

## THE PATHS OF HURRICANES CONNIE AND DIANE

WILLIAM T. CHAPMAN, JR. AND YOUNG T. SLOAN

National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

### 1. INTRODUCTION

Tracks of tropical cyclones in August show that a large percentage of the storms that form in the central Atlantic east of the West Indies move on a west-northwesterly course just north of these islands and then make a shallow curve to a more northwesterly direction along or near the Atlantic Seaboard. An abrupt change in direction that usually follows a marked slowing down of the storm on its northwesterly course is often termed the point of recurvature. The direction of recurvature is usually northeasterly which takes the storm out to sea. When the storm arrives at the point of recurvature it is at the most difficult position for predicting its future direction. Storms moving inland usually begin filling rapidly and their winds decrease somewhat in intensity. However, the threat of damage from strong winds, heavy rains, and floods usually prevails along the entire path of the storm.

This article deals with two hurricanes, Connie and Diane, that crossed the North Carolina coast near the middle of August 1955 and inflicted great damage over a large area of the eastern seaboard. Connie was first detected at 0630 GMT August 4 (fig. 1) about 1,200 miles east of San Juan, P. R. and moved on an irregular course west-northwestward to northwestward just north of the West Indies. By 1230 GMT August 11, when it was southeast of the North Carolina coast, Connie began decreasing its forward motion thus indicating a strong tendency to recurve. It turned abruptly north-northeastward and crossed the North Carolina coast near Cherry Point at 1500 GMT, August 12. On crossing the coastline, Connie weakened, but remained an intense storm as it continued generally northward to near the latitude of Washington, D. C. It then turned northwestward and began filling rapidly as it crossed the higher terrain of Pennsylvania and filled further as it moved into the Great Lakes area.

Diane, the weaker of the two storms, was first detected at 0630 GMT August 11 (fig. 1) about 450 miles northeast of San Juan, P. R. and moved on an erratic course generally northward for two days. It then turned to a more stable west-northwest direction similar to Connie's path. Unlike Connie, Diane did not give any indication of recurving by slowing down its forward motion. Rather, it continued on its regular course northwestward and

crossed the North Carolina coast near Wilmington about 1500 GMT August 17, some 100 miles west of the area that Connie hit five days earlier. As Diane passed inland over the rougher terrain of central North Carolina it filled rapidly and continued weakening as it turned slowly northward toward Martinsburg, W. Va., crossing the high terrain of Virginia. Near the latitude of Martinsburg, W. Va., Diane abruptly turned to the northeast with little change in intensity until it started slowly deepening after passing off the coast near Long Island. Very heavy rains occurred along the track of both storms.

In our review of these two storms we shall investigate the applicability of some of the techniques that are used

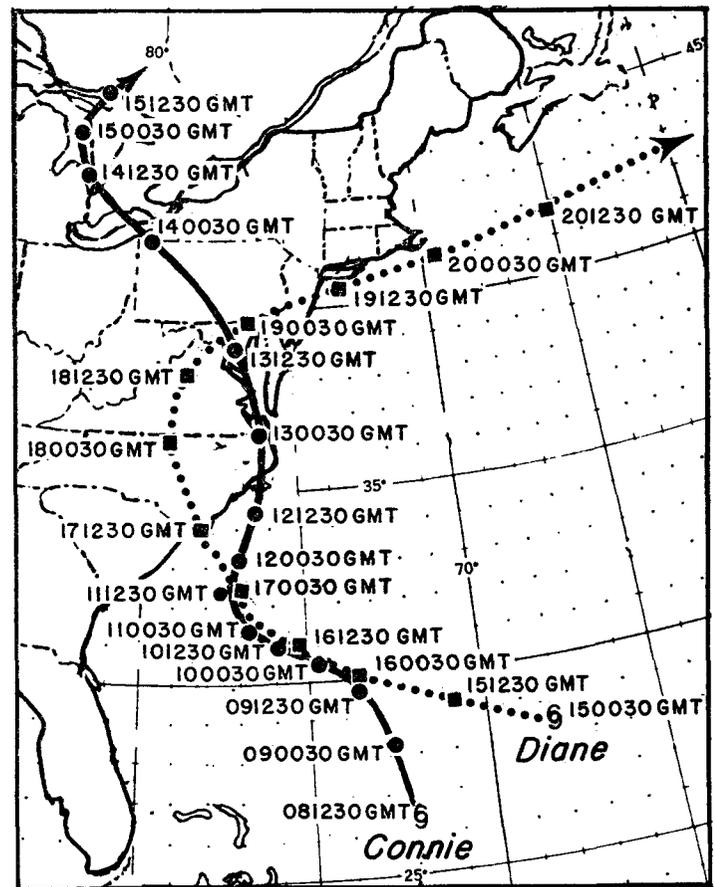


FIGURE 1.—Tracks of Hurricane Connie (solid line) and Hurricane Diane (dotted line) with 12-hourly positions indicated.

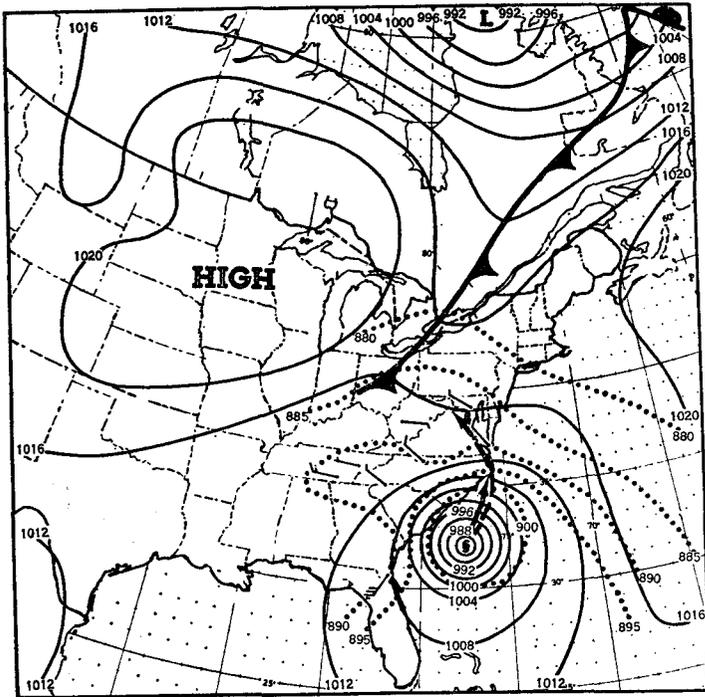


FIGURE 2.—Surface map, 1230 GMT, August 11, 1955, with 700-500-mb. thickness (mean virtual temperature) for 1500 GMT August 11 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of hurricane and dashed arrow indicates axis of the warm tongue.

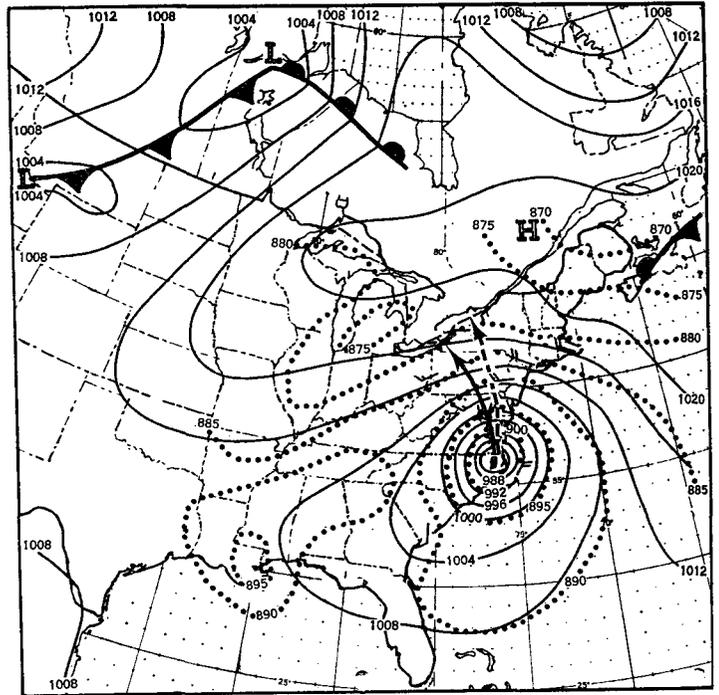


FIGURE 4.—Surface map, 0030 GMT August 13, 1955, with 700-500-mb. thickness (mean virtual temperature) for 0300 GMT August 13 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of the hurricane and dashed arrow indicates axis of the warm tongue.

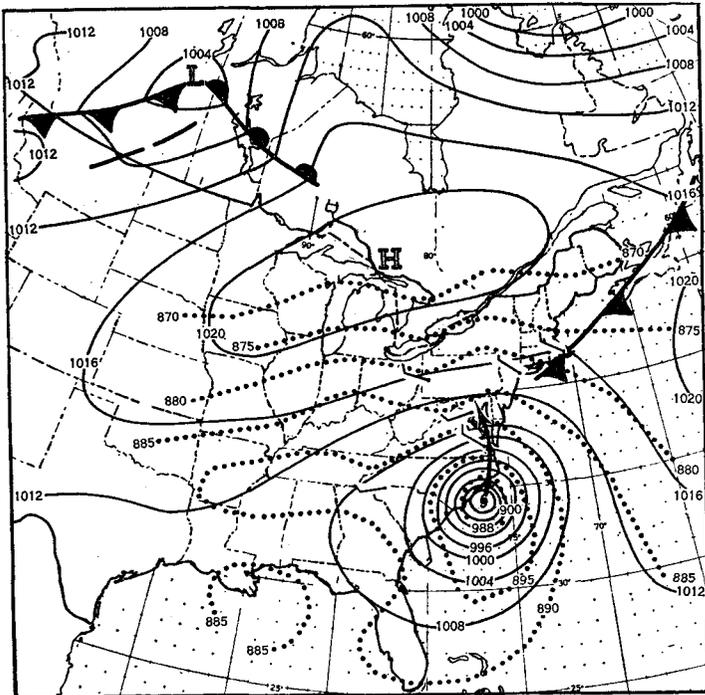


FIGURE 3.—Surface map, 1230 GMT August 12, 1955, with 700-500-mb. thickness (mean virtual temperature) for 1500 GMT August 12 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of the hurricane which in this instance coincided with the axis of the warm tongue.

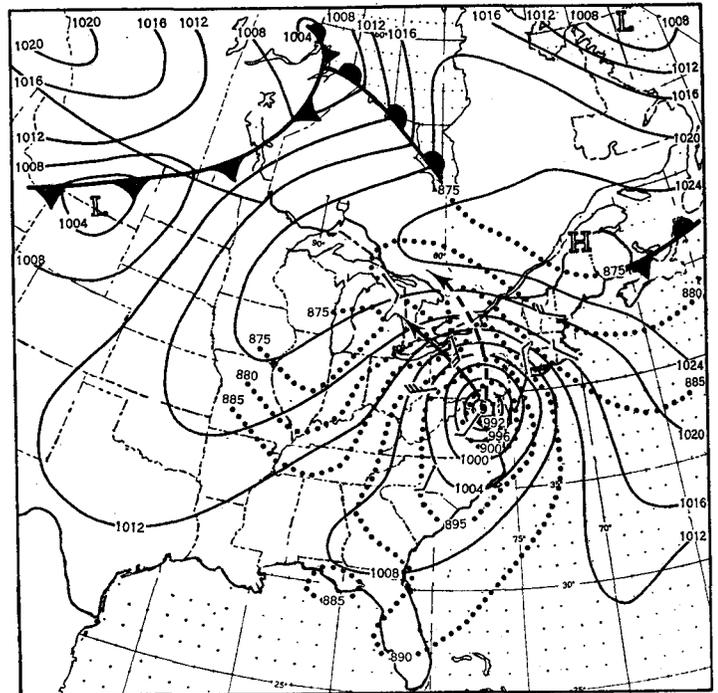


FIGURE 5.—Surface map, 1230 GMT August 13, 1955, with 700-500-mb. thickness (mean virtual temperature) for 1500 GMT August 13 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of the hurricane and dashed arrow indicates axis of the warm tongue.

at National Weather Analysis Center in predicting the 24-hour movement of hurricanes, namely Simpson's [1] warm tongue technique, Riehl and Haggard [2] computations, and high level steering.

## 2. SURFACE SYNOPTIC FEATURES

The dominant features of the 1230 GMT August 11 surface map (fig. 2) were: Hurricane Connie located just off the Carolina coast, a high center over the North Central States, another high center southeast of Newfoundland, and a cold front extending southwestward from eastern Canada across the eastern Lake Region. By 1230 GMT August 12 (fig. 3), Connie had recurved north-northeastward to just off Cherry Point, N. C., after first slowing to almost a halt some 12 hours earlier. As the cold front continued eastward across southeastern Canada, the High in the North Central States moved over the Great Lakes and began building eastward toward the St. Lawrence Valley. Another frontal system (fig. 4) moved into the Northwestern States with a wave developing near Lake Winnipeg. As the new frontal system moved northeast into the northwestern portion of Hudson Bay, as indicated on the 1230 GMT August 13 surface map (fig. 5), the High from the central Great Lakes moved rapidly eastward toward Maine with indications at this time for amalgamation with the High over the western Atlantic which had shown only a slow eastward motion from its position on the 11th. With this eastward shift of the High from the Great Lakes, Connie continued northward for about 12 hours and then started moving slightly west of north after passing Norfolk, Va. It was apparently coming under the influence of the strong easterly component developing to its north. During the next 24 hours Connie continued northwestward across central Pennsylvania and western New York, being steered around the blocking High to the northeast which finally amalgamated with the Atlantic cell by the end of the period. Connie continued filling in the Great Lakes region and was finally absorbed by the system from the west.

The dominant features of the surface map for 1230 GMT August 16 (fig. 6), when Diane was some 200 miles southeast of the Carolinas, were somewhat different from those just described when Connie was located off the Carolinas. A weak high center was located over eastern Pennsylvania with an east-west frontal system across the northern United States and southern Canada. This system was characterized by a weak wave over the Great Lakes and an occlusion in western Canada with a Low at the point of occlusion just north of Montana. A 1026 High was centered over Hudson Bay and another stationary High was located east of Bermuda. By the 1230 GMT August 17 map, figure 7, the waves in southern Canada had deepened a little and moved northeastward about  $5^\circ$  while the high center from Hudson Bay had moved rapidly southeastward to the vicinity of Nova Scotia.

Meanwhile Diane continued on a slow but regular north-west path to near Wilmington, N. C. Through the 24-hour period ending at 1230 GMT, August 18 (figs. 8 and 9), the waves along the northern United States border continued eastward with the High over Nova Scotia passing east-southeastward off Newfoundland. A weak high cell began to appear in eastern Iowa as Diane continued its slow curve north-northeastward toward Martinsburg, W. Va. By the end of the period, marked deepening of the occluded system over western Hudson Bay was noted while the first wave, now north of Diane, began filling. With continued deepening over Hudson Bay the occluded front and trough were accelerated eastward during the next 24 hours as the first wave continued filling. Apparently as a result of the deepening that had taken place in the vicinity of Hudson Bay the zonal westerlies aloft increased across southern Canada with a resultant build eastward of the ridge aloft and at the surface over Iowa. This action of the westerlies was instrumental in forcing Diane to take a sharp turn eastward after passing north of Washington, D. C. It passed off the coast south of Long Island, N. Y., at 1230 GMT, August 19, as the High from Iowa moved eastward into Indiana.

## 3. SIMPSON'S WARM TONGUE TECHNIQUE

By using charts of the difference in height between the 700-mb. and 500-mb. levels (mean virtual temperature) Simpson [1] has found that a tongue of warmer, lighter air is associated with the moving tropical cyclone and extends from 800-1,200 miles in advance of the storm. This tongue is oriented with its major axis parallel to the movement of the cyclone. An excellent lag exists, such that the orientation of the tongue at any instant usually indicates the direction of the cyclone's movement for the ensuing 24-hour period.

Thickness charts, 700-500 mb., were constructed for both storms, beginning when the storms were well off the Carolinas. These charts were superimposed on the corresponding regular 12-hourly surface charts (figs. 2-9). To support our analysis of the thickness charts, drawn for increments of 50 feet from subtracted data (obvious errors in data were corrected by reference to the surrounding thermal field), we calculated the thermal winds adjacent to the storm when data were available. One will note that when drawing for such small increments with sparse data it is highly desirable that all stations report and that the reports be quite accurate in order to arrive at a correct analysis. This also stresses the need for numerous RAWIN reports since PIBALS do not go high enough.

The first chart drawn for Connie (fig. 2) was for 1500 GMT August 11 when Connie was about 100 miles southeast of the Carolinas. This position for Connie was very critical prognostic-wise since we had noted a tendency for recurvature from surface indications. No wind reports were received from Charleston, S. C., or Cape

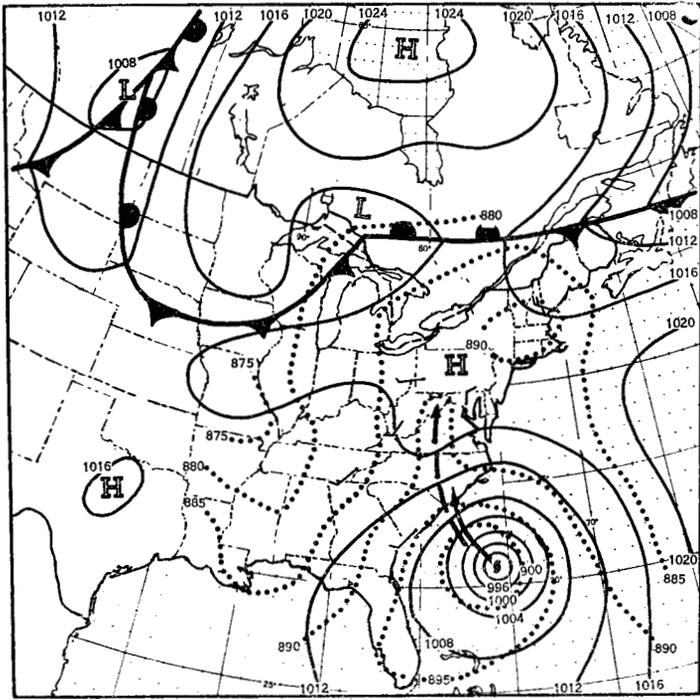


FIGURE 6.—Surface map, 1230 GMT August 16, 1955, with 700–500-mb. thickness (mean virtual temperature) for 1500 GMT August 16 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of the hurricane and dashed arrow indicates axis of the warm tongue.

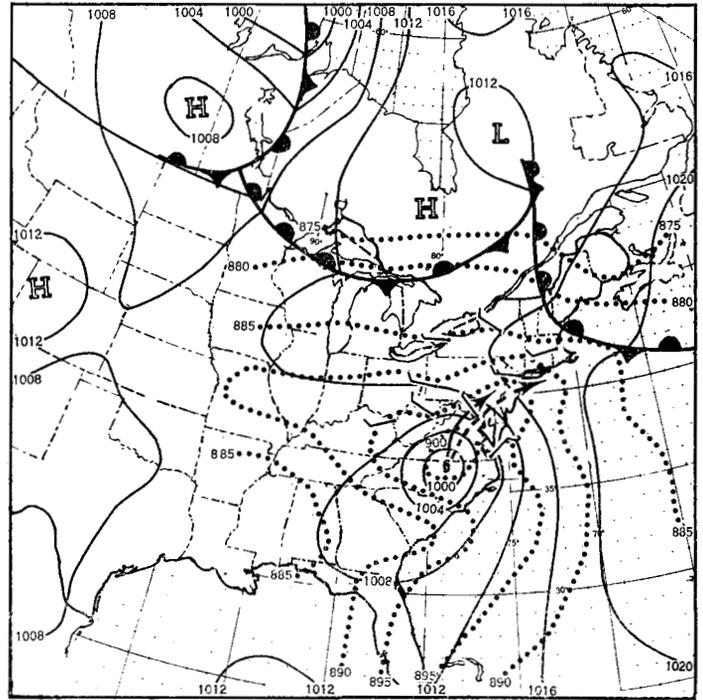


FIGURE 8.—Surface map, 0030 GMT August 18, 1955, with 700–500-mb. thickness (mean virtual temperature) for 0300 GMT August 18 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of the hurricane and dashed arrow indicates axis of the warm tongue.

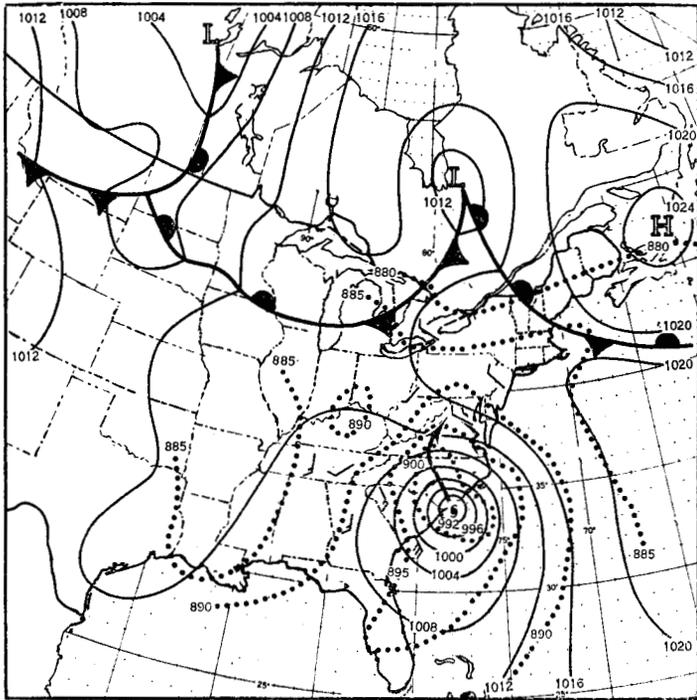


FIGURE 7.—Surface map, 1230 GMT August 17, 1955, with 700–500-mb. thickness (mean virtual temperature) for 1500 GMT August 17 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of the hurricane which in this instance coincided with the axis of the warm tongue.

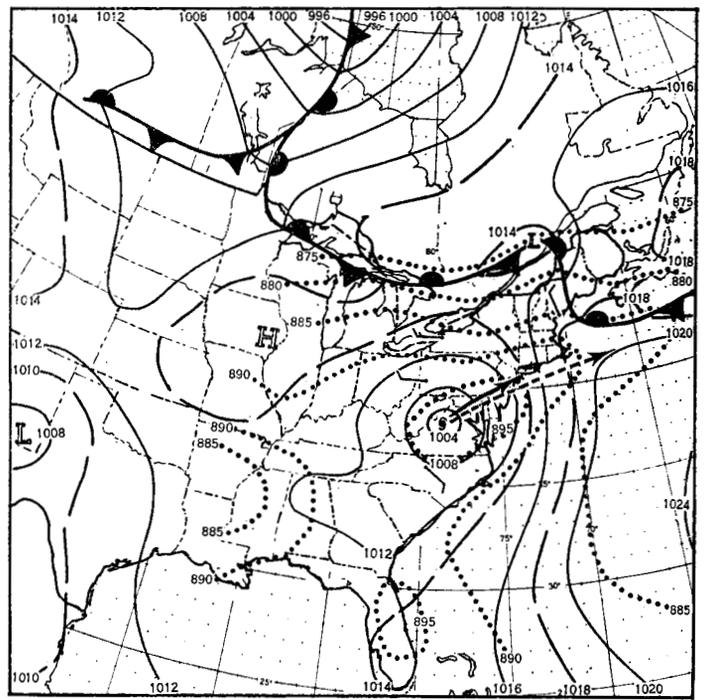


FIGURE 9.—Surface map, 1230 GMT August 18, 1955, with 700–500-mb. thickness (mean virtual temperature) for 1500 GMT August 18 represented by dotted lines. Thermal winds for this layer are represented by conventional means. Heavy arrow is actual 24-hour movement of the hurricane and dashed arrow is axis of the warm tongue.

Hatteras, N. C., so we had no nearby thermal wind computations to support our thickness analysis. The position of the axis of the warm tongue, shown toward the north-northeast instead of west-northwest, was based on the continuity of the warm tongue axis for the previous 24 hours which indicated a marked trend toward increasing to the north while the residual tongue northwestward was weakening. With sparse or doubtful data one can see how the technique becomes quite subjective.<sup>1</sup>

The next chart constructed was for 1500 GMT August 12, after Connie had curved north-northeastward and was approaching the eastern tip of North Carolina (fig. 3). Supported by thermal winds, the axis of the warm tongue is indicated northward just west of Norfolk and east of Washington which coincides with the movement of Connie. The charts for 0300 and 1500 GMT August 13 (figs. 4 and 5), supported fairly well by thermal winds, indicate an axis a little west of north through eastern Pennsylvania and central New York. The actual path of the storm through the above period made an angle of 20°-30° toward the west from the warm tongue axis. This small deviation is believed to be due to the blocking effect of the High to the north of Connie as suggested earlier in the discussion of surface features and will be discussed in more detail later.

For Diane, the first chart constructed was for 1500 GMT August 16 (fig. 6), when the storm was located some 200 miles southeast of the Carolinas. As Diane did not show any marked tendency to slow its forward motion on approaching the coast, continuity considerations called for the axis of the warm tongue to lie northwestward across southern North Carolina and the actual path of Diane was along this axis. The thickness chart for 1500 GMT August 17 (fig. 7) indicates a continued northwest axis of the warm tongue through North Carolina followed by a curve northward through western Virginia. The path of Diane again coincided with this axis. The first hint of Diane's recurving sharply toward the northeast is shown in figures 8 and 9 when the warm tongue, supported by thermal winds, showed an axis northeastward along a line south of Hempstead, N. Y., and Nantucket, Mass. Diane's path throughout its course along the Atlantic Seaboard followed closely the warm tongue axis described by Simpson.

4. RIEHL AND HAGGARD COMPUTATIONS

Riehl [3] states that tropical storms move with a direction and speed closely approximating that of the tropospheric current surrounding them. If the flow at 500 mb., or some parameter based on this flow, can be taken as the tropospheric current then the storm's velocity can be determined from these charts. Further, if the com-

<sup>1</sup> During a conversation with Mr. Simpson on this phase of the storm and its apparent ill-defined warm tongue, he stated he had noted a similar effect with Carol last year and feels that this lack of a well-defined warm tongue can be explained by the fact that both storms had a very slow forward speed at the time. He said theoretical considerations show that the development of the warm tongue is directly related to the progressive forward motion of the storm.

TABLE 1.—Comparison of actual 24-hour movement of Connie and Diane with prognosticated movement computed by the Riehl and Haggard method

Time of 500-mb. chart		Computed 24-hour movement		Actual movement	
CONNIE					
GMT	August 1955				
1500	11	2.0° N.	0.8° E.	2.8° N.	0.5° E.
1500	12	3.8° N.	2.1° E.	5.2° N.	1.0° W.
0300	13	4.9° N.	0.8° E.	5.5° N.	3.2° W.
1500	13	5.5° N.	1.8° W.	4.0° N.	5.4° W.
DIANE					
1500	16	2.5° N.	2.8° W.	3.5° N.	2.2° W.
1500	17	5.0° N.	1.0° E.	4.0° N.	0.2° E.
0300	18	5.0° N.	4.2° E.	3.3° N.	4.0° E.
1500	18	2.8° N.	5.2° E.	2.2° N.	5.5° E.

putations are not made too close to the storm center, the forces which will act on the storm during the next 24 hours might be included.

Following the technique outlined by Riehl and Haggard [2] and using the 500-mb. charts of NWAC (reanalyzed carefully for computed data or late data when needed), table 1 was prepared giving computations of the N-S and E-W components of the movement of Connie and Diane as compared to the actual movement. The computations were made for the same times as those for Simpson's technique and follow the surface positions of the two storms (figs. 2-9). This technique foretold accurately Connie's recurvature toward the eastern tip of North Carolina and its continued northward movement. However, it failed to catch the westward movement of Connie after passing Norfolk, Va. This deviation, we feel, is due to the fairly rapid change in the 500-mb. pattern after that time. In figure 10A is shown the advection chart that is used often at NWAC as a qualitative tool in making our 500-mb. prognostic charts. In the chart the 1000-500-mb. thickness lines are superimposed on the 1000-mb. contours for 1500 GMT August 12. Note the strong warm advection indicated toward Hudson Bay as cooler air holds over the Great Lakes. This pattern suggests that height rises will develop aloft in the eastern Hudson Bay and St. James Bay area. Figure 10B, the 500-mb. 12-hour height change chart for 0300 GMT August 13, verifies such height rises. Figure 10C shows the advection chart for 0300 GMT August 13, the second half of the forecast period during which the computations for Connie broke down. Again note the field of warm advection proceeding eastward across eastern Canada. Also at this time the warm advection with the tropical cyclone became quite noticeable over the New England States. The overall change in heights for 24 hours in eastern Canada is shown (fig. 10D) to be more than +400 feet. This height rise was effective in developing the block to the north of Connie and increasing the east-to-west component north of the storm thus steering it westward. When using the Riehl and Haggard technique it is necessary to determine

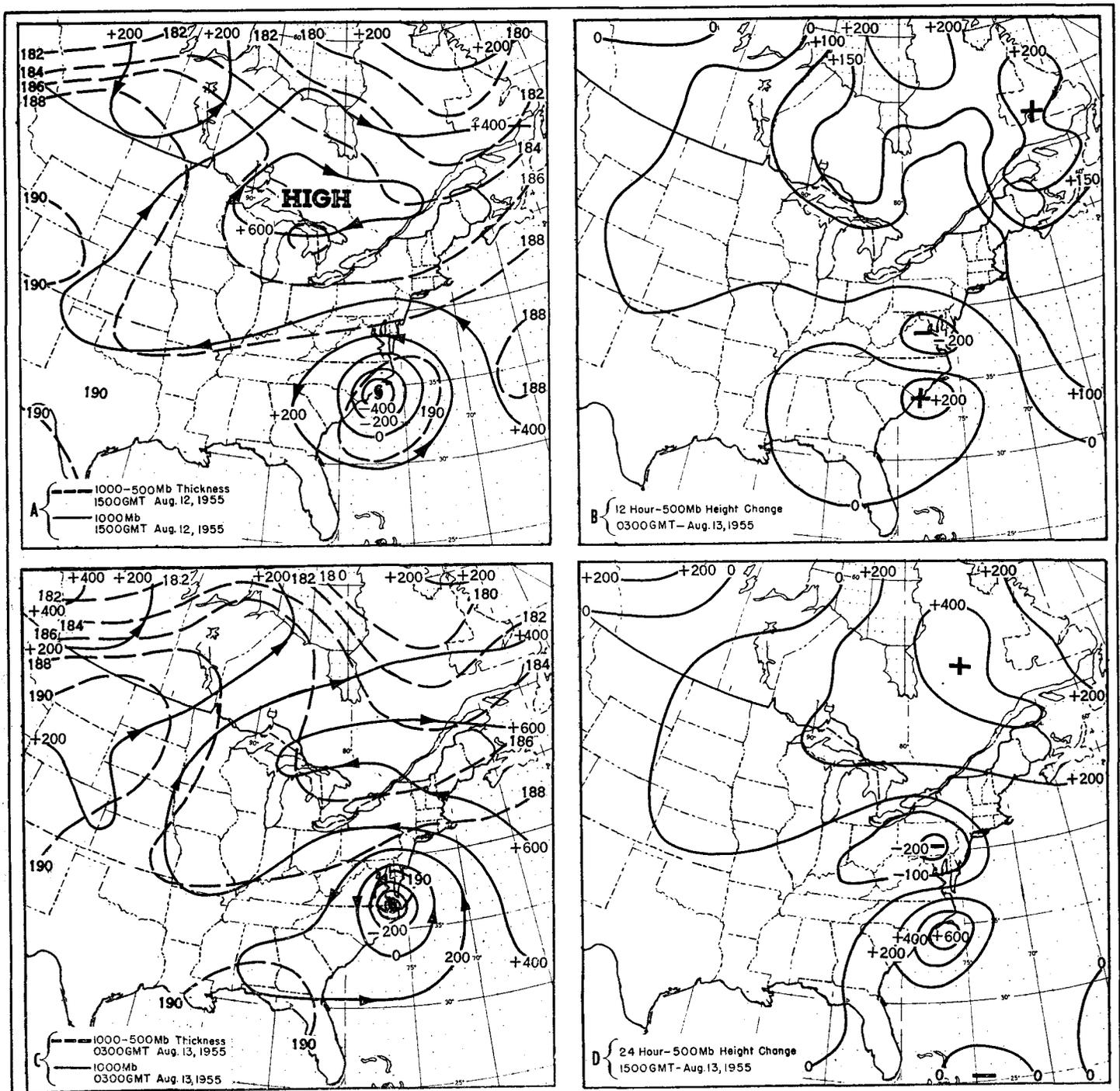


FIGURE 10.—(A) Isopleths of current 1000–500-mb. thickness (dashed) superimposed on the 1000-mb. contours (solid) for 1500 GMT August 12, 1955; (B) the 500-mb. height change in the 12-hour period following map A; (C) the current 1000–500-mb. thickness (dashed) superimposed on the 1000-mb. contours for 0300 GMT August 13, 1955; (D) the 500-mb. height change in the 24-hour period following map A.

beforehand any marked changes in the 500-mb. pattern that may occur within the forecast period for which allowances have to be made.

For Diane (fig. 11 A–D) the advection and height change charts do not indicate any large scale changes in the 500-mb. pattern adjacent to the storm through the period August 17–18. However, the area of widespread

deepening over northern Hudson Bay was instrumental in speeding up the zonal westerlies across southern Canada. Correspondingly the ridge over the Central States built eastward and followed a minor trough across the New England States. This building of the ridge west of Diane was effective in curving the storm path more sharply to the east. It may be noted in table 1 that less north com-

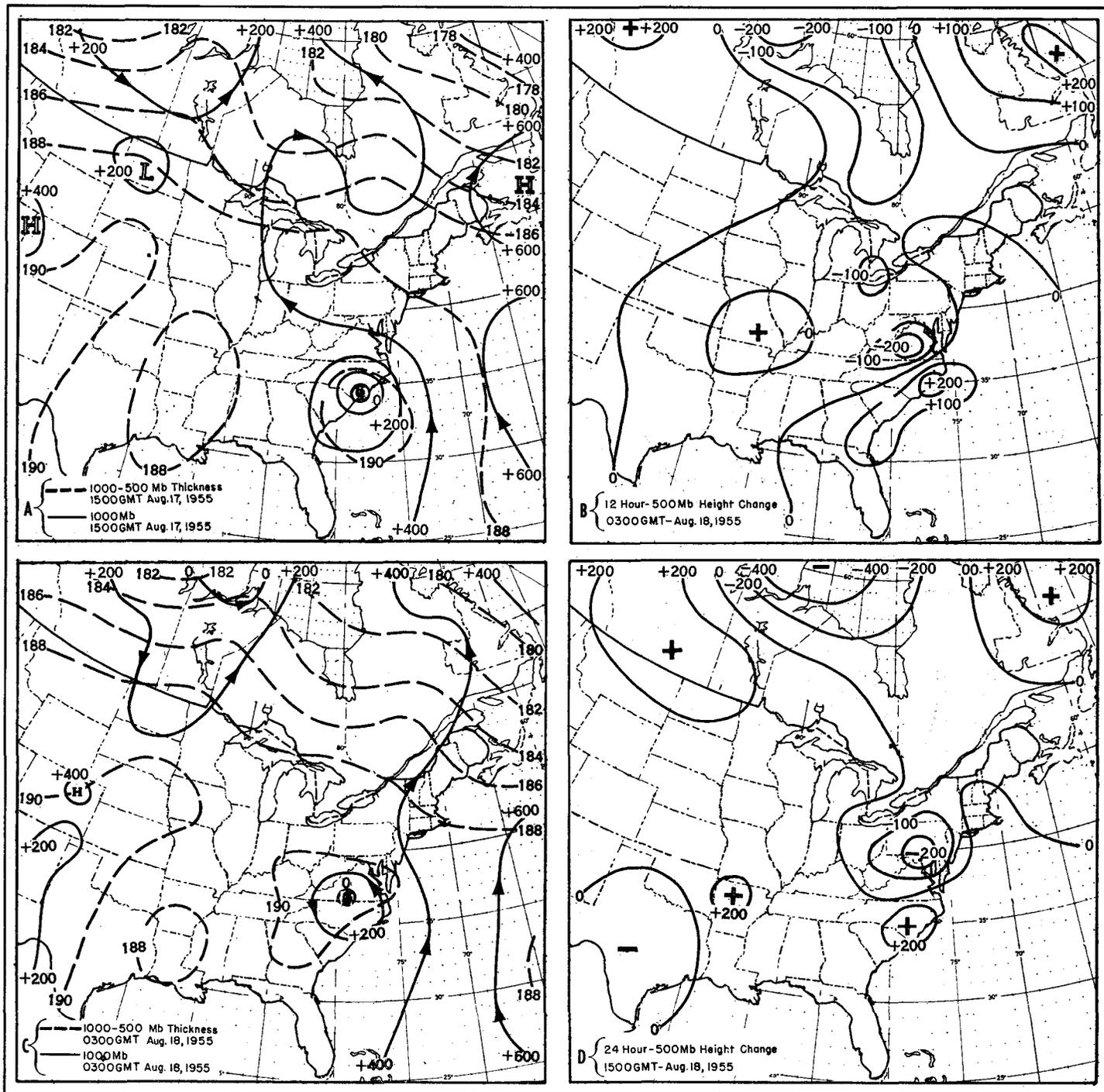


FIGURE 11.—(A) Isoleths of current 1000–500-mb. thickness (dashed) superimposed on the 1000-mb. contours (solid) for 1500 GMT August 17, 1955; (B) the 500-mb. height change in the 12-hour period following map A; (C) the current 1000–500-mb. thickness superimposed on the 1000-mb. contours for 0300 GMT August 18, 1955; (D) the 500-mb. height change in the 24-hour period following map A.

ponent occurred than was forecast. The Riehl and Haggard technique gave good results for the movement of Diane.

### 5. HIGH LEVEL STEERING

In the earlier studies of tropical meteorology such authorities as Bowie and Weightman [4] and Mitchell [5] emphasized the steering of tropical storms by the current within which they were embedded. Often the 3-km. level

was thought to be a good steering level. With the advent of higher and more numerous upper air reports, Norton [c. f. 6], Simpson [1], Dunn [7, 8], and others have found it necessary to go to very high levels in the troposphere to obtain a steering level free of the influence of well-developed tropical storms.

The actual existence of a so-called steering level has not been fully accepted. Recent studies by Simpson [9] have

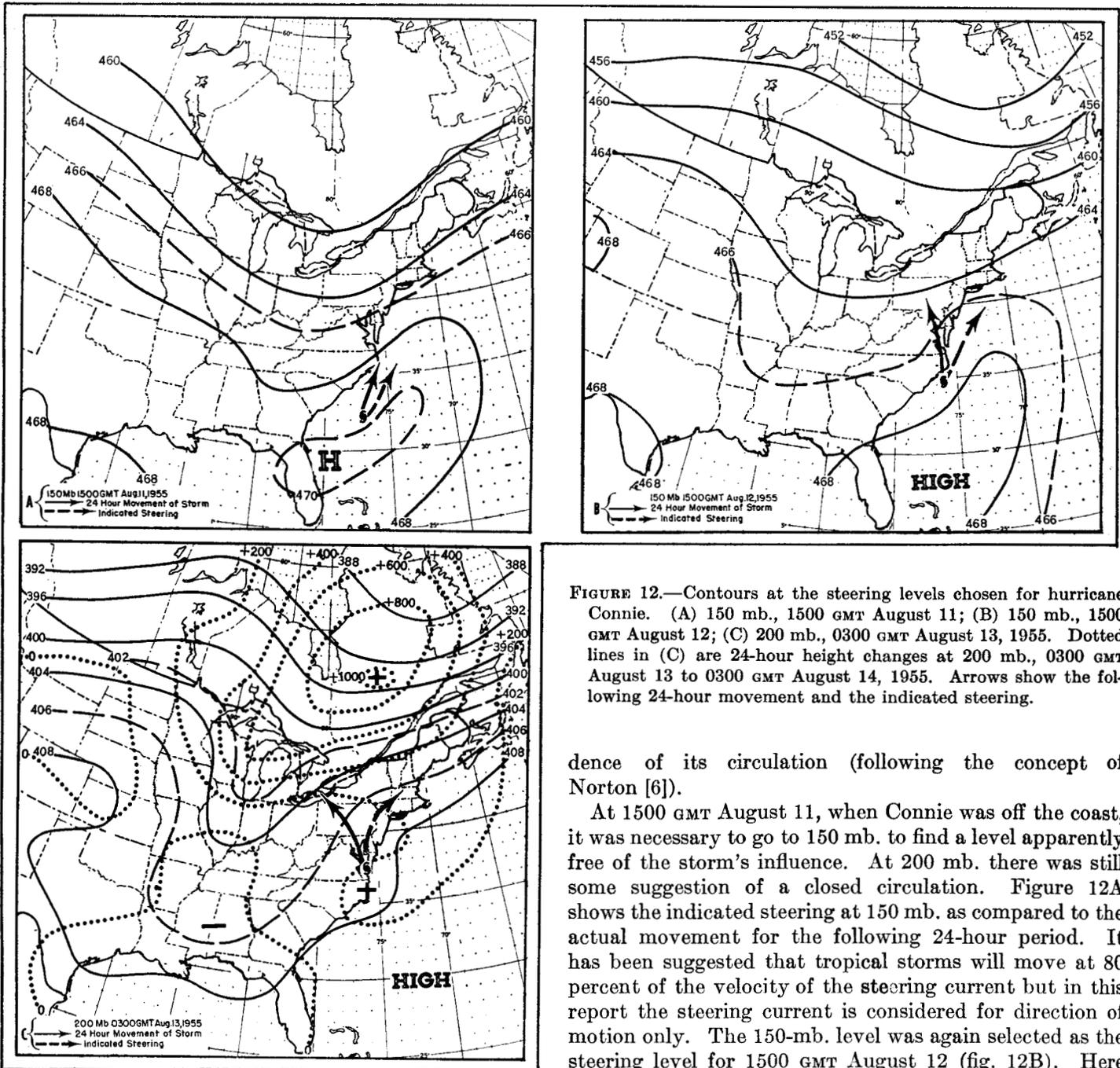


FIGURE 12.—Contours at the steering levels chosen for hurricane Connie. (A) 150 mb., 1500 GMT August 11; (B) 150 mb., 1500 GMT August 12; (C) 200 mb., 0300 GMT August 13, 1955. Dotted lines in (C) are 24-hour height changes at 200 mb., 0300 GMT August 13 to 0300 GMT August 14, 1955. Arrows show the following 24-hour movement and the indicated steering.

dence of its circulation (following the concept of Norton [6]).

At 1500 GMT August 11, when Connie was off the coast, it was necessary to go to 150 mb. to find a level apparently free of the storm's influence. At 200 mb. there was still some suggestion of a closed circulation. Figure 12A shows the indicated steering at 150 mb. as compared to the actual movement for the following 24-hour period. It has been suggested that tropical storms will move at 80 percent of the velocity of the steering current but in this report the steering current is considered for direction of motion only. The 150-mb. level was again selected as the steering level for 1500 GMT August 12 (fig. 12B). Here we note, as with the other techniques, a deviation beginning to show up when the indicated steering is compared to the actual movement. The upper level steering suggested a continued northeast track whereas the storm was beginning to turn north and just west of north. At 0300 GMT August 13, as the storm had filled some aloft, the 200-mb. level could be selected for steering (fig. 12C). For the first part of the period a northerly path was indicated with a turn later to the northeast through eastern Pennsylvania. However, from this time the storm continued west of north and northwestward across Pennsylvania. This deviation was to be expected since steering by the current in which the storm is embedded

suggested a much more complex structure in which small cellular anticyclonic eddies form outward at higher levels from the storm's center. However, on the basis of usage by numerous forecasters, it is of interest to investigate the relation between the future movement of the storm after it has passed into mid-latitudes and the smooth flow at some higher unaffected level above the storm. The simplicity of this technique is obvious, with results obtained from a direct inspection of higher level charts where emphasis has been placed on reliable wind data. Thus, for our purposes the steering level is considered as simply the first level above the storm where there exists no evi-

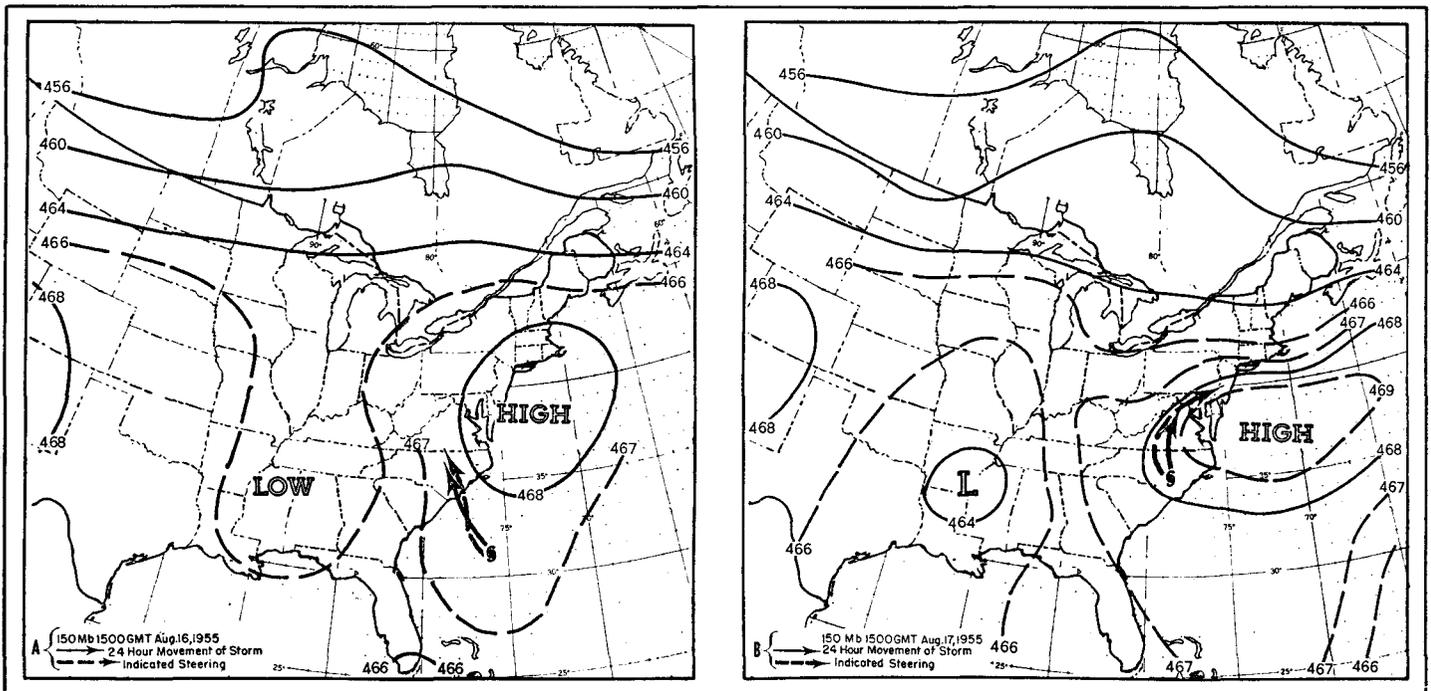
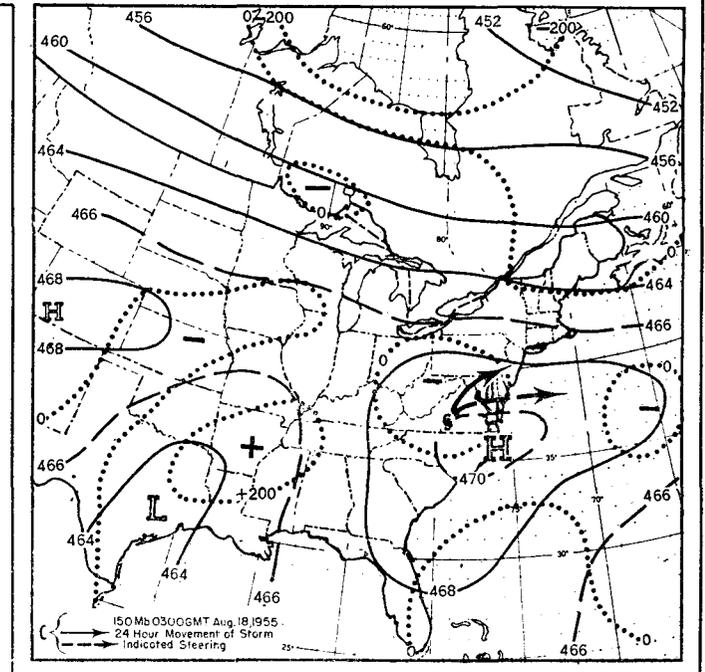


FIGURE 13.—Contours at the steering levels chosen for hurricane Diane. (A) 150 mb., 1500 GMT August 16; (B) 150 mb., 1500 GMT August 17; (C) 150 mb., 0300 GMT August 18, 1955. Dotted lines in (C) are 24-hour height changes at 150 mb., 0300 GMT August 18 to 0300 GMT August 19, 1955.

assumes that little change, other than that from the tropical storm, will take place in the current, and we have already seen, in the discussion of the breakdown of the Riehl and Haggard technique at this same point in Connie's path, that fairly rapid changes occurred in the flow at 500 mb. during the next 24 hours. These changes were necessarily reflected at higher levels. In figure 12C are indicated the height changes that occurred in eastern Canada at the 200-mb. level during the next 24 hours. Height rises of the magnitude of 1,000 feet occurred east of James Bay and were sufficient to produce a backing of the steering level winds over Pennsylvania to 150°. Such a shift in the steering winds agrees with the actual path of Connie across Pennsylvania. As a result of the large height rises over the Great Lakes and eastern Canada a cut-off Low formed over Michigan and drifted southward simultaneously with the backing of the steering winds. In effect, the steering level winds became a part of the circulation of the newly formed Low.

The best steering level for Diane was found to be the 150-mb. level. Note from figure 13 that this level gave good results for the indicated steering compared to the actual path of the storm. The 24-hour 150-mb. height changes indicated on figure 13C as dotted contours show only small-scale changes for the period 0300 GMT August 18 to 0300 GMT August 19.



### 6. CONCLUSIONS

Since hurricanes cause great damage over the areas they traverse, every known technique which can aid in forecasting their movement must be applied and the results carefully weighed. In doing this it is necessary for the analyst to pay strict attention to all details of the surface and upper air analysis. It is felt that too little attention is given to objective techniques as compared to short range forecast aspects such as following hourly positions of the storm's eye, which may be oscillating within the

storm thus leading one to assume a false shift in direction of the storm. After the forecaster has considered the overall general circulation in relation to the storm's environment and finds no indicated changes that may affect the environment for the forecast period, he can use with confidence the above discussed techniques. However, by making suitable quantitative adjustments for any changes indicated in the circulation such as developing blocks, deepening polar troughs, and changes in the zonal westerlies which may affect the storm's environment, the forecaster can modify the results of the technique with a resulting improved forecast tool. At times all techniques, especially upper steering, through the lack of data or through the inaccuracy of data received become quite subjective and, as a consequence, the analyst's confidence in them is reduced.

#### ACKNOWLEDGMENTS

The authors wish to express their thanks to the staff of the National Weather Analysis Center for their aid in the preparation of this report, and especially to Messrs. A. K. Showalter, F. W. Burnett, C. M. Lennahan, V. J. Oliver, and R. H. Simpson for their helpful suggestions and constructive criticism. We are also indebted to the staff of the Daily Map Unit who prepared the illustrations.

#### REFERENCES

1. R. H. Simpson, "On the Movement of Tropical Cyclones," *Transactions, American Geophysical Union*, vol. 27, No. 5, October 1946, pp. 641-655.
2. H. Riehl and W. H. Haggard, "Prediction of Tropical Cyclone Tracks," Second Research Report, Task 12, U. S. Navy, Bureau of Aeronautics, Project AROWA, 1953, 32 pp.
3. H. Riehl, *Tropical Meteorology*, McGraw-Hill Book Co., Inc., New York, 1954, 392 pp.
4. E. H. Bowie and R. H. Weightman, "Types of Storms of the United States and Their Average Movement," *Monthly Weather Review Supplement* No. 1, Washington, D. C., 1916, 37 pp. and 114 charts.
5. C. L. Mitchell, "West Indian Hurricanes and Other Tropical Cyclones of the North Atlantic," *Monthly Weather Review Supplement* No. 24, Washington, D. C., 1924, 47 pp.
6. R. C. Gentry, "Forecasting the Formation and Movement of the Cedar Keys Hurricane, September 1-7, 1950," *Monthly Weather Review*, vol. 79, No. 6, June 1951, pp. 107-115.
7. G. E. Dunn, "Brief Survey of Tropical Atlantic Storms," Lecture Notes, Institute of Tropical Meteorology, Rio Piedras, P. R., 1944.
8. G. E. Dunn, "Tropical Cyclones," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 887-901.
9. R. H. Simpson, "On the Structure of Tropical Cyclones as Studied by Aircraft Reconnaissance," Annex II of *Causes and Characteristics of Thunderstorms and Other Atmospheric Disturbances*, Seventh Interim Report submitted in accordance with Public Law 657, 80th Congress, U. S. Weather Bureau, Washington, D. C., July 1955.