure 1.—200-mb. streamline chart for 0000 GMT, September 10, 1961, with nephanalysis for 2120 GMT, September 9 superimposed. "A" and "C" indicate anticyclonic and cyclonic centers; previous positions are shown by X's. Full wind barb equals 10 kt.; pennant 50 kt. Dashed lines indicate limit of TIROS pictures from which nephanalysis was made.

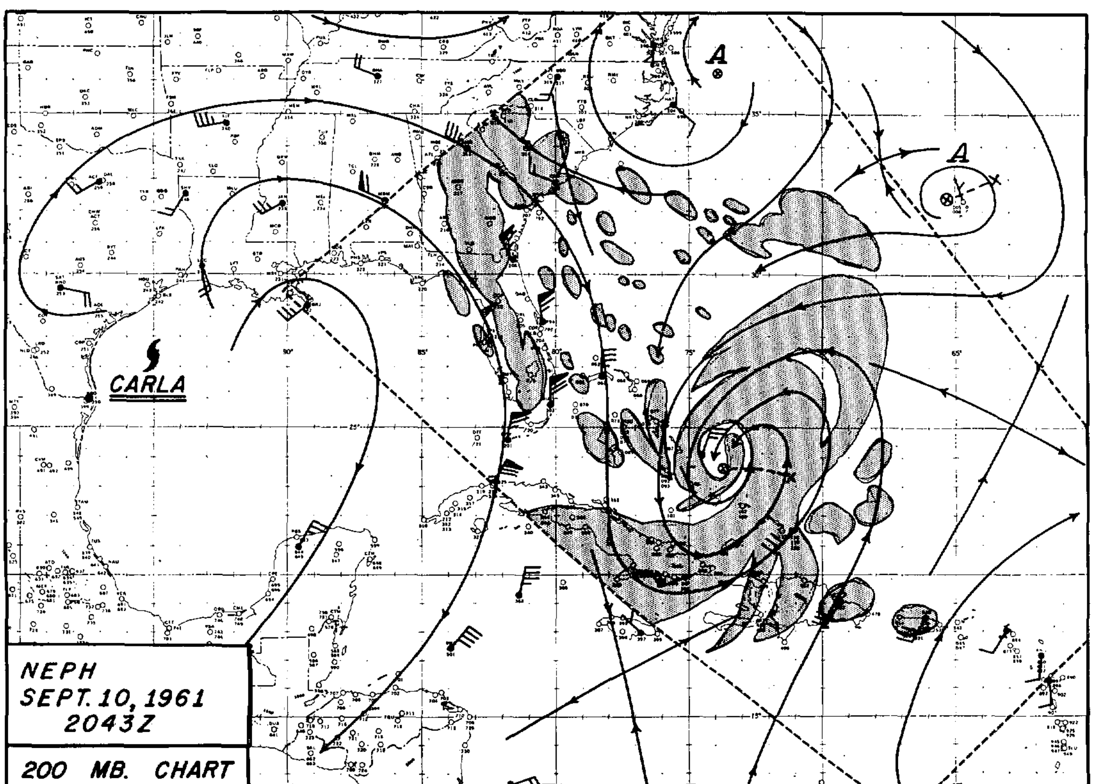

Figure 2.—200-mb. streamline chart for 0000 GMT, September 11, with nephanalysis for 2043 GMT, September 10.

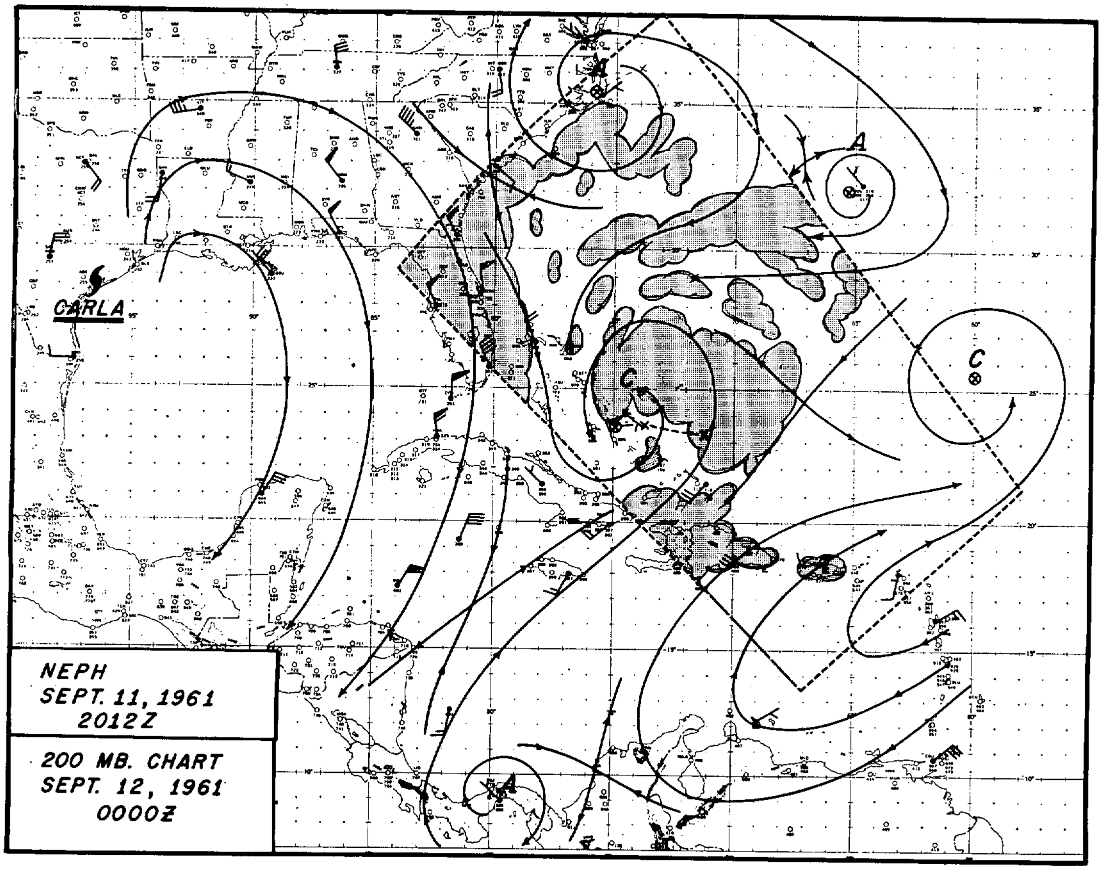

FIGURE 3.—200-mb. streamline chart for 0000 GMT, September 12, with nephanalysis for 2012 GMT, September 11.

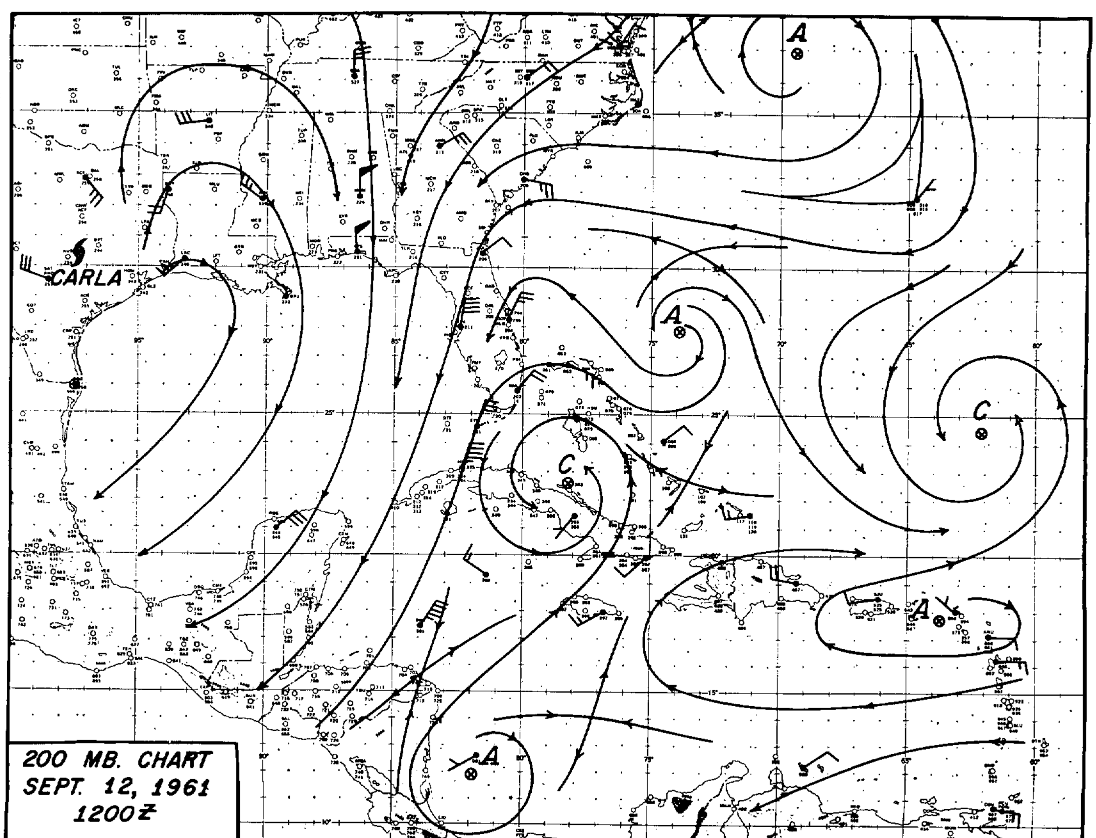

FIGURE 4.—200-mb. streamline chart for 1200 GMT, September 12.

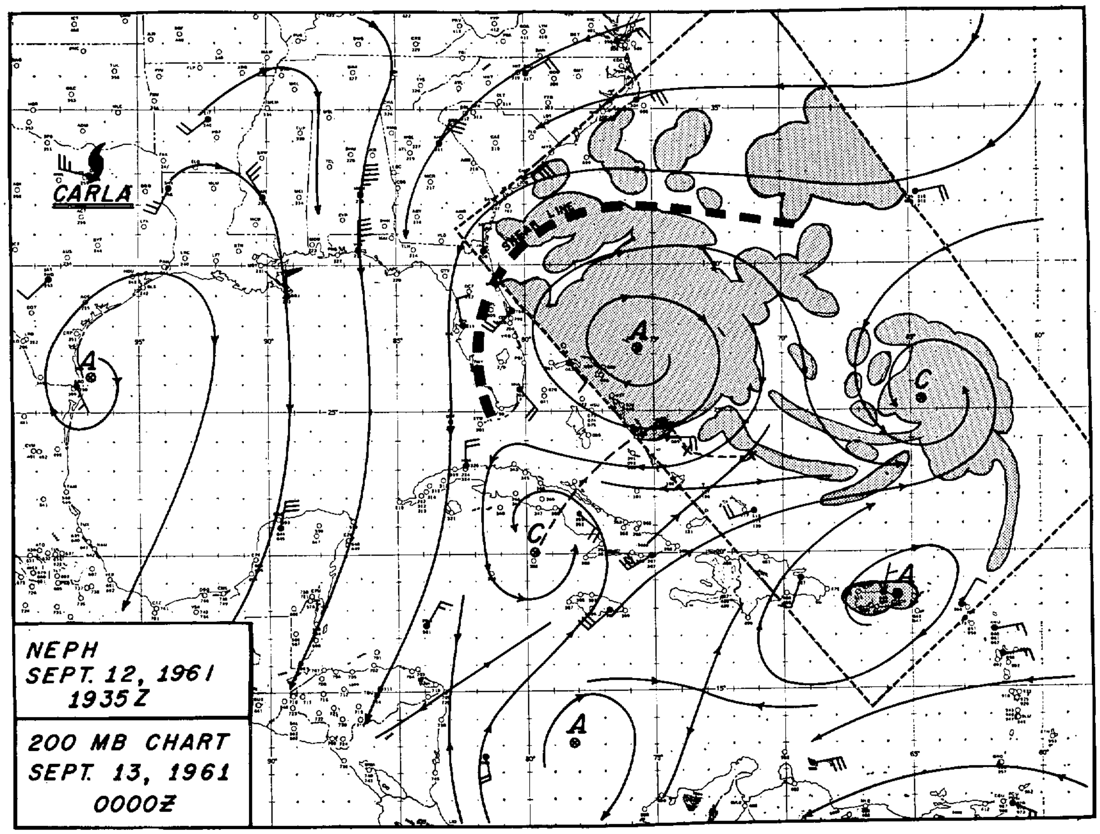

Figure 5.—200-mb. streamline chart for 0000 GMT, September 13, with nephanalysis for 1935 GMT, September 12.

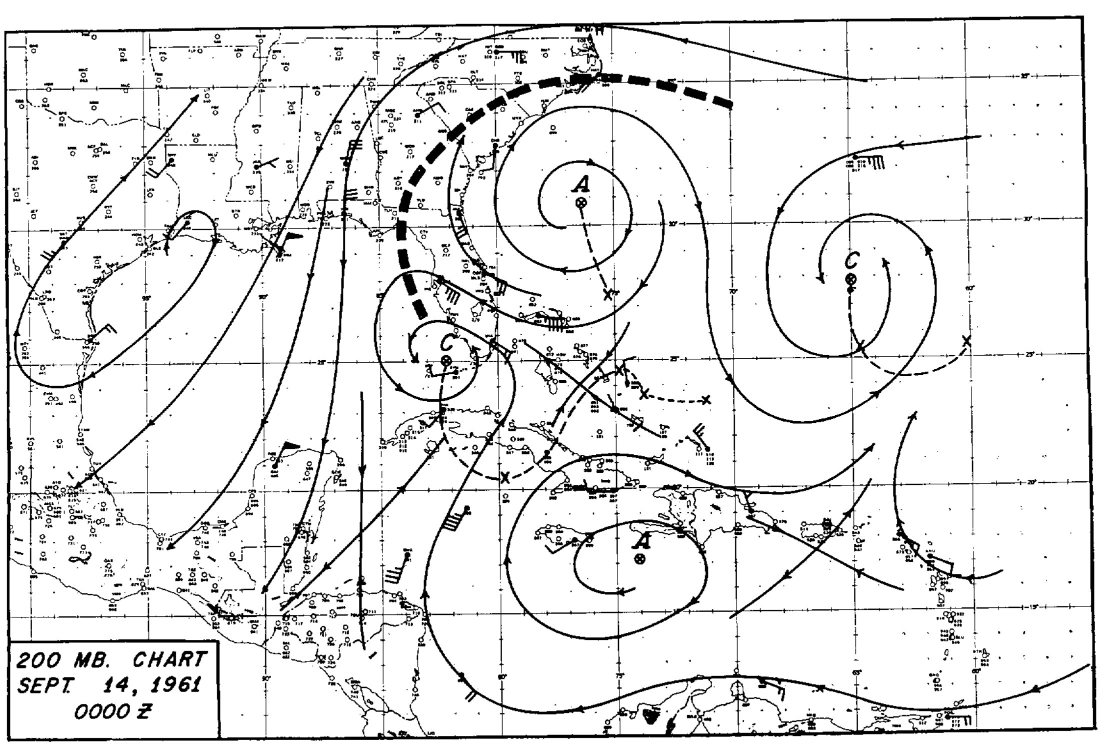

Figure 6.—200-mb. streamline chart for 0000 GMT, September 14.

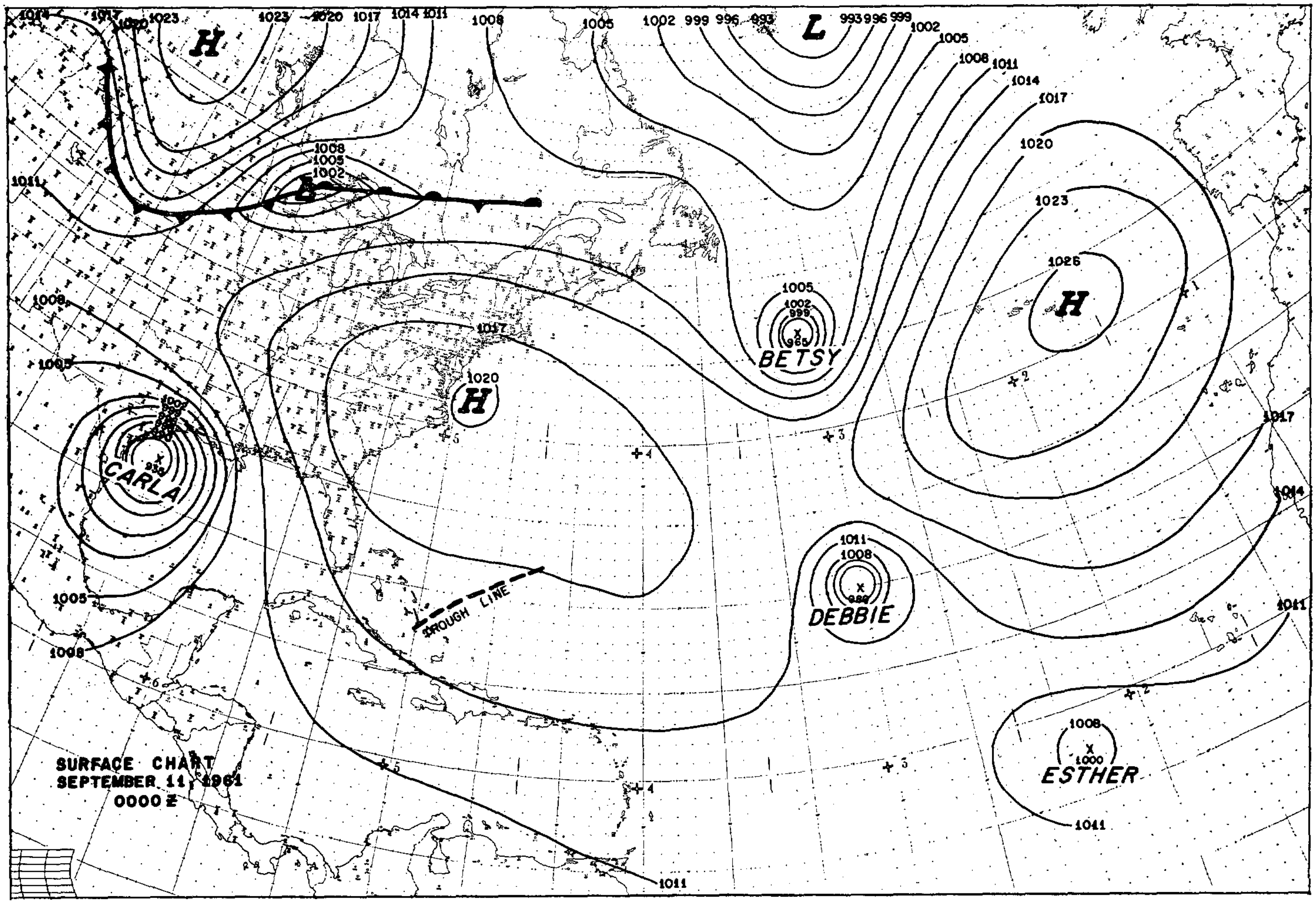

Figure 7.—Surface pressure map showing positions of four hurricanes at 0000 GMT September 11, 1961.

The 200-mb. streamlines have been superimposed on these photos along with 200-mb. winds from several land stations mainly in the Bahama Islands.

Suface ship reports indicate the clouds in figure 12 are mainly middle and high types. The only low clouds reported were either type 1 or 2 (undeveloped cumulus) and of these amounts were less than 50 percent coverage. The gross features of the cloud pattern associated with the Low in figure 12 are not unlike those found in surface cyclones. Even though this circulation was confined to the upper troposphere the characteristic spiral structure was present. It is interesting to note that the cloud pattern shown in figure 12 agrees with Palmén's [11] model of extratropical cutoff Lows; i.e., upward vertical motion and cloudiness to the east of the low center and downward motion and clearing to the west. This statement is not intended to imply dynamic similarity between the Low viewed in figure 12 and the polar cutoff Lows described by Palmén.

In figure 13, the complexity of the cloud pattern increases. Recall that the cold Low was at this time reflected downward into the surface pressure pattern as a northeast-southwest trough (fig. 8). In response to the increasing amplitude at the surface, low cloudiness and convective activity began to develop under this cloud shield. The elongation of the cloudiness along the NE–SW axis is evident in figure 13 and even more so on the nephanalysis shown in figure 2. This makes cloud interpretation extremely difficult because we are viewing the remains of a prior existing high cloud shield in which are now embedded cumulonimbus tops. Note the two ship reports near 28° N., 69° W. in figure 8. One is reporting lightning and the other rain shower with cumulonimbus clouds. The spiral characteristic continued and the cloud photo still suggests a cyclonic circulation.

Twenty-four hours later the spiral feature disappeared as the convection continued to increase (fig. 14). The individual cloud elements pictured north of the large overcast area are probably tops of cumulonimbus. It is very hard to envision a cyclone in this cloud pattern.

Figure 15 is the most interesting picture in the series. The two cloud masses in the photo are associated with distinctly different synoptic features which existed at different levels in the tropical atmosphere. The cloud mass near the northern Bahama Islands is the cirrus shield over the convective activity which developed along the surface trough. This circulation was best defined in the lower troposphere. The cloud mass farther east between Bermuda and Puerto Rico is associated with a second high-level cold Low. This Low, like the first one in its earlier stages, was not strong enough to influence the surface pressure pattern at this time and the clouds were mainly middle and high types. The bands seen between the two cloud systems on figure 15 appear to be cumulus lines oriented along the surface wind flow. The presence of these lines makes the cloud pattern very difficult to interpret. The bands seem to converge into the more solid cloud mass to the east and thus give the impression of a surface Low south of Bermuda. One could very easily assign the wrong level to this vortex. On the other hand, one might also be tempted to hypothesize that the cumulus bands are part of the cloud mass to the west and infer a surface cyclone in that area. This was the solution accepted by the operational section of the National Weather Satellite Center (NWSC). Figure 16 is a copy of the nephanalysis prepared for facsimile transmission by NWSC. The picture in figure 15 was one of several used in this analysis. Note the cyclonic vortex indicated at 26.5° N., 73.0° W.

Neither of these solutions is correct as can be seen on figures 5 and 10. As a matter of fact the only vortex present near latitude 26.5° N., 73.0° W. was an anticyclone in the upper troposphere. It should be pointed out in behalf of the people making the nephanalyses that this was an operational analysis and subject to rather harsh time limits. Criticism of the operational section is not intended in any way; but rather, attention is called to the difficulties which can arise in the use of satellite pictures for inferring flow patterns.

The question which now might be asked is, can this type of development (cyclogenesis within a cold vortex) be recognized in the earlier stages from satellite pictures? Based on the above study the answer would have to be no, at least not until the closed circulation forms. The important events as far as cloud changes are concerned all took place under a cirrus shield. It was not until the surface vortex formed that low-level cloud bands were visible outside of the high overcast.

Before closing this section, two other points need to be discussed which are significant to operational people. These have been implicit in the above discussion but perhaps not obvious. First, it will be extremely fortunate if the cloud patterns in upper cold Lows do have the spiral characteristic suggested in figures 12 and 13. This means we will be able to locate these features quite accurately in areas of limited data. The problem of distinguishing the level of the cyclone still exists. It is hoped either the absence or presence of cumulus bands may prove to be a good indicator. Second, even though a cloud mass such as shown near the Bahama Islands, on figure 15, is extremely difficult to interpret, knowledge of its mere presence is important to the forecaster. His attention is thereby called to the possibility of something significant and he can turn to conventional methods for clarification.

3. COMMENTS ON DEVELOPMENT

During the past several years, our knowledge of tropical cyclones has increased greatly. Part of this had been due to the collection of detailed data by highly instrumented aircraft operated in support of the National Hurricane Research Project.

However, the key to storm development continues elusive. This is perhaps best stated by Palmén [12]: "The ease in outlining the necessary conditions of climatological and geographical nature for the formation of tropical cyclones is matched by the difficulty of the next step, which is to develop a satisfactory theory of the actual formation."

Much attention has been focused on the high levels in search of the starting mechanism. Sawyer [15], and more recently Alaka [1], suggest dynamic instability at this level. A model was proposed by Riehl [14] which resulted in high-level divergence. Colón and Nightingale [2] found tropical cyclogenesis was more likely when the 200-mb. flow over the developing region was anticyclonic and possessed a southerly component. The common factor in these papers is the existence of a high-level anticyclone near or over the formation point. It is also generally believed that correct positioning of the upper anticyclone occurs through relative motion between the low- and high-level systems.

In the case presented in this study, the High (shown in fig. 4) is of thermal origin and developed through the release of latent heat. The idea that thermal Highs form this way is not new. Riehl [13] documented such a development in 1958. However, the synoptic pattern in his case was somewhat different in that an upper High was already in existence; intensification resulted when a surface disturbance moved under it. In the present case the thermal High apparently developed entirely as a result of heating from convective activity which was first instigated by an upper cold Low. Yanai [16] also recently emphasized the importance of latent heat in tropical cyclogenesis.

Unfortunately, it is possible to make only a few quantitative statements. The only station close enough to show evidence of the heating was Grand Bahama Island, which showed an average warming in the layer from 850 mb. to 200 mb. of about 1° K. per day for a 48-hr. period, ending at 1200 GMT September 13, or a total warming of approximately 2.0° K. (fig. 17). The mean tropical sounding for September (after Jordan [7]) is included in figure 17 for comparative purposes.

The thermal High approached in magnitude a so-called

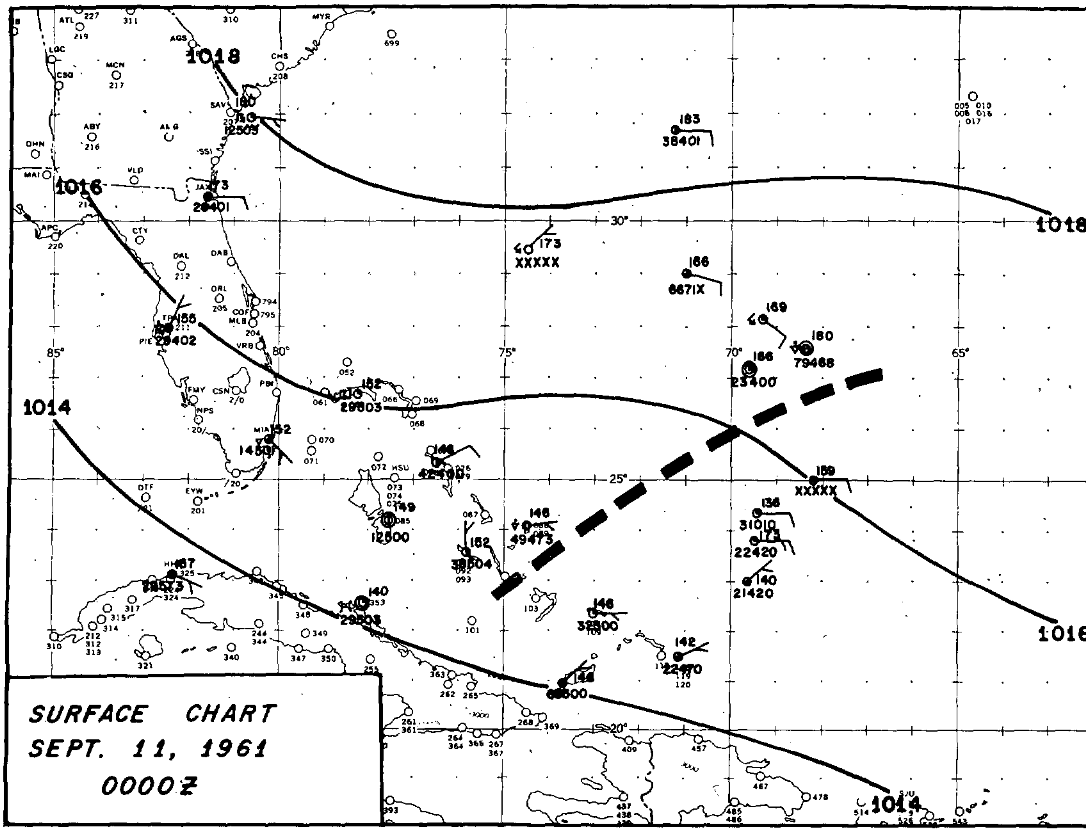

FIGURE 8.—Surface pressure chart for the extreme southwestern portion of the North Atlantic, including Florida, Cuba, and the Bahamas, 0000 GMT, September 11, 1961. Heavy dashed line indicates trough line. Ship reports are included only in the vicinity of the trough. Plotted data include wind, pressure, present weather, and cloud group.

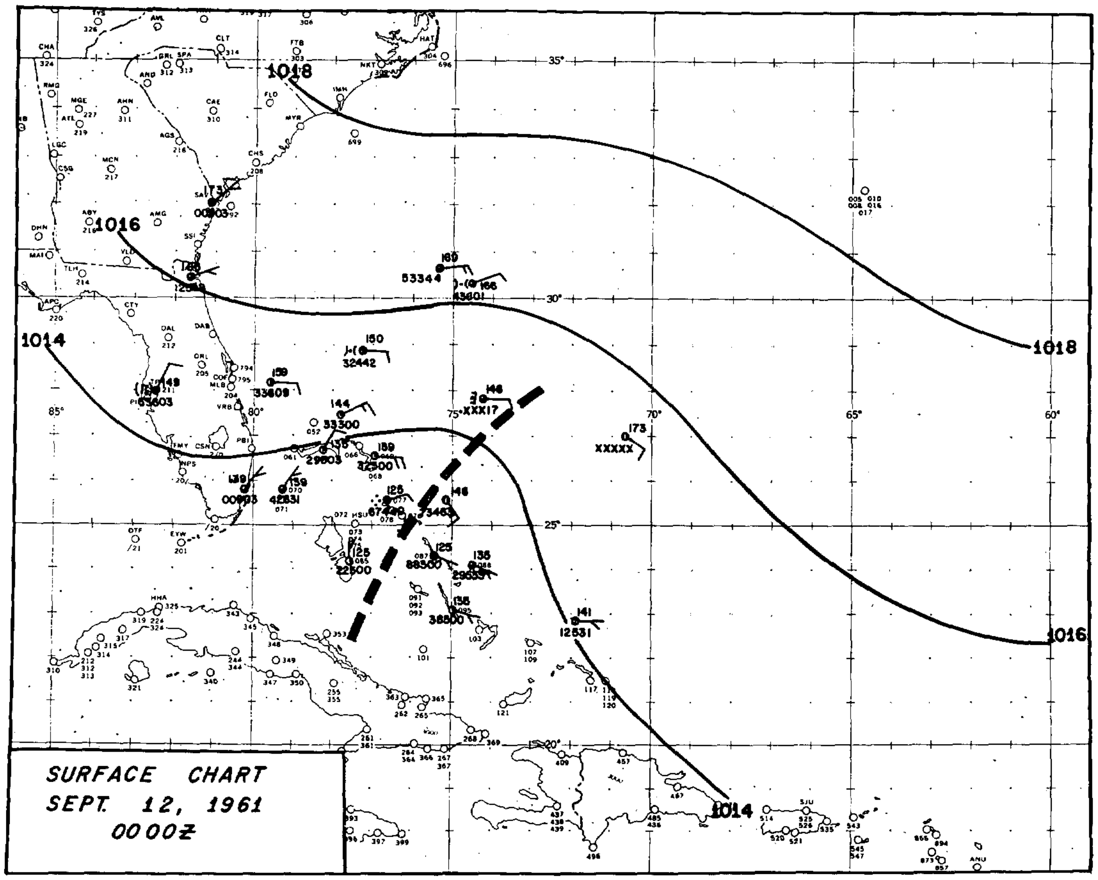

FIGURE 9.—Surface pressure chart for 0000 GMT, September 12, 1961.

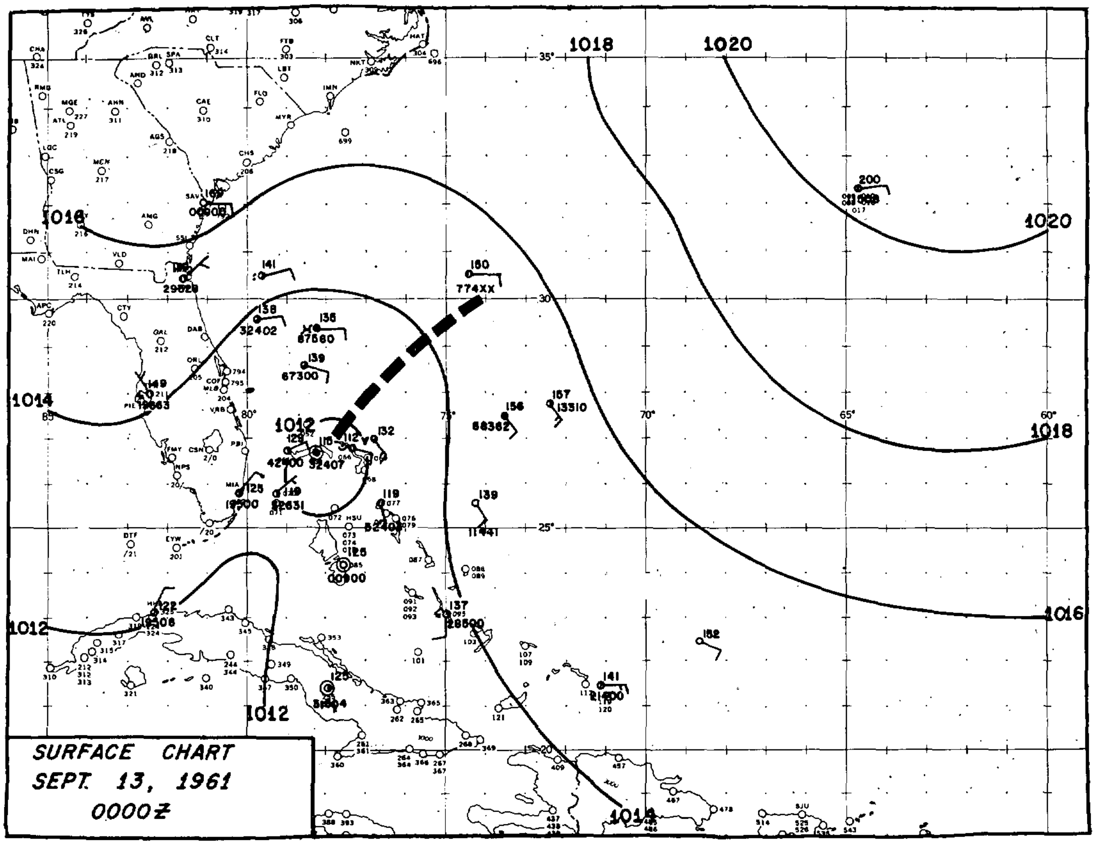

Figure 10.—Surface pressure chart for 0000 GMT, September 13, 1961.

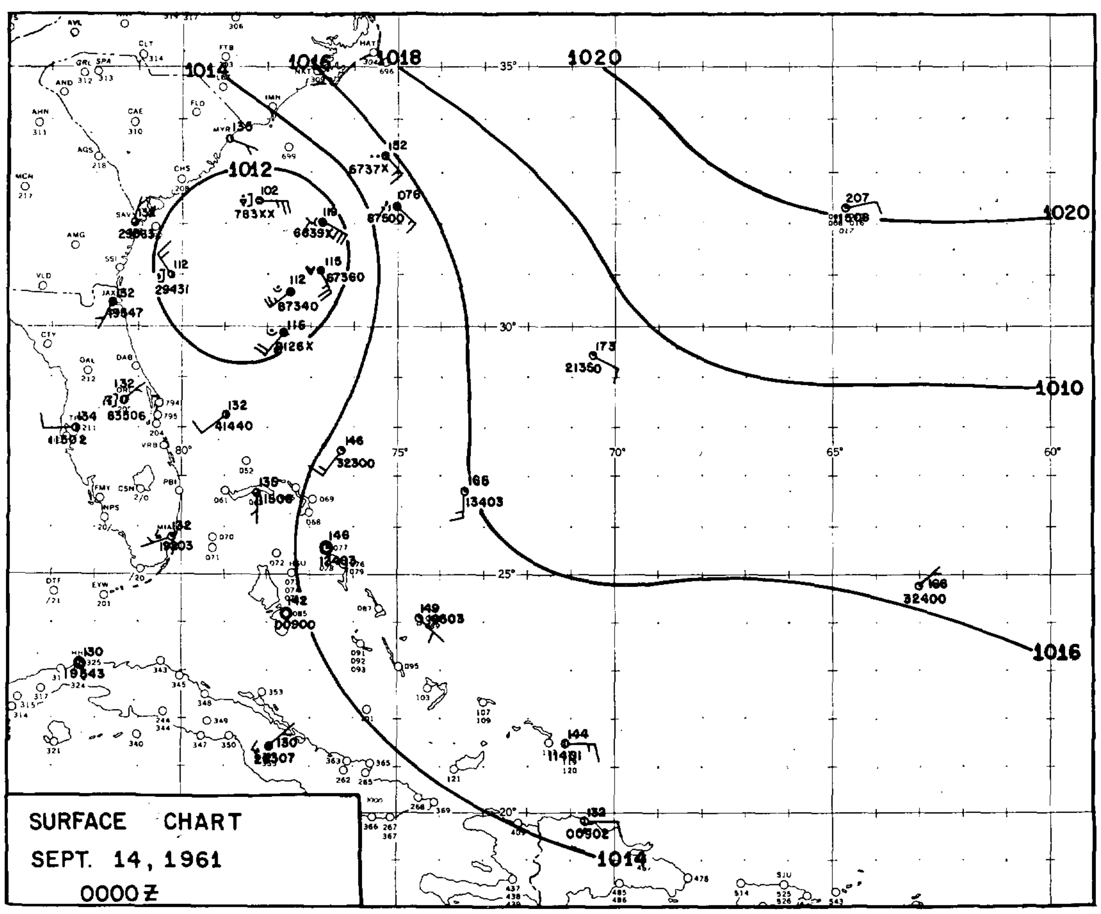

Figure 11.—Surface pressure chart for 0000 GMT, September 14, 1961

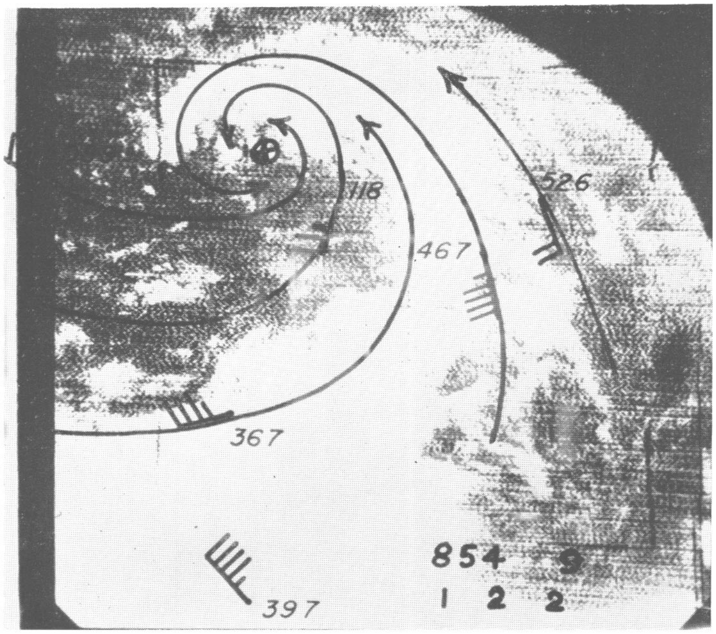

FIGURE 12.—TIROS picture at approximately 2120 GMT, September 9, 1961, used in the nephanalysis shown in figure 1. 200-mb. winds at several stations and 200-mb. streamlines are superimposed.

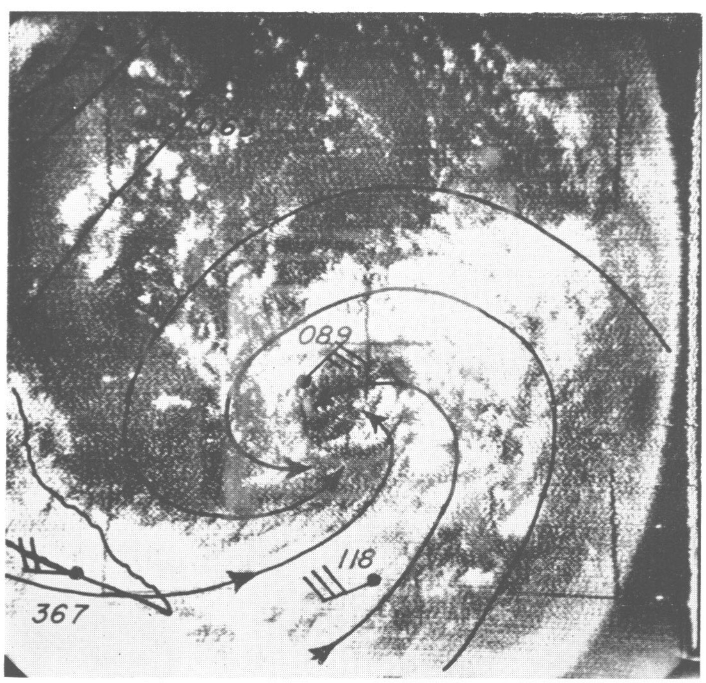

FIGURE 13.—TIROS picture at approximately 2043 GMT, September 10, 1961, used in the nephanalysis shown in figure 2.

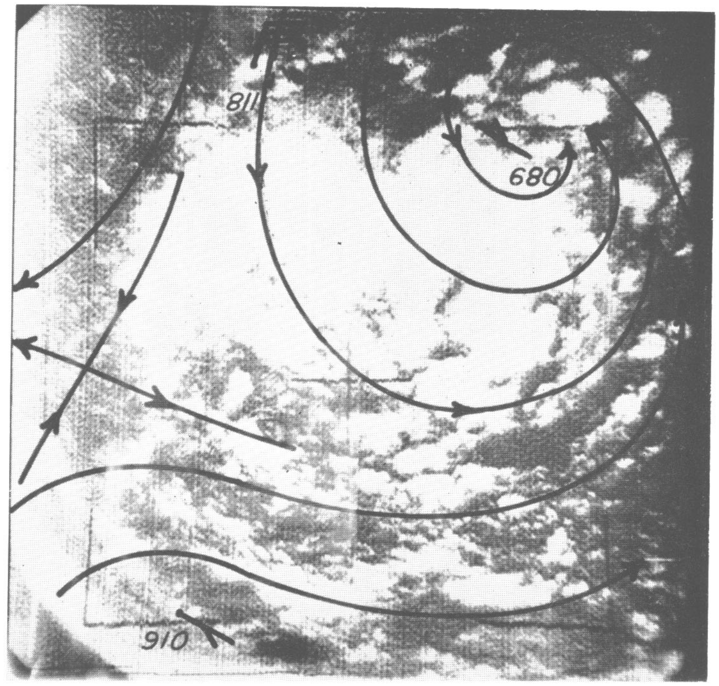

FIGURE 14.—TIROS picture at approximately 2012 GMT, September 11, 1961, used in the nephanalysis shown in figure 3.

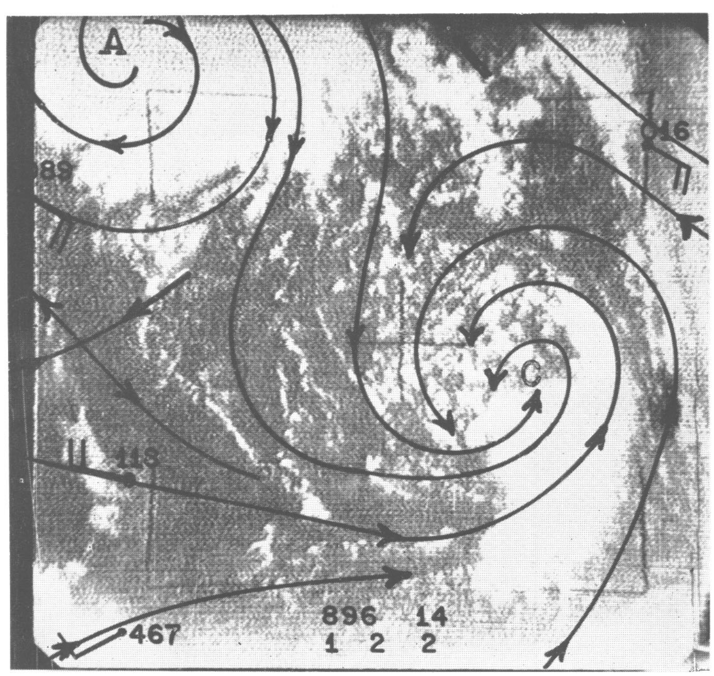

FIGURE 15.—TIROS picture at approximately 1935 GMT, September 12, 1961, used in the nephanalysis shown in figure 5.

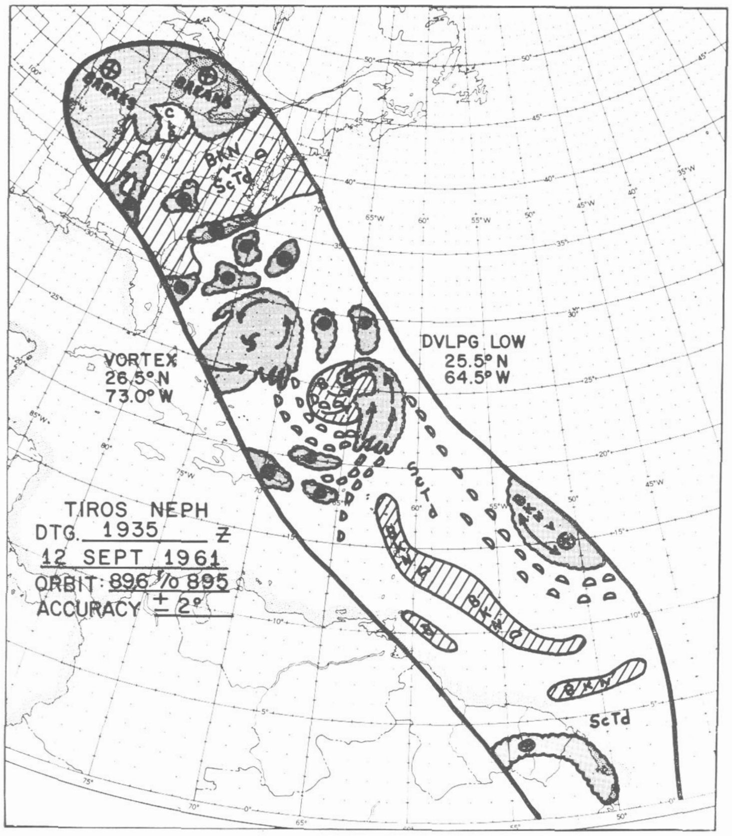

FIGURE 16.—Copy of the nephanalysis for facsimile transmission made by the National Weather Satellite Center in Washington. The picture shown in figure 15 was one of several used in this analysis.

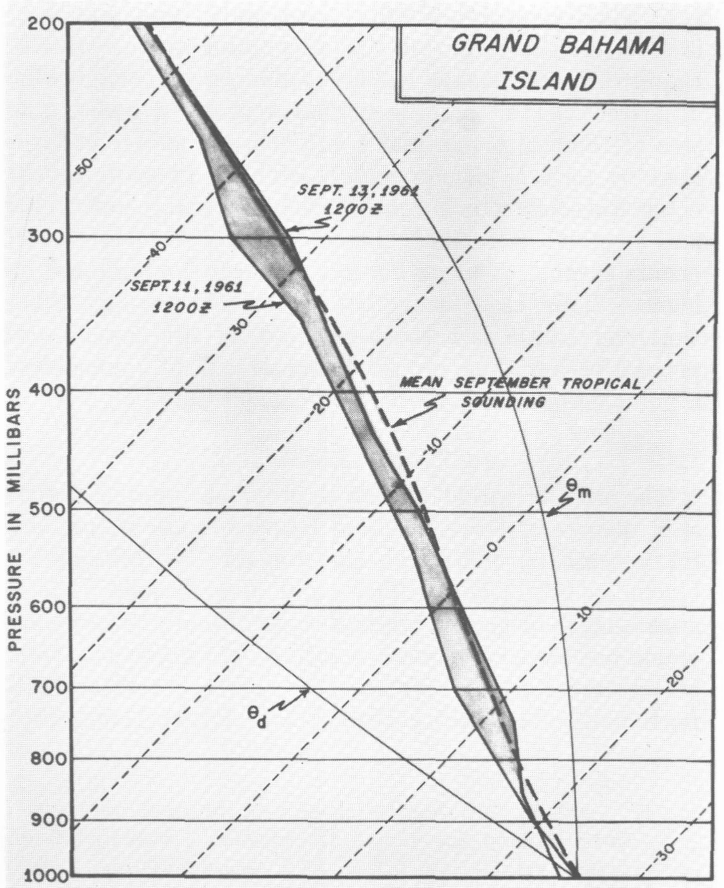

FIGURE 17.—Temperature soundings for Grand Bahama Island (about 90 mi. east of Miami) shown on a skew $T-\log p$ diagram. Shaded area represents the warming for a 48-hour period during which the thermal High formed. Dashed line is the mean tropical September sounding after Jordan [7].

"maximum anticyclone;" i.e. one in which the absolute angular momentum is equal to zero. This term has been used by Riehl in his courses on tropical meteorology. If we let c be the tangential wind speed at some radius, r, then the absolute angular momentum per unit mass of air is:

$$\text{Angular Momentum}=r\left(c+\frac{fr}{2}\right)$$

This is equal to zero when the flow is anticyclonic and $c=fr/2$.

If we assume that the winds at Miami, Cocoa (794), and San Salvador (089) in figure 5 are representative of the other sections of the anticyclone, we can compare these with the calculated wind required for a maximum High.

From figure 5, a radius of 240 n.mi. requires a critical wind of about 27 kt.; similar calculations from figure 6 give a critical wind of 30 kt. Comparison of the computed winds with the actual winds from figures 5 and 6 shows that the thermal High was near its maximum amplitude.

4. CONCLUSIONS

1. This case study demonstrates some of the problems one encounters when interpreting cloud patterns in terms of circulation features. In spite of these difficulties, cloud pictures show great potential as an operational analysis aid. TIROS photos make conventional data more meaningful and permit one to draw more accurate conclusions. On the other hand, circulation features inferred from cloud pictures *alone* can be quite misleading. Correct interpretations result from supplementing the standard meteorological observations with TIROS data. This emphasizes the need to *increase* the existing distribution of weather observing stations.

2. It is unlikely that the early stages of tropical cyclogenesis within a cold vortex will be recognized from TIROS pictures alone since the important changes take place under a high cloud shield.

3. The cloud structure associated with high-level cold Lows in the Tropics appears to have a characteristic spiral feature which can be easily recognized.

4. Finally, and probably most important, new light is shed on the origin of the upper anticyclone which is required by various development models. The High which appeared on the high-level charts prior to cyclogenesis was of thermal origin and resulted from release of latent heat by an area of convection. This is in contrast with other theories which require a pre-existing anticyclone and suggest that correct positioning of this upper feature occurs through relative motion between the high and low levels. This case study also supports the hypothesis that convection is a *necessary* part of the development process rather than merely being a result of cyclogenesis, a point emphasized recently by LaSeur [9].

ACKNOWLEDGMENTS

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